

# Brain systems mediating semantic and syntactic processing in deaf native signers: Biological invariance and modality specificity

Cheryl M. Capek<sup>a,1</sup>, Giordana Grossi<sup>b</sup>, Aaron J. Newman<sup>c</sup>, Susan L. McBurney<sup>d</sup>, David Corina<sup>e</sup>, Brigitte Roeder<sup>f</sup>, and Helen J. Neville<sup>g</sup>

<sup>a</sup>School of Psychological Sciences, University of Manchester, Zochonis Building, Manchester M13 9PL, United Kingdom; <sup>b</sup>Department of Psychology, State University of New York at New Paltz, 600 Hawk Drive, New Paltz, NY 12561; <sup>c</sup>Department of Psychology, Psychiatry, and Surgery, Neuroscience Institute, and Brain Repair Centre, Dalhousie University, Halifax, NS, Canada B3H 4J1; <sup>d</sup>Department of Linguistics, Cognitive Neuropsychology Laboratory, University of Washington, Seattle, WA 98195; <sup>e</sup>Center for Mind and Brain, University of California, 267 Cousteau Place, Davis, CA 95618; <sup>f</sup>Department of Biological Psychology and Neuropsychology, University of Hamburg, Von-Melle-Park 11, 20146 Hamburg, Germany; and <sup>g</sup>Department of Psychology, 1227 University of Oregon, Eugene, OR 97403

Edited by Michael I. Posner, University of Oregon, Eugene, OR, and approved March 31, 2009 (received for review October 10, 2008)

**Studies of written and spoken language suggest that nonidentical brain networks support semantic and syntactic processing. Event-related brain potential (ERP) studies of spoken and written languages show that semantic anomalies elicit a posterior bilateral N400, whereas syntactic anomalies elicit a left anterior negativity, followed by a broadly distributed late positivity. The present study assessed whether these ERP indicators index the activity of language systems specific for the processing of aural-oral language or if they index neural systems underlying any natural language, including sign language. The syntax of a signed language is mediated through space. Thus the question arises of whether the comprehension of a signed language requires neural systems specific for this kind of code. Deaf native users of American Sign Language (ASL) were presented signed sentences that were either correct or that contained either a semantic or a syntactic error (1 of 2 types of verb agreement errors). ASL sentences were presented at the natural rate of signing, while the electroencephalogram was recorded. As predicted on the basis of earlier studies, an N400 was elicited by semantic violations. In addition, signed syntactic violations elicited an early frontal negativity and a later posterior positivity. Crucially, the distribution of the anterior negativity varied as a function of the type of syntactic violation, suggesting a unique involvement of spatial processing in signed syntax. Together, these findings suggest that biological constraints and experience shape the development of neural systems important for language.**

electrophysiology | sign language | syntax

**S**igned languages, such as American Sign Language (ASL), are fully developed, natural languages containing all of the linguistic components of spoken languages, but they are conveyed and perceived in a completely different form than those used for aural-oral languages. (Aural-oral is used here to refer to both written and spoken language forms.) Thus, investigations of signed language processing provide a unique opportunity for determining the neural substrates of natural human language irrespective of language form. The present study used event-related brain potentials (ERPs) to examine semantic and syntactic processing of ASL sentences in deaf native signers of ASL and compared these findings to those from previous studies of aural-oral language.

Lesion and neuroimaging studies suggest that remarkably similar neural systems underlie signed and spoken language comprehension and production. The studies illustrate the importance of a left frontotemporal network for language processing irrespective of the modality through which language is perceived. In particular, neuroimaging studies of sentence processing using written (e.g., refs. 1 and 2), spoken (e.g., refs. 3–5),

and audiovisual (6, 7) stimuli have shown reliable left hemisphere-dominant activation in regions such as the inferior frontal gyrus and the posterior superior temporal cortex in hearing users of spoken language. [Recent studies have shown that sentence processing relies on a widely distributed brain network extending beyond perisylvian areas. For example, behavioral deficits in sentence comprehension can also follow damage to a number of the left hemisphere areas, including the anterior superior temporal gyrus, posterior middle temporal gyrus, and middle frontal cortex (8). In addition, neuroimaging studies of sentence processing often show activation in regions within and beyond the perisylvian cortex (e.g., ref. 9).] Similarly, studies of signed sentence processing in deaf and hearing native signers have shown significant activation of the inferior frontal and superior temporal cortices of the left hemisphere (7, 10–13). These neuroimaging studies of signers are largely consistent with neuropsychological evidence from deaf patients who show evidence of frank linguistic deficits following left, but not right, hemisphere damage (14–16).

More controversial is the role of the right hemisphere in linguistic processing of signed languages. Though neuroimaging studies (e.g., refs. 10–12, 17, and 18) have shown that signed language processing also recruits regions within the right hemisphere, studies of right hemisphere-damaged signers often report intact core-linguistic abilities (16). However, Poizner et al. (16) reported 2 subjects with right hemisphere damage who were shown to have impaired performance on a syntax comprehension measure that required processing of spatialized components of ASL grammar. The factors important in the right hemisphere involvement in signed language processing have not been systematically investigated because previous studies examining the neural organization of signed sentences did not separately assess different types of linguistic processing. The present study examines the brain processes associated with semantics and syntax in a signed language.

One hypothesis for the role of the right hemisphere in signed language processing is specifically to enable the use of space in conveying signed language grammar. In particular, whereas aural-oral language utilizes word order and/or inflectional morphology such as case markers to distinguish grammatical refer-

Author contributions: D.C., B.R., and H.J.N. designed research; C.M.C., G.G., A.J.N., and S.L.M. performed research; C.M.C. analyzed data; and C.M.C., G.G., A.J.N., D.C., B.R., and H.J.N. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

<sup>1</sup>To whom correspondence should be addressed. E-mail: cheryl.capek@manchester.ac.uk.

This article contains supporting information online at [www.pnas.org/cgi/content/full/0809609106/DCSupplemental](http://www.pnas.org/cgi/content/full/0809609106/DCSupplemental).







clearly implicate distinguishable neural subsystems involved in the processing of “spatial syntax” in ASL depending on the processing demands, and suggest a more complex organization for the neural basis of syntax than a unitary “grammatical processing” system. It remains to be determined whether the processing of spatial syntax in signed languages relies on systems not used for syntactic processing in aural-oral languages (as might be inferred from findings discussed previously of greater right hemisphere activation in some fMRI studies of ASL) or whether the distinction observed in the present data might also be found in spoken languages if comparable violations could be constructed.

In summary, the invariance of the pattern of results across aural-oral and signed languages demonstrates the existence of strong biological constraints in the organization of brain systems involved in lexical-semantic processing as indexed by the N400. The presence of an early left anterior negativity and P600 for the reversed verb agreement violations further supports previous work suggesting that the syntax of signed languages shares many of its neural underpinnings with spoken languages. At the same time, the right-lateralized negativity elicited by unspecified verb agreement violations in ASL suggests that the agreement systems of signed languages may impose certain unique processing demands that recruit additional brain regions not typically implicated in the processing of spoken language syntax. This difference points to the critical role of experience in shaping the organization of language systems of the brain.

## Methods

**Participants.** The 15 participants (10 female, average age = 30 years, range 23–47 years) were congenitally and profoundly deaf adults; they had no known neurological impairments, nor were they taking psychotropic medications. All were right-handed according to self-report and the Edinburgh Handedness Inventory (55). In accordance with the University of Oregon research guidelines they gave written consent; they received a monetary fee for their participation. Participants learned ASL from birth from their deaf parents. Though they learned written English in school, all used ASL as their primary language and rated it as the language they felt most comfortable using.

**Stimuli.** The 245 experimental sentences were produced by a female deaf native signer of ASL, videotaped, digitized, and presented at the rate of natural sign. One hundred and twenty-five of the sentences were well-formed, semantically coherent sentences, and the remaining 120 contained an error. Thirty-one sentences contained a semantic error. Normative counts of psycholinguistic parameters, such as frequency, do not exist for ASL; however, where possible, the psycholinguistic features pertaining to the items’ referent were taken into account. Target items in the semantically appropriate and anomalous conditions were matched on imageability and familiarity ( $P$  values  $>0.1$ ). In addition, semantically anomalous signs were chosen from the same linguistic category as semantically appropriate signs. A native signer judged the semantically anomalous signs as inappropriate given the sentential context.

Thirty sentences contained a reversed verb agreement error; that is, the verb moved from the object to the subject, instead of the opposite direction. Twenty-six sentences contained an unspecified verb agreement error in which the subject and object were set up in space, but instead of directing the verb from the subject toward the object, the signer directed the verb to a location in space that had not been defined. To ensure that the lateralized distributions of the evoked potentials elicited by the verb agreement violations were not due to spatial working memory demands possibly involved in the maintenance of the location of the referent or orienting attention to the its location, the direction of motion was reasonably well balanced across conditions. In particular, the ratio of sentences moving leftward:rightward across the verb agreement target items were 45:55 for canonical verb agreement, 53:47 for the reversed verb agreement violations, and 50:50 for the unspecified verb agreement violations. Twenty-eight sentences contained a subcategorization error (i.e., the intransitive verb was followed by a direct object); the results for this condition are not discussed here. Each sentence containing a violation had a corresponding sentence that was semantically and syntactically correct. One set of 31 canonical sentences served as matched controls for both groups of sentences containing verb agreement violations; they were presented twice to

equate “good”/“bad” responses. Nine sentences additional were repeated: 4 canonical sentences (2 semantic, 2 subcategorization) and 5 anomalous sentences (2 semantic, 2 reversed verb agreement, and 1 subcategorization) to reduce the likelihood that previously viewed sentences would influence participants’ acceptability judgments (i.e., participants concluding that a sentence was “good” because they had already seen the “bad” version). In addition, 16 filler sentences were included to reduce predictability of the sentence structure. To maintain participants’ attention to the stimuli, the sentences varied in length, and in the anomalous conditions the error occurred at various (but never sentence-final) positions across sentences. Two ASL linguists determined the stimulus onsets by identifying, for each target sign, the frame where the hand-shape information of the critical sign was clearly visible, excluding transitional movements leading to the onset of the sign.

**Procedure.** Before the ERP recording, each participant viewed videotaped instructions and sample sentences produced by a deaf native signer. Participants were told that in the experiment, they would view a signer producing ASL sentences; some would be “good” ASL and others would be “bad” ASL. Because many deaf individuals are accustomed to communicating with people who use other forms of sign that do not rely on ASL syntax (e.g., Signed English) as well as those with varying fluencies of ASL, participants were instructed to judge the sentences critically and only accept well-formed, semantically coherent ASL as “good” sentences.

Participants were given a set of 16 practice sentences (6 were “good”; 10 contained errors, including 2 semantic, 3 reversed verb agreement, 3 unspecified verb agreement, and 2 subcategorization) to become familiar with the stimuli and experimental procedures.

Data were collected over 2 sessions, each one on a different day (mean days apart = 4.4). Stimuli were presented in a different pseudorandom order for each participant, and each participant viewed the same stimuli in a different order across both sessions to obtain adequate signal to noise. At each experimental session, participants sat comfortably in a dimly lit, sound-attenuated, electrically shielded booth in a mobile ERP laboratory. Stimuli were displayed on a CRT monitor located 57 inches from the participant’s face; thus, signs subtended a visual angle of 5° vertically and 7° horizontally. The sequence of events was the following. First, 3 asterisks were displayed slightly above the center of the screen so the participants’ eyes would be positioned at the location of the signer’s face; the participant pressed a button with either hand to immediately elicit the first frame of the sentence, which was held briefly (500–800 ms) to allow the participant to fixate on the signer’s face, then the sentence began. Following the sentence, the final frame was displayed for 1,000 ms before a question mark appeared on the screen and the participant responded (“good” or “bad”) via a button press. To reduce motion artifact, participants were instructed not to respond until the question mark appeared on the screen. Accuracy was emphasized over speed; thus, participants proceeded through the sentences and responded at their own pace. To guard against response bias, participants responded “good” with one hand for one session and with the other hand for the second session; the order of response hand was randomized across participants.

**ERP Recording and Analyses.** Electrical activity was recorded from the scalp from 29 tin electrodes sewn into an elastic cap (Electro-Cap) according to an extended International 10–20 system montage (FZ, FP1/FP2, F7/F8, F3/F4, FT7/FT8, FC5/FC6, CZ, T3/T4, C5/C6, CT5/CT6, C3/C4, PZ, T5/T6, P3/P4, TO1/TO2, O1/O2). To monitor eye movement and blinks, additional electrodes were placed on the outer canthus of each eye and below the right eye. Impedances were less than 5 K $\Omega$  for eye electrodes and less than 2 K $\Omega$  for scalp and mastoid electrodes. Data from all scalp and vertical eye electrodes were referenced online to an electrode placed over the right mastoid; the data were reaveraged offline to the average of the left and right mastoids, and the 2 horizontal eye electrodes were referenced to each other (for electrode montage, see Fig. S1).

The EEG was amplified (–3 dB cutoff, 0.01–100 Hz bandpass) using Grass Model 12 Neurodata Acquisition System amplifiers and digitized online (250-Hz sampling rate). Offline, trials with eye movement, blinks, or muscle movements were identified using artifact rejection parameters tailored to each participant. Only artifact-free trials were kept for further analyses, resulting in the retention of at least 80% of trials across participants (82% semantically correct, 81% semantically anomalous, 83% canonical verb agreement, 84% reversed verb agreement, and 80% unspecified verb agreement). The EEG for each participant was averaged for each condition before applying a 60-Hz bandpass digital filter to remove artifacts due to electrical noise and normalized relative to a calibration pulse (200 msec, 10  $\mu$ V) that was recorded on the same day as each participant’s data. For each sentence condition, trials

were averaged together over an epoch of 1,200 msec with a 200-msec pre-stimulus baseline. Only trials that participants responded to correctly were included.

As stated previously, repeated-measures ANOVAs were conducted, with 5 within-participants factors: sentence type condition (C, 2 levels: anomalous, canonical), hemisphere (H, 2 levels: left, right), anterior-posterior (A/P, 6 levels: frontal [F7/8, F3/4], frontotemporal (FT7/8, FC5/6), temporal [T3/4, C5/6], central [CT5/6, C3/4], parietal [T5/6, P3/4], occipital [TO1/2, O1/2]) and lateral-medial (L/M, 2 levels: lateral [F7/8, FT7/8, T3/4, CT5/6, T5/6, TO1/2], medial [F3/4, FC5/6, C5/6, C3/4, P3/4, O1/2]). Mean amplitude at each electrode site was the dependent measure. To correct for possible inhomogeneity of variances, the Greenhouse-Geisser (56) corrected *P* values are reported for statistics involving factors with more than 2 levels. The time windows for the ERP components were first assessed by a visual inspection of the waveforms from each participant and the grand average of all 15 participants. The precise latency range for ERP components was determined by performing repeated-measures ANOVAs on adjacent 25-msec epochs over the sites showing the largest mean amplitude (P3/P4, O1/O2 for the N400, over all sites for the broadly distributed P600). The onset and offset for each component were defined as the first and last of 3 consecutive significant (i.e., *P* < 0.05) ANOVAs, respectively. As stated

previously, these analyses revealed that the N400 occurred 300–875 msec poststimulus onset. The P600 started at 475 msec for reversed verb agreement violation and 425 msec for unspecified verb agreement violations. This component continued to be significant throughout the remainder of the post-stimulus epoch (1,200 msec). The anterior negativity has a relatively early latency and a focal distribution, so to determine the onset and offset of this effect, 20-msec bins, moving by a 10-msec time window, were measured across the anterior 3 rows, revealing that this effect occurred 140–200 msec after the onset of reversed verb agreement violations and at 200–360 msec after the onset of unspecified verb agreement violations.

**ACKNOWLEDGMENTS.** The authors thank D. Waligura, L. White, T. Mitchell, D. Coch, W. Skendzel, D. Paulsen, J. Currin, and B. Ewan. We also thank Mike Posner for comments on an earlier version of this paper. The project described was supported by National Institutes of Health National Institute on Deafness and Other Communication Disorders Grants R01 DC00128 (to H.N.) and R01 DC003099 (to D.C.). This article's contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Institutes of Health. B.R. is supported by the German Research Foundation (DFG, Ro 1226/1-1, 1-2). A.J.N. is supported by the Canada Research Chairs program. Requests for the sentence video can be made directly to the authors.

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