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Sensorimotor characteristics of sign translations modulate EEG  
when deaf signers read English

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1 ABSTRACT

2 Bilingual individuals automatically translate written words from one language to  
3 another. While this process is established in spoken-language bilinguals, there is less  
4 known about its occurrence in deaf bilinguals who know signed and spoken languages.  
5 Since sign language uses motion and space to convey linguistic content, it is possible  
6 that action simulation in the brain's sensorimotor system plays a role in this process. We  
7 recorded EEG from deaf participants fluent in ASL as they read individual English  
8 words and found significant differences in alpha and beta EEG at central electrode sites  
9 during the reading of English words whose ASL translations use two hands, compared  
10 to English words whose ASL translations use one hand. Hearing non-signers did not  
11 show any differences between conditions. These results demonstrate the involvement of  
12 the sensorimotor system in cross-linguistic, cross-modal translation, and suggest that  
13 action simulation processes may be key to deaf signers' language concepts.

14

15 Keywords: sign language, action simulation, translation, reading, ASL; EEG

1                   Sensorimotor characteristics of sign translations modulate EEG  
2                                   when deaf signers read English

3  
4 1. Background

5 Cross-linguistic translation occurs when a bilingual person automatically accesses  
6 mental lexicons for both known languages even when translation is not required (Baten,  
7 Hofman, & Loeys, 2010; Duyck, Van Assche, Drieghe, & Hartsuiker, 2007; Lemhöfer &  
8 Dijkstra, 2004). Substantial evidence demonstrates cross-linguistic translation in  
9 spoken languages among bilinguals who use two spoken languages (unimodal  
10 bilinguals; Midgley, Holcomb, & Grainger, 2009; Thierry & Wu, 2007). Researchers  
11 have made comparatively less progress regarding how deaf bilinguals link meaning  
12 between languages that rely on different modalities—for example, written language (e.g.,  
13 English) and sign language (e.g., American Sign Language, ASL). It is possible that while  
14 processing written English, deaf bilinguals activate the corresponding ASL translations.  
15 Both behavioral and psychophysiological evidence suggests that automatic cross-  
16 linguistic translation does occur when deaf signers read English (Giezen, Blumenfeld,  
17 Shook, Marian, & Emmorey, 2015; Giezen & Emmorey, 2015; Meade, Midgley, Sehyr,  
18 Holcomb, & Emmorey, 2017; Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011). These  
19 researchers use phonological interference paradigms, presenting pairs of written words,  
20 some of which have ASL translations that share phonological properties (e.g., location of  
21 sign). Thus, participants in these studies may become aware of the experimental  
22 manipulation, possibly using conscious strategies to complete the experimental task  
23 (Meade et al., 2017). The canonical language networks in the brain have been identified  
24 as a likely mechanism for how this phenomenon occurs (Meade et al., 2017).

1           Since sign language uses motion and space to convey linguistic content, an  
2 individual who is fluent in sign language may implicitly draw upon their brain's  
3 sensorimotor system during cross-linguistic, cross-modal translation. A consideration of  
4 ASL-related processing without discussion of the sensorimotor system of the brain is  
5 incomplete (Corina, Lawyer, & Cates, 2013; Emmorey, McCullough, Mehta, &  
6 Grabowski, 2014; Gutierrez-Sigut, Payne, & MacSweeney, 2016). For instance, while  
7 perceiving ASL is likely to rely on some modality-independent processing, such as the  
8 recruitment of classical phonology regions during ASL phonology tasks (Petitto et al.,  
9 2016), recent work shows that hearing interpreters process sign language phonology by  
10 activating visuo-motor systems to relay gestural input to the language network  
11 (Kanazawa et al., 2017). Since ASL signs are produced with the hands and arms,  
12 producing ASL is associated with increased activity in the primary sensory and motor  
13 cortices (Emmorey et al., 2014; Emmorey, Mehta, McCullough, & Grabowski, 2016).

14           Thus, we know that the sensorimotor systems are involved in sign processing to  
15 some extent. But, we don't know how the sensorimotor system is involved in cross-  
16 modal, cross-linguistic translation in deaf readers. Embodied cognition theorists posit  
17 that perception is grounded in one's own ability to act (Barsalou, 2008; Creem-Regehr  
18 & Kunz, 2010; Gallese & Sinigaglia, 2011). One instantiation of this theory is the action  
19 observation system (AON) of the human brain, which includes brain regions that are  
20 uniquely sensitive to other people's actions (Caspers, Zilles, Laird, & Eickhoff, 2010;  
21 Molenberghs, Cunnington, & Mattingley, 2012). The AON is thought to include the  
22 putative human mirror neuron system, which has been a topic of much debate (Gallese,  
23 Gernsbacher, Heyes, Hickok, & Iacoboni, 2011; Hickok, 2009; Kessler & Garrod, 2013;  
24 Rizzolatti & Sinigaglia, 2010, 2016). One likely function of the mirroring system, and of

1 the AON, is action simulation—a phenomenon wherein somatosensory and motor  
2 aspects of an action are simulated even in the absence of action production. For  
3 instance, an observer of dance may draw upon her own sensorimotor system to simulate  
4 the movements involved in another person’s dance routine (Calvo-Merino, Glaser,  
5 Grezes, Passingham, & Haggard, 2005; Calvo-Merino, Grèzes, Glaser, Passingham, &  
6 Haggard, 2006; Gardner, Goulden, & Cross, 2015; Kirsch & Cross, 2015), or a person  
7 may mentally simulate an imagined action (Decety, 1996; Jiang, Edwards, Mullins, &  
8 Callow, 2015).

9 Action simulation results in changes in the sensorimotor alpha (8-13 Hz) and  
10 beta (~14-25 Hz) rhythms present within the EEG signal. Typically, imagining or  
11 observing actions leads to a suppression, or desynchronization, of alpha and beta  
12 rhythms measurable at electrodes over the primary somatosensory and primary motor  
13 cortices (Avanzini et al., 2012; de Lange, Jensen, Bauer, & Toni, 2008;  
14 Muthukumaraswamy, Johnson, & McNair, 2004; Quandt & Marshall, 2014). When  
15 measured at central electrodes overlying the central sulcus, 8-13 Hz alpha suppression is  
16 most linked to activity within the primary somatosensory cortex, and 14-22 Hz beta  
17 suppression is more correlated with activation of the primary motor cortex (Ritter,  
18 Moosmann, & Villringer, 2009; Salmelin & Hari, 1994).

19 A growing body of literature has examined the functionality of the AON and  
20 mirroring-related regions in sign language processing, given the visual-spatial  
21 movements required to produce signs, and the action observation processes which are  
22 likely to be involved in sign perception. Using functional magnetic resonance imaging  
23 (fMRI), a number of studies have shown little to no involvement of classical “mirroring”  
24 processes during deaf signers’ perception of ASL (Corina & Gutierrez, 2016; Corina &

1 Knapp, 2006; Emmorey, Xu, Gannon, Goldin-Meadow, & Braun, 2010). Emmorey and  
2 colleagues (2010) examined the differences in mirroring activity between hearing non-  
3 signers and deaf signers during observation of pantomimes (e.g. peeling an imaginary  
4 banana) and ASL action verbs. Results showed activations for pantomimed actions and  
5 ASL verbs in regions associated with mirror-related processing in hearing non-signers.  
6 Deaf signers showed no significant activations in these mirroring areas when viewing  
7 pantomimes. These results echo that of Corina et al. (2006), which indicate insignificant  
8 recruitment of the AON for deaf signers during observation of intransitive self-oriented  
9 actions (e.g. rubbing one's eyes), transitive object-oriented actions (e.g. opening a door),  
10 and ASL signs, while fronto-parietal activations were observed for hearing non-signers  
11 under these same conditions. These results suggest that hearing non-signers recruit the  
12 AON when observing ASL while deaf signers do not. MacSweeney et al.'s (2004) work  
13 on gesture and sign language, however, demonstrates that deaf signers recruit parts of  
14 the AON more robustly during sign language perception compared to a non-language  
15 gestural communication system. In contrast, hearing non-signers showed the opposite  
16 effect (communication system > BSL) in similar AON areas. Taken together, these  
17 studies indicate that more research exploring the interaction between bimodal language  
18 experience and the AON is needed.

19

#### 20 1.1 The current study

21 Drawing upon existing work, we designed a study to assess whether implicit cross-  
22 modal, cross-linguistic translation would affect sensorimotor EEG rhythms, indicating  
23 the involvement of the sensorimotor system in the translation occurring when deaf  
24 signers read English. If the sensorimotor system is involved in this process, we would be

1 able to conclude that action simulation processes occur during reading, wherein deaf  
2 readers unconsciously simulate ASL translations of English words.

3         Functional neuroimaging has shown that the right primary sensory and motor  
4 cortices are more active when deaf signers produce two-handed signs, compared to one-  
5 handed signs (Emmorey et al., 2016), a pattern which is in line with existing work using  
6 non-linguistic movements (Toyokura, Muro, Komiya, & Obara, 2002). If direct action  
7 simulation processes were involved during cross-linguistic, cross-modal translation  
8 processes, we expect that English words with a two-handed ASL translation would result  
9 in greater alpha and beta desynchronization over the right pre- and post-central region.

10         One line of work has asked whether reading action-related language invokes  
11 action simulation processes, in the same way as observing action does. While there is  
12 some divergence regarding this hypothesis (Kemmerer & Gonzalez-Castillo, 2010;  
13 Postle, McMahon, Ashton, Meredith, & de Zubicaray, 2008), a number of studies have  
14 demonstrated that reading action words results in somatotopic activation of  
15 sensorimotor cortices, suggesting that implicit simulation of action may contribute to a  
16 reader's comprehension of a written word (Hauk, Johnsrude, & Pulvermüller, 2004;  
17 Hauk & Pulvermüller, 2011; Pulvermüller, Härle, & Hummel, 2001; Schaller, Weiss, &  
18 Müller, 2017). The current study draws upon this work to examine sensorimotor EEG  
19 rhythms during single word reading.

20         We collected EEG from across the scalp as deaf signers and hearing non-signers  
21 read English words for which the ASL translations used either one or two hands. The  
22 design allowed us to compare sensorimotor involvement between words with one- and  
23 two-handed ASL translations for each group. Our task involved no mention of ASL, and  
24 there was no deliberate interference stemming from ASL phonology. This design

1 removed the issue of awareness of ASL phonology during the reading task, allowing for  
2 an entirely passive approach. The work we describe here is the first time-frequency EEG  
3 analysis of neural activity while deaf signers read.

4 We predicted that deaf signers would show significant differences in alpha and  
5 beta EEG rhythms during the reading of English words whose ASL translations use  
6 either 1 or 2 hands. Specifically, we expected that the increased sensorimotor demands  
7 of carrying out a 2-handed sign would be reflected in the simulated neural activity,  
8 resulting in differences over the right fronto-central regions overlying primary  
9 sensorimotor cortices and other key regions of the AON (e.g., premotor cortex and  
10 supplementary motor area). The right laterality of this effect was predicted since a key  
11 difference between a 1-handed ASL sign (always produced with the dominant hand) and  
12 a 2-handed ASL sign is the use of the left hand. We expected that both the alpha rhythm  
13 of the EEG signal (~8-13 Hz) and the beta rhythm (~14-25 Hz) would show greater  
14 desynchronization in response to 2-handed signs. We were less confident in the  
15 direction of the effect for the beta rhythm, given the complex nature of the beta rhythm  
16 (Spitzer & Haegens, 2017). We expected that the hearing group would show no  
17 significant differences between conditions, given that they do not know ASL and thus  
18 there should be no automatic translation processes occurring in this group.

19

## 20 2. Materials and Methods

### 21 2.1 Participants

22 Twenty-four Deaf fluent signers (12 females; 1 declined to respond) and twenty-two  
23 Hearing non-signers (8 females; 1 declined to respond) participated in the experiment  
24 (mean age = 28.9 years, SD = 8.99). Participants signed an informed consent form



1 presented in written English and American Sign Language that had been approved by  
 2 the university Institutional Review Board. All Deaf signers were self-identified as fluent  
 3 in American Sign Language with 91.6% reporting they started using ASL at or before the  
 4 age of 5 (mean = 2.88, SD = 5.36, median = 1). The hearing non-signers reported  
 5 normal hearing and no knowledge of any signed language. All participants self-reported  
 6 as neurologically healthy, having normal or corrected vision, and all but two reported  
 7 being right-handed. Educational, demographic, and language background information  
 8 is shown in Tables 1 and 2.

9

	Deaf	Hearing
Some high school	0	0
High school	4 (16.7%)	0
GED	1 (4.2%)	0
Some college	3 (12.5%)	1 (4.5%)
Associates	0	2 (9.1%)
Bachelors	4 (16.7%)	7 (31.8%)
Some grad school	2 (8.3%)	3 (13.6%)
Masters	6 (25%)	8 (36.4%)
Doctorate	4 (16.7%)	1 (4.5%)

10 Table 1. Formal education. Self-reported highest educational degree obtained for Deaf  
 11 and Hearing participants.

12  
 13

	Deaf	Hearing	t-test <i>p</i> value
Age (years)	30.8 (11.6)	27.1 (4.5)	.16
Current written English use <sup>a</sup>	1.5 (.9)	1.3 (.6)	.41
% Written English understanding <sup>b</sup>	87.8 (17.5)	93.9 (21)	.30
% Written English production <sup>b</sup>	81 (20.7)	91 (21)	.09
Current ASL use <sup>a</sup>	1.3 (.5)		
ASL understanding <sup>b</sup>	90.8 (10.9)		
ASL production <sup>b</sup>	95 (6.2)		

<sup>a</sup> Self-reported rating on a 7-point scale ranging from 1 = “All the time” to 7 = “Only on special occasions (e.g. home for the holidays)”.

<sup>b</sup> Self-rated proficiency on a sliding scale from 0 (poorly) – 100 (fluently).

14 Table 2. Demographics and language background information for all participants.

15

16

17

## 1 2.2 Stimuli

2 We created two words lists, each containing 40 words. One list consisted of English  
3 words for which the ASL translation uses only one hand ('one-handed' or 1H words; e.g.,  
4 warm); the other list contained English words for which the ASL translation uses two  
5 hands ('two-handed' or 2H words; e.g., family). We selected the words by choosing ASL  
6 signs from the ASL-Lex database (Caselli, Sehyr, Cohen-Goldberg, & Emmorey, 2016)  
7 whose English translations fulfilled our criteria. None of the words selected were verbs;  
8 the stimulus set included nouns, adjectives, and adverbs. We aimed to select words  
9 which had a very reliable ASL translation, avoiding words with many variations of ASL  
10 translations. This was determined in consultation with deaf experimenters fluent in  
11 ASL.

12 There were no significant differences between the English words contained in 1H  
13 and 2H lists for any of the following measures: word length, frequency, number of  
14 phonemes, imageability, mean reaction time and standard deviation during a lexical  
15 decision task, and mean reaction time and standard deviation during a naming task  
16 (Balota et al., 2007; MRC Psycholinguistic Database: Machine Usable Dictionary.  
17 Version 2.00; Kučera & Francis, 1967). See Table 3 for summary statistics.

18 There were no significant differences between the ASL sign translations of the  
19 English words contained in the 1H and 2H lists for any of the following measures of the  
20 signs: frequency in ASL, iconicity, and flexion (Caselli et al., 2016). See Table 3 for  
21 summary statistics.

22 An additional 12 animal words were included in the experiment, for use as  
23 "catch" trials. The data related to these animal words was not analyzed at any point.

24

SENSORIMOTOR CHARACTERISTICS OF SIGN 11

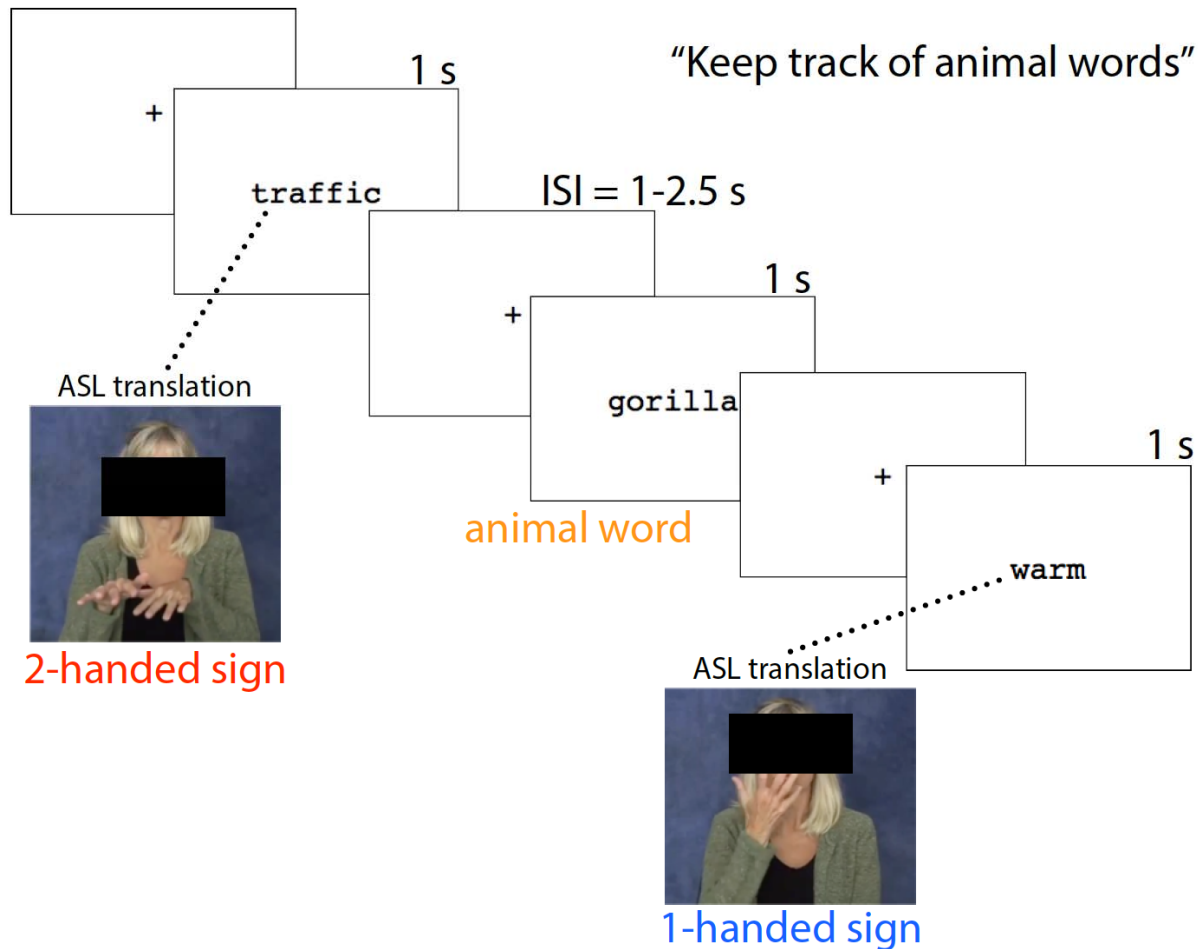
	1H words: M (SD)	2H words: M (SD)	t-test <i>p</i> value	
English norms	Word length	5.20 (1.67)	5.72 (2.17)	.23
	Frequency (K&F)	102.36 (151.44)	108.93 (142.30)	.84
	Log frequency (HAL)	9.62 (1.69)	10.01 (1.44)	.27
	# phonemes	4.09 (1.11)	4.55 (1.34)	.10
	Lexical Decision RT M	605.55 (45.50)	617.54 (62.97)	.33
	Lexical Decision RT SD	202.14 (63.97)	217.57 (87.57)	.37
	Naming RT M	605.47 (42.57)	607.26 (42.74)	.85
	Naming RT SD	127.97 (58.10)	127.89 (52.68)	.99
	Imageability	509.47 (112.49)	541.97 (80.48)	.20
ASL norms	Frequency (ASL-Lex)	4.74 (.75)	4.49 (1.01)	.22
	Iconicity	3.71 (1.68)	3.73 (1.34)	.97
	Flexion	3.38 (2.20)	3.63 (2.18)	.61

1  
2 Table 3. English and ASL norms for 2 categories of stimuli: 1-handed (1H) words, and 2-  
3 handed (2H) words.  
4

5 2.3 Experimental Design

6 Stimuli were individual English words presented in the center of 27” computer monitor  
7 approximately 2.5 feet from the participant. Word stimuli were presented in four blocks  
8 with a break after each block. Each block included 23 words consisting of 1-handed, 2-  
9 handed, and animal words that were pseudorandomized. Each word was presented once  
10 during the experiment, for a total of 40 1H trials and 40 2H trials. Participants were  
11 instructed to count how many animal words they observed in one block and reported  
12 their answer to the experimenter during the breaks between blocks. These responses  
13 were not recorded, as the purpose of this task was to ensure participant alertness  
14 throughout the study. If a participant gave any significantly deviant responses,  
15 experimenters would check in with participants to ensure they were attending to the  
16 experiment. This did not occur for any participants.

## SENSORIMOTOR CHARACTERISTICS OF SIGN 12



1

2 Figure 1. Overview of experimental task. Participants saw one word at a time displayed  
3 on a screen and were instructed to mentally count animal words (catch trials). Trials of  
4 interest were English words whose ASL translation required either one hand (1H) or two  
5 hands (2H).

6

### 7 2.4 Recording

8 EEG was recorded from 64 active Ag/AgCl electrodes using an actiCAP setup (Brain

9 Products GmbH, Germany), in combination with SuperVisc electrode gel. Data were

10 recorded using an online Cz reference and an AFz ground. Saline gel (SuperVisc, Brain

11 Products) was inserted into each electrode to lower impedances below 25 k $\Omega$ .

12 The EEG signals were amplified by the individual electrode amplifiers, and again by a

13 24-bit actiCHAMP amplifier (Brain Vision LLC, Morrisville, NC). Hardware filter

1 settings included a high-pass filter (.53 Hz) and a low-pass filter (120 Hz). Data was  
2 collected at a 1000 Hz sampling rate.

3

#### 4 2.5 Data Preparation

5 All data processing was implemented using EEGLAB v. 14.1.1 (Delorme & Makeig,  
6 2004). Data were referenced offline to the average of the two mastoid electrodes (TP9  
7 and TP 10). Data were filtered offline using a .1 Hz high-pass and a 100 Hz low-pass  
8 filter. Epochs were extracted from the continuous EEG, time locked to each stimulus of  
9 interest (all 1-handed, 1H, and 2-handed words, 2H). Onset of the stimulus was  
10 considered time 0, and epochs included data from -1.5 s to 2.5 surrounding each  
11 stimulus onset. A baseline period was defined as -200 to 0 s prior to stimulus onset. We  
12 ran an independent component analysis (ICA) on each epoched dataset (two datasets  
13 per participants: 1H and 2H). A trained experimenter visually inspected ICA results for  
14 each dataset and removed ICs deemed to be eyeblink artifacts or other non-brain  
15 artifacts (mean and mode number of ICs removed per participant = 1). Trials were  
16 removed from further analysis if they included large amounts of artefactual activity, as  
17 judged by a highly-trained experimenter (total # of trials removed: 3 1H for one  
18 participant; 3 2H for one participant and 1 2H for 3 participants). All datasets were  
19 compiled into one study folder and assigned groups (Deaf and Hearing) and conditions  
20 (1H and 2H).

21

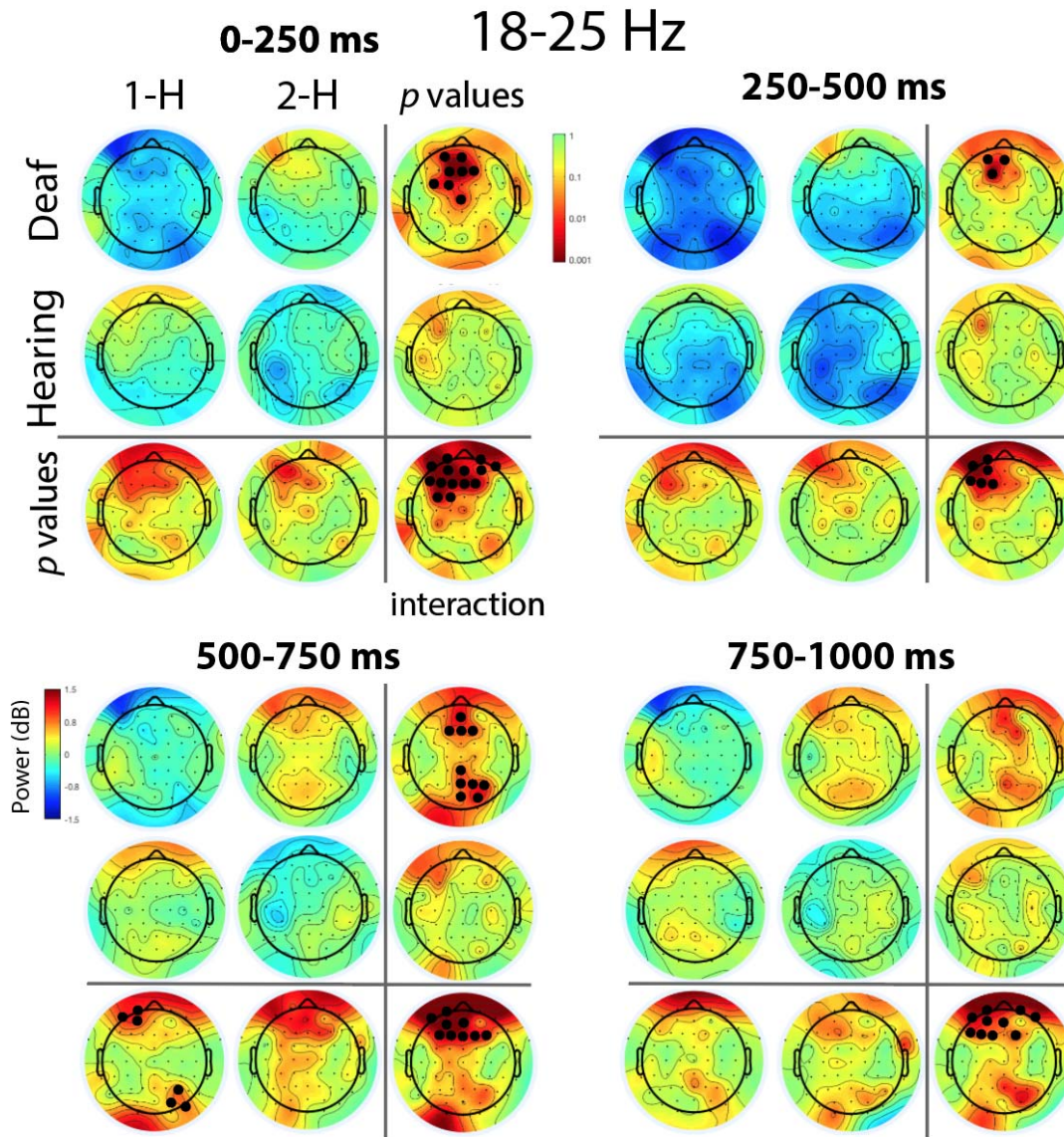
#### 22 2.6 Time-Frequency Analysis

1 Event-related spectral perturbation (ERSP) was computed at each electrode within our  
2 central region of interest (ROI), conducting a paired t-test (1H vs. 2H) for each group  
3 (Deaf and Hearing).

4 We conducted planned t-tests to obtain a full picture of the characteristics of the  
5 data, driven by a priori predictions developed before data analysis. For these planned  
6 tests, we analyzed all scalp electrodes at four frequency bands: low alpha (8-10 Hz), high  
7 alpha (11-13 Hz), low beta (14-17 Hz) and high beta (18-25 Hz). For each frequency  
8 band, we divided the epoch of interest into four bins, encompassing the entire time the  
9 stimulus was present on the screen: 0-250 ms, 250-500 ms, 500-750 ms, and 750-1000  
10 ms. For each analysis, we considered an effect to be of interest if it was significant at  
11 three adjacent electrodes. To control for multiple comparisons, we used a Bonferroni  
12 corrected  $p$  values of .016 ( $.05 / 3$ ) as the threshold for significance.

13 To get a more fine-grained view of the time and frequency dynamics of  
14 sensorimotor EEG during word perception, we calculated ERSPs at 21 electrodes  
15 comprising a region of interest over the pre- and post-central gyrus. The 21 electrodes  
16 included were FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, CP5, CP3,  
17 CP1, CPz, CP2, CP4, and CP6. At each of these electrodes we compared time-frequency  
18 plots (from 0-1000 ms in time and 8 to 25 Hz in frequency, encompassing the alpha and  
19 beta ranges) between 1-handed and 2-handed words for both the Deaf and Hearing  
20 groups. We were particularly interested in significant effects seen at these electrodes  
21 since alpha and beta rhythms present at central electrodes are closely tied to activity in  
22 pre- and post-central gyri (primary motor and primary somatosensory cortices,  
23 respectively), which are key components of the AON (Arnstein, Cui, Keyzers, Maurits, &  
24 Gazzola, 2011; Perry & Bentin, 2009; Ritter et al., 2009). For these region-of-interest

- 1 analyses we used a  $p$  value of .05, with a false-discovery rate correction applied to
- 2 control for false positives.



- 3
- 4 Figure 2. High beta activity (18-25 Hz) across the analysis epoch, 0-1000 ms. Two-way
- 5 ANOVA comparison (2 Groups: Deaf and Hearing; 2 Conditions: 1-Handed words, 1H
- 6 and 2-Handed words, 2H) across 64 scalp electrodes, for each of four time bins. Within
- 7 each time bin,  $p$ -values for interaction effects,  $p$ -values for main effects, and the average
- 8 upper-beta power (in dB) for each cell are shown. Electrodes at which the  $p$ -value was
- 9  $>.016$  are colored in black (minimum cluster size = 3 electrodes). For EEG power maps,
- 10 cool colors indicate a decrease in power, warm colors indicate and increase in power.
- 11 For  $p$ -value maps, cooler colors indicate high  $p$  values, warmer colors indicate lower  $p$ -
- 12 values.
- 13

1 3. Results

2 3.1 Alpha and beta activity across the scalp

3 No significant differences between 1H and 2H words were observed at any time bin in  
4 the lower alpha band (8-10 Hz) for either Deaf or Hearing groups.

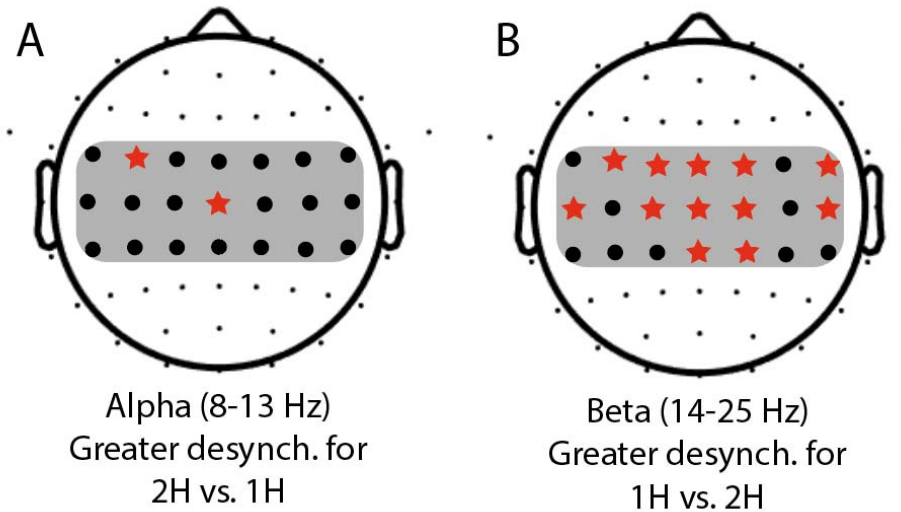
5 In the upper alpha band (11-13 Hz), there was a significant interaction effect ( $p <$   
6  $.016$ ) between the Groups and the Conditions. The significant interaction effect was  
7 observed at 5 frontal electrodes (F7, AF7, FP1, FP2, and AF8) from 500-750 ms  
8 following stimulus onset. No pairwise comparisons yielded significant results, so this  
9 effect was not further interpreted. No significant differences were observed at any other  
10 time bin.

11 In the lower beta band (14-17 Hz), there was a significant Group x Condition  
12 interaction in all four time bins spanning 0-1000 ms post stimulus onset. In the 250-  
13 500, 500-750, and 750-1000 ms bins, pairwise comparisons revealed significant  
14 differences in low beta band power between Deaf and Hearing groups, for observation of  
15 2-handed words only. In all three time bins, the significant effects were observed at left  
16 frontal electrodes and reflected higher beta power in the Deaf group when reading 2-  
17 handed words, compared to the Hearing group. No significant differences were seen  
18 between conditions for the Hearing group.

19 In the upper beta band (18-25 Hz), there was a significant Group x Condition  
20 interaction observed during each of the four time bins spanning 0-1000 ms post  
21 stimulus onset. For all four time bins, pairwise comparisons revealed a significant  
22 difference in high beta power during observation of one-handed vs. two-handed words,  
23 for the Deaf group only. In all time bins, the significant effects were observed at fronto-  
24 central electrodes (see Figure 2), reflecting higher beta power during the reading of two-

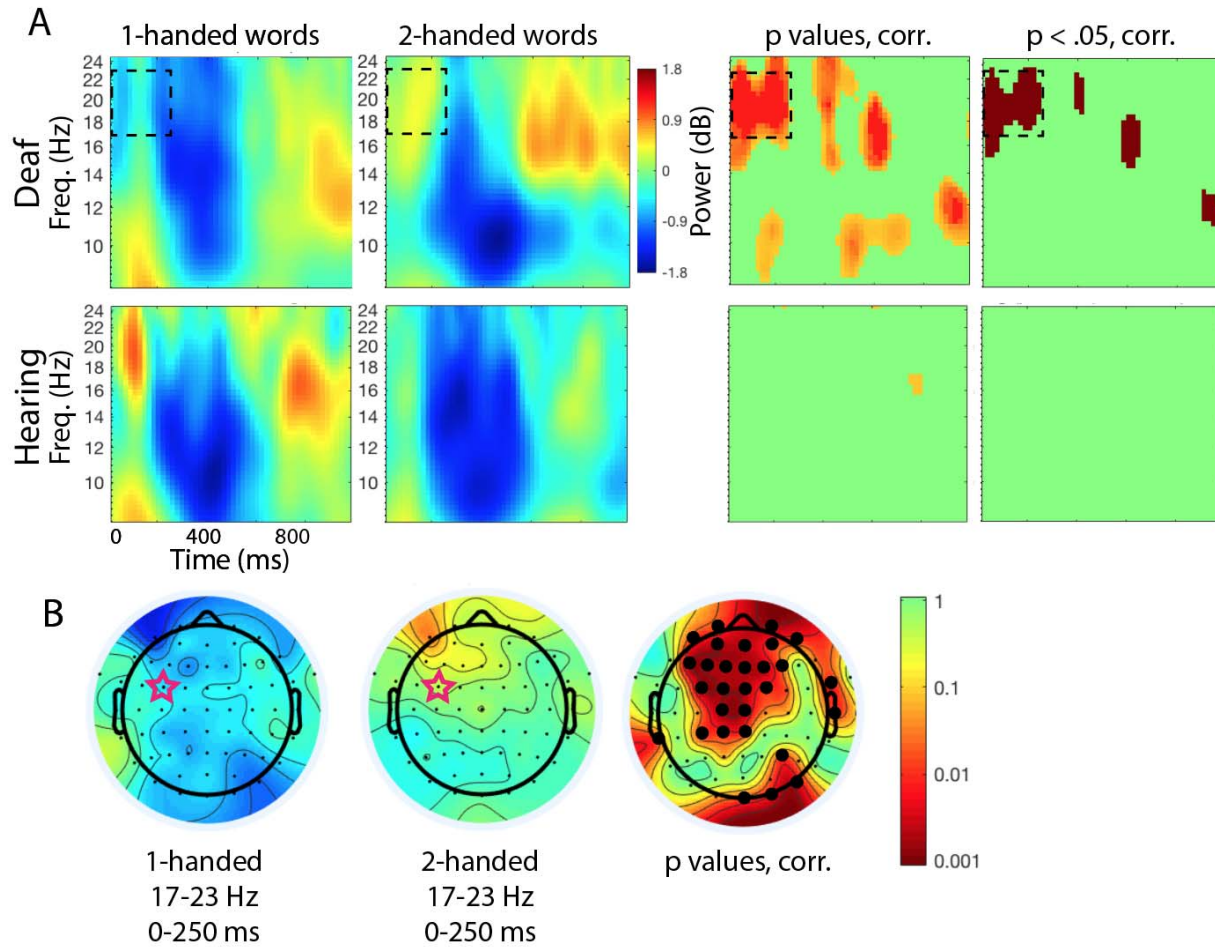


1 handed words compared to one-handed words. In the 500-750 ms bin, a significant  
2 difference was also observed over right parieto-occipital sites, driven by higher beta  
3 power in this area for 2-handed words. No significant differences were seen between  
4 conditions for the Hearing group.



5  
6 Figure 3. Alpha and beta power across the central region of interest (ROI) in the Deaf  
7 group. The 21 electrodes comprising the central ROI are shaded. **A.** For any electrode  
8 where alpha (8-13 Hz) power was significantly different during viewing of English words  
9 with one- and two-handed (1H and 2H) ASL translations, the electrode is shown with a  
10 red star ( $p < .05$ , FDR corrected). At two electrodes there was significantly greater  
11 desynchronization during viewing of 2H words compared to 1H words. **B.** For any  
12 electrode where beta (14-25 Hz) power was significantly different during viewing of  
13 English words with 1H and 2H ASL translations, the electrode is shown with a red star  
14 ( $p < .05$ , FDR corrected). At all starred electrodes there was significantly greater  
15 desynchronization during viewing of 1H words compared to 2H words.

## SENSORIMOTOR CHARACTERISTICS OF SIGN 18



1  
2  
3 Figure 4. Alpha and beta power during presentation of English words. **A.** Time-  
4 frequency representation of ERSPs in response to word onset at time = 0 (duration of  
5 word presentation = 1000 ms) for electrode FC3 (starred in Figure 3B). The first two  
6 columns show responses to English words with 1- and 2-handed ASL translations,  
7 respectively. The third column shows  $p$  values of the comparison of the first two panels,  
8 with the False Discovery Rate (FDR) correction applied. The fourth column shows  $p$   
9 values thresholded at  $p < .05$ , FDR corrected. Cool colors indicate a decrease in power,  
10 warm colors indicate an increase in power. **B.** Time-frequency responses in the Deaf  
11 group across the scalp for 1-handed and 2-handed conditions, at times and frequencies  
12 corresponding to the dashed boxes in Figure 3A. Rightmost plot shows the statistical  
13 comparison between the conditions; electrodes significant at the  $p < .05$  threshold, FDR  
14 corrected, are marked with a black circle.  
15

### 16 3.2 Time-frequency analyses at electrodes in Central region

17 In the Hearing group, there were no significant effects of Condition at any time in the  
18 alpha or beta frequency ranges at any electrode in the central region.

1           In the Deaf group, two out of 21 electrodes showed significant effects of Condition  
2 (1-H vs. 2-H) on alpha power (8- 13 Hz) at some point during the analysis epoch ( $p <$   
3  $.05$ , FDR corrected). For both of these electrodes, there was lower alpha power in the 2H  
4 condition compared to the 1-H condition (see Figure 3).

5           In the Deaf group, twelve out of 21 central electrodes showed significant effects of  
6 Condition (1-H vs. 2-H) on beta power (14-25 Hz) at some point during the analysis  
7 epoch ( $p < .05$ , FDR corrected). For all twelve of these electrodes, the direction of the  
8 effect was the same: there was lower beta power in the 1H condition compared to the 2H  
9 condition (see Figures 3 and 4).

10

#### 11 4. Discussion

12 We aimed to investigate if deaf signers simulate sensorimotor properties of ASL signs as  
13 they read English words. Based on existing work demonstrating English-to-ASL cross-  
14 modal, cross-linguistic translation, we questioned whether neural activity differentiated  
15 between English words whose ASL translations had gross sensorimotor differences: how  
16 many hands are used to produce the signs. Here, we present evidence that when Deaf  
17 signers read, alpha and beta range EEG rhythms respond differently to English words  
18 whose ASL translations differ in this way. The pattern of results presented here supports  
19 the notion of cross-modal, cross-linguistic translation, and suggests that re-enactment  
20 of the actions used to produce the signs constitutes one mechanism involved in this  
21 phenomenon.

22

#### 23 4.1 Central alpha effects

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1 We predicted that there would be significantly greater alpha desynchronization over  
2 central electrodes in response to reading 2H words compared to 1H words, based on the  
3 greater gross motor effort required to perform a two-handed movement compared to a  
4 movement that uses one hand. While our results do support this prediction, the effect  
5 was not particularly strong. Two electrodes within the central region showed statistically  
6 significant support for this pattern of results. Additionally, several electrodes (e.g., FC3,  
7 from 200-800 ms, seen in Figure 4) showed effects that trended toward significance in  
8 the alpha rhythm but did not pass our criteria to be considered significant. Nevertheless,  
9 the results seen in the central alpha rhythm do provide some evidence that the  
10 sensorimotor cortex is more active when a Deaf signer reads English words whose ASL  
11 translations use both hands.

12 It is likely that the relation between number of hands used to produce an action  
13 and degree of sensorimotor cortex activity is not entirely straightforward, thus clouding  
14 this pattern of results. For instance, the relation between recruitment of sensorimotor  
15 cortex and degree of movement may vary depending on the actor's expertise with the  
16 movements (Koeneke, Lutz, Wüstenberg, & Jäncke, 2004; Vogt et al., 2007). One other  
17 factor which may affected the direction of our results is frontal inhibition mechanisms  
18 reflected by the differences in frontal beta activity between the two conditions. During  
19 voluntary production of movements, alpha desynchronization is usually most evident  
20 over the contralateral hemisphere, especially in the pre-movement preparation period  
21 (Pfurtscheller & Lopes da Silva, 1999). Thus, one might have expected that we would see  
22 most evident differences in the alpha rhythm over the right hemisphere, given that the  
23 primary difference between the 1H words and the 2H words is the involvement of the  
24 left hand (for which the right sensorimotor cortex is contralateral). However, our results

1 did not fit this prediction. This is likely because during action observation (or, in this  
2 case, action simulation), the alpha response is bilateral in nature, since there is no pre-  
3 movement motor preparation involved (Avanzini et al., 2012). The pre-movement motor  
4 preparation during action production is typically a more bilateral response. Overall, the  
5 current results do suggest that gross sensorimotor characteristics of ASL signs are  
6 activated when deaf signers read English, there is more work to do with regard to  
7 comparing various types of sensorimotor characteristics. For instance, future work may  
8 more carefully consider the symmetry of ASL sign translations, or the type of  
9 movements used when producing the signs.

10

#### 11 4.2 Fronto-central beta effects

12 We predicted that reading words with 2-handed ASL translations would result in greater  
13 beta desynchronization compared to 1-handed words, due to the typical decrease in beta  
14 power when sensorimotor processing demands are increased. However, the experiment  
15 yielded significant results going in the opposite direction: reading words with 1-handed  
16 translations was associated with greater beta desynchronization. Different effects in  
17 different subdivisions of the alpha and beta bands is typical, and perhaps representative  
18 of different aspects of stimulus processing (Weiss & Mueller, 2012). While the majority  
19 of the sensorimotor beta literature shows desynchronization in situations of greater  
20 sensorimotor engagement, plenty of studies have demonstrated the opposite effect of  
21 less desynchronization associated with sensorimotor engagement, in line with our  
22 current findings (Cheyne et al., 2003; Neuper & Pfurtscheller, 2001; Pfurtscheller,  
23 Krausz, & Neuper, 2001; Quandt, Marshall, Bouquet, & Shipley, 2013; Spitzer &  
24 Haegens, 2017). In the field as whole, the exact nature of the relationship between beta

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1 power and sensorimotor engagement is not entirely clear, but beta rhythms are thought  
2 to have an important role in the relationship between sensorimotor processes and  
3 language (Spitzer & Haegens, 2017; Weiss & Mueller, 2012).

4 Our beta EEG results were most evident at frontal and fronto-central electrodes.  
5 While both 1H and 2H words resulted in some beta desynchronization, the Deaf group  
6 showed significantly less desynchronization when reading English words with a 2-  
7 handed ASL translation compared to English words with a 1-handed ASL translation  
8 (see Figure 4). And, immediately after stimulus onset, as well as ~600 ms after stimulus  
9 onset, a clear beta synchronization (i.e., beta rebound) is evident. Multiple processes  
10 may be reflected in these results, including some simulation of the action, as reflected in  
11 the beta desynchronization, but also inhibition of covert imitation, seen in the higher  
12 beta power for words whose ASL translations would require greater demands on the  
13 sensorimotor system. Frontal beta power has been associated with inhibition of motor  
14 processes (Alegre et al., 2004; Walsh, Kühn, Brass, Wenke, & Haggard, 2010),  
15 suggesting the possibility that the frontal beta effects we report here are due to greater  
16 inhibition of motor simulation processing when Deaf signers read 2H English words.  
17 The frontal distribution of our beta-range effects may implicate these frontal inhibitory  
18 processes related to the blocking of actual movement production during the viewing of  
19 2H words.

20 An alternate explanation for the frontal beta effects is that mentally simulating  
21 one-handed signs actually requires increased sensorimotor control. It may be that  
22 although signers show greater primary sensorimotor cortex activity during production  
23 of two-handed signs (Emmorey et al., 2016), the processes occurring during mental  
24 simulation of signs are quite different. For instance, it is possible that since one-handed

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1 signs are inherently asymmetric (one hand is moving and the other is stationary),  
2 frontal inhibitory mechanisms are differently recruited for these 1-handed signs as  
3 compared to symmetric 2-handed signs. In addition, our results may be influenced by  
4 the fact that the 2H word group included both words for which the ASL translation  
5 involved a symmetric sign (e.g., FAMILY, with the left and right hands moving  
6 symmetrically with identical handshapes) and words for which the ASL translation  
7 involved an asymmetrical sign (e.g., KEY, for which both the handshapes and  
8 movements differ for each hand). It is likely that action simulation processes vary  
9 significantly depending on the symmetry of an imagined action, with symmetrical  
10 bimanual actions associated with significantly less sensorimotor cortex activity  
11 compared to asymmetrical actions, as has been shown during execution of bimanual  
12 actions (Sadato, Yonekura, Waki, Yamada, & Ishii, 1997). This is also likely to be  
13 sensitive to the complexity of the actions (Toyokura et al., 2002), presenting yet another  
14 factor which should be further studied in future work.

15 The analysis at the central region of interest revealed significant effects upon the  
16 beta rebound effect present in the ERSP. Starting around 600 ms post-stimulus onset, a  
17 clear synchronization of beta power is evident in the 2H condition for the Deaf group  
18 only (see Figure 4A). This so-called “beta rebound” occurred at most electrodes in the  
19 central ROI, always in the same direction with increased beta power in the 2H  
20 condition. The beta rebound is a typical characteristic of the sensorimotor beta rhythm,  
21 generally following the initial beta desynchronization associated with onset of a  
22 performed or observed action (Avanzini et al., 2012; Pfurtscheller & Lopes da Silva,  
23 1999). We had not explicitly predicted a difference in beta rebound activity between the  
24 two conditions, but it is interesting to consider its meaning since the effect was quite

1 robust. Beta synchronization and beta rebound are related to onset and stopping of  
2 movement (Alegre, Alvarez-Gerriko, Valencia, Iriarte, & Artieda, 2008), and the beta  
3 rebound effect is closely linked to activity in the primary motor cortex (Parkes,  
4 Bastiaansen, & Norris, 2006). These beta rebound effects, in combination with the  
5 alpha-band desynchronization effects seen in response to 2H words, support our  
6 original predictions: that reading 2H words would result in greater activity in the  
7 primary sensory and motor cortices compared to reading 1H words.

8 Human and primate work both show that an increase in frontal beta power may  
9 also be indicative of maintenance of an item in visual short-term memory, maintenance  
10 of a current state of mind, or cognitive control mechanisms more generally (Stoll et al.,  
11 2016; Weiss & Mueller, 2012). The robust frontal beta effects we report here may be the  
12 result of a number of higher-level cognitive control processes. In addition, we do see  
13 evidence for greater activity in primary sensory and motor cortices in response to 2H  
14 words, as we originally predicted. Given the basic manipulation of this study, in which  
15 we compared EEG responses to English words with ASL translations that varied on  
16 large-scale sensorimotor characteristics, we are confident that any inhibitory or control-  
17 based mechanisms stem from the somatosensory and motor-related requirements of the  
18 hand and body movements required to produce the related ASL signs. The lack of  
19 significant differences between the two word groups on English and ASL linguistic  
20 parameters lends additional support to this claim. Finally, since no significant effects  
21 were observed in the Hearing group, it is clear that these differences reflect a process  
22 arising from an individual's experiences as a Deaf ASL signer.

23

24 4.3 General discussion



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1 The observed differences in alpha and beta rhythm EEG power occurred in the context  
2 of a single-word reading task. Our participants were tasked with keeping track of how  
3 many animal words (e.g., bear, duck) they saw, with the intention of ensuring they were  
4 processing the semantics of each word. Our findings demonstrate that very soon after  
5 word onset, the sensorimotor characteristics (e.g., use of one or two hands) of the ASL  
6 translations of these words affected the sensorimotor EEG rhythms—with significant  
7 effects within the first 250 ms. Other recent work has shown that the beta rhythm is  
8 sensitive to sensorimotor associations with words during a reading task very soon after  
9 onset of the stimulus—within 140 ms of word onset (Bechtold, Ghio, Lange, &  
10 Bellebaum, 2018), which is consistent with our findings. The current results show that  
11 multiple processes affect sensorimotor EEG rhythms when signers read individual  
12 English words. This work is the first demonstration of these effects, and future studies  
13 in this area could further dissociate between various categories of signs (e.g.,  
14 symmetrical and asymmetrical two-handed signs) as well as exploring other  
15 sensorimotor characteristics of signs beyond the one-hand vs. two-hand distinction.  
16 Future studies along these lines can clarify which aspects of action simulation (e.g.,  
17 motor imagery, tactile mirroring) contribute to cross-modal, cross-linguistic translation  
18 in deaf signers.

19 Future work must also carefully consider the role of ASL and English competence  
20 relating to action simulation processes. It has been shown in recent years that signers  
21 who are weaker in ASL may rely more heavily on internal representations of the  
22 sensorimotor aspects of sign (Corina & Gutierrez, 2016). In our current work, the Deaf  
23 group comprised a diverse group of self-identified fluent deaf signers with a range of  
24 fluency in ASL and in English (and in some cases, in other written or signed languages).

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1 A next step of this work would restrict participation to participants with more tightly-  
2 controlled language backgrounds, in order to statistically assess the role of English  
3 fluency and ASL fluency upon the strength of the sensorimotor representations  
4 simulated during reading. Our current study did not include a standardized measure of  
5 either ASL or English competency, which could provide further objective information to  
6 paint a more complete picture of this phenomenon.

7

### 8 5. Conclusion

9 Here we present findings suggesting that sensorimotor characteristics of signs are called  
10 upon when Deaf signers read English words. We reveal for the first time the neural  
11 oscillatory dynamics occurring during this process, indicating that both alpha and beta  
12 EEG oscillations reflect sensorimotor characteristics of ASL signs during cross-modal,  
13 cross-linguistic translation. The alpha rhythm showed some desynchronization in  
14 response to English words for which the ASL translation uses both hands, compared to  
15 words for which the translation uses one hand. This finding was in line with our  
16 predictions that such alpha desynchronization would result due to increased activity in  
17 the central region overlying the primary sensory and motor cortices. On the other hand,  
18 the beta rhythm displayed the opposite pattern, with robust effects showing a  
19 pronounced desynchronization in response to “one-handed” English words, compared  
20 to “two-handed” words. We suggest this pattern may be due to increased sensorimotor  
21 control and inhibition involved in simulating one-handed signs, or due to frontal  
22 inhibitory processes related to the blocking of actual movement production during the  
23 viewing of 2H words. It is important to keep in mind that the findings in the Deaf group  
24 may not be easily interpretable using a literature that largely has drawn from hearing

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1 participants; it is possible, and even likely, that neural oscillatory activity during  
2 language processing shows notable differences between deaf and hearing populations,  
3 much as do other aspects of neurobiology of language (Corina, Lawyer, & Cates, 2012).  
4 Our work demonstrates the need for a more complete understanding of how ASL and  
5 English overlap and interact with one another in Deaf bilingual readers.

6

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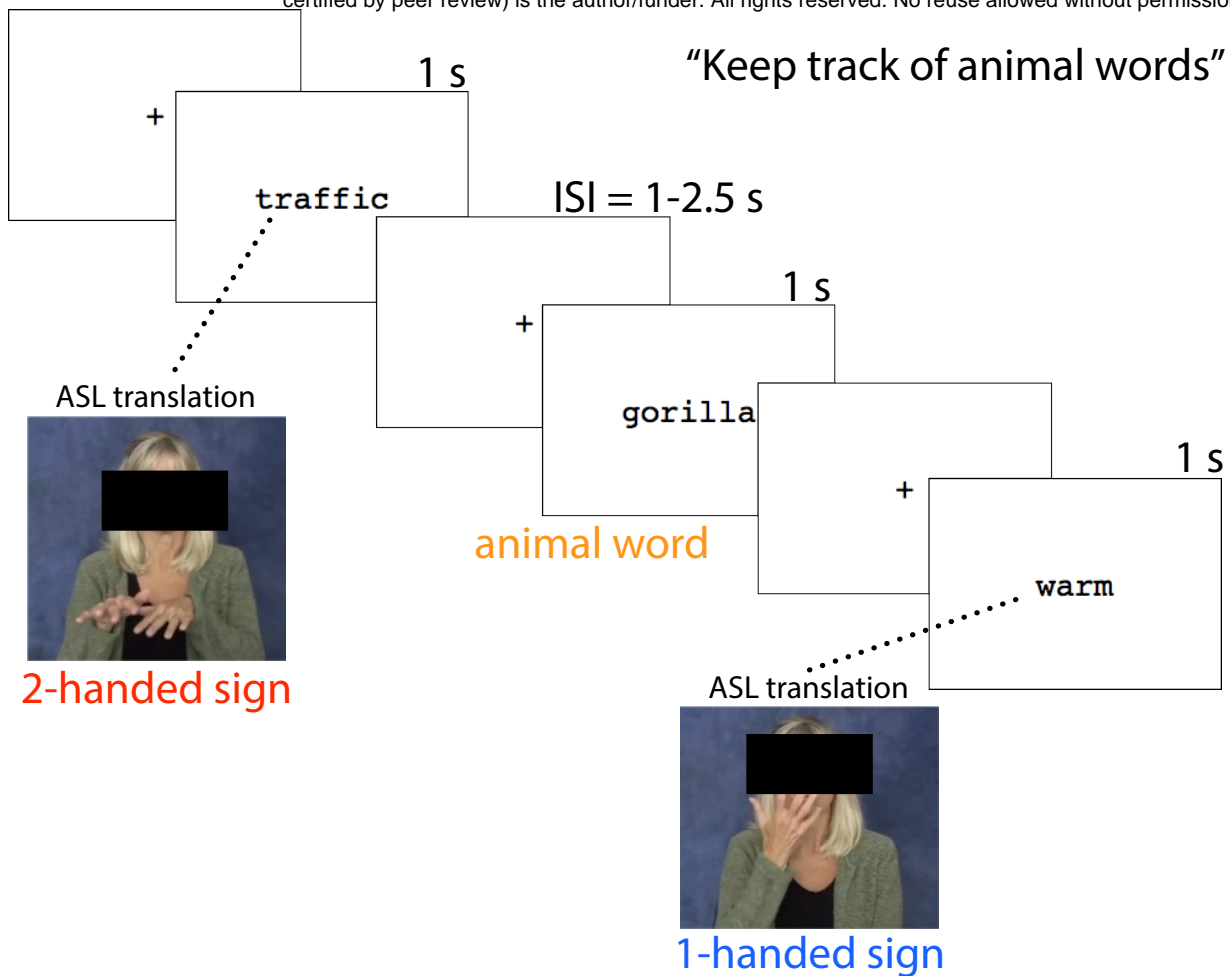
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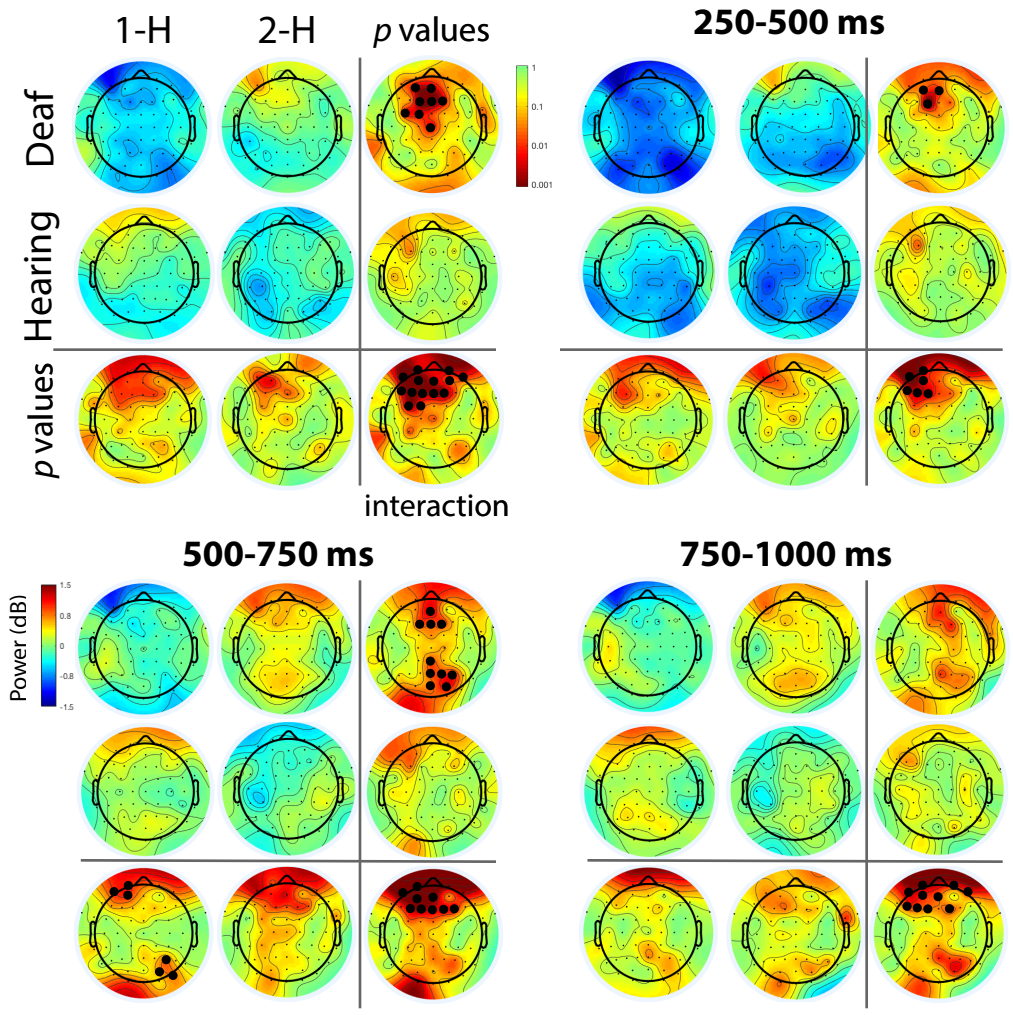
## SENSORIMOTOR CHARACTERISTICS OF SIGN 39

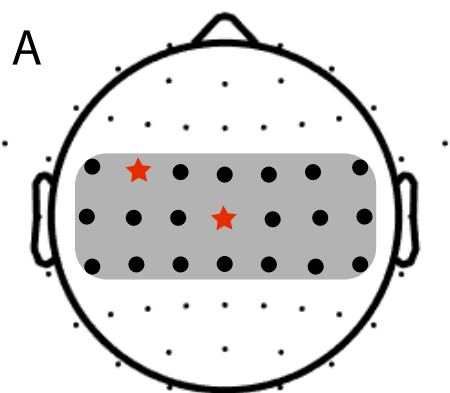
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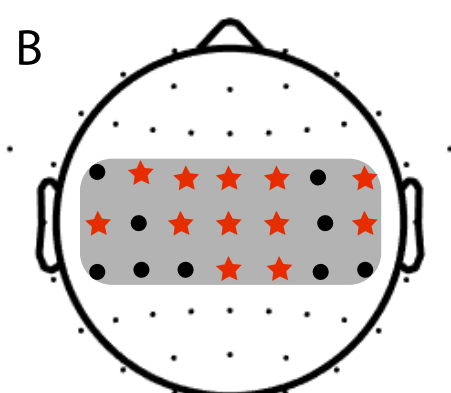


0-250 ms 18-25 Hz





Alpha (8-13 Hz)  
Greater desynch. for  
2H vs. 1H



Beta (14-25 Hz)  
Greater desynch. for  
1H vs. 2H

