Same Sentences, Different Grammars, Different Brain Responses: An MEG study on Case and Agreement Encoding in Hindi and Nepali Split-Ergative Structures

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Abstract. At first glance, the brain's language network appears to be universal, but languages clearly differ. How does the language network adapt to the specific details of individual grammatical systems? Here, we present an MEG study on case and agreement in Hindi and Nepali. Both languages use split-ergative case systems. However, these systems interact with verb agreement differently – in Hindi, case features conspire to determine which noun phrase (NP) the verb agrees with, but not in Nepali. We found that left inferior frontal and left anterior temporal regions are sensitive to case features in both languages. However, the left temporoparietal junction shows a unique sensitivity to specific combinations of subject and object case morphology. We suggest that this brain response unique to Hindi reflects the need to determine which NP agrees with the verb, a specific property of Hindi grammar. This shows that brain activity reflects psycholinguistic processes that are intimately tied to grammatical features.

Keywords: syntax, sentence processing, MEG, ergativity, case, agreement

Highlights

- Left inferior frontal lobe and left anterior temporal lobe distinguish accusative objects versus bare object NPs in Hindi and Nepali
- Left temporo-parietal junction shows sensitivity to object-agreement constructions in Hindi that is absent in Nepali
- Both left temporo-parietal junction and left inferior frontal lobe may support prediction and encoding of agreement relations in Hindi
- MEG can reveal differences in neural activity that reflect specific requirements of different grammatical systems

1. Introduction

Languages can appear quite different from one another. Nonetheless, a typical human can learn and use any natural human language. The organization of the brain's "language network" appears to be largely uniform across languages, despite the diversity in features they may have, or the kinds of information that their structures encode (Dunagan et al. 2022; Malik-Moraleda et al. 2022), although some results suggest systematic differences (Wei et al. 2023). Given the reasonable assumption that neural structures and language processing strategies are essentially the same across languages, differences in neural activity should reflect the way that a uniform representational and processing system deals with parametric differences between grammatical systems. For example, a predictive processing mechanism will predict the arguments of a verb from the verb in a subject-verb-object (SVO) language, whereas the verb might be predicted from both arguments in an subject-object-verb (SOV) language (see Bornkessel-Schlesewsky & Schlesewsky 2016). Identifying systematic differences in neural activity in language processing can serve as a key strategy for relating relating grammatical descriptions, processing mechanisms, and neurobiology.

We examine this question through the lens of case and agreement dependencies. Case morphology, such as the difference between nominative *he* and accusative *him*, provide the reader or listener with important cues to 'who-did-what-to-whom' via syntactic relations. Like case, agreement also guides the comprehender in identifying entities in the sentence. In English, the verb agrees (corresponds in form) with the subject noun phrase (NP) in number – *the boy quickly run-**s**, the boy-**s** quickly run*. However, different languages require that the verb relates to its arguments differently. For instance, in many languages, such as Hindi, Nepali, Arabic, or Hebrew, the verb agrees with its subject in gender, unlike English – *the boy quickly run-**s**, the girl quickly run-**s***.

Here, we leverage the "split-ergative" agreement systems of two very typologically similar languages: Hindi and Nepali. Hindi and Nepali are both subject-object-verb languages from the Indo-Aryan language family. In both languages, the subject noun phrase (NP) requires an ergative case suffix (ने -*ne* in Hindi, ले -*le* in Nepali) in simple past (perfective) sentences, but not in the simple present. In the present tense, the verb agrees with the "bare" subject in number, gender, and person, much like Western European languages. However, in the simple past tense,

the languages use different rules. In Hindi, the verb usually agrees with the object in the simple past, and not with the subject carrying the ने *-ne* suffix. In Nepali, the verb also agrees with the subject carrying the ले *-le* suffix in the past tense, i.e., no difference is observed between present and past tense in Nepali.

These grammatical features mean that different information is accessible at different points in Hindi and Nepali, in sentences that are otherwise structurally similar. In Nepali, comprehenders can identify the expected number, gender, and person of the verb shortly after hearing or reading the subject NP, regardless of its case. However, in Hindi, the comprehender's knowledge of the verb's form differs depending on the presence of the ergative suffix ने *-ne*. If the subject NP is bare, then Hindi comprehenders know the verb will match with the subject NP in number, person, and gender, just as in Nepali. If the subject NP has the ergative suffix ने *-ne*, the comprehender must wait to encounter the object NP to know the verb's features. In other words, Nepali speakers can always identify the subject NP as the 'controller' of the agreement with the verb. However, Hindi speakers must examine the morphology of the subject NP to determine whether the following object NP is the controller.

Here, we investigate whether this difference in accessibility of information translates into different patterns of brain activity. Here, we focus on the brain activity at the object NP. In Hindi, the ergative case signals that the object NP is the agreement controller, and thus brain activity at the subsequent object reflects computing and predicting the relevant features of the verb. This should contrast with the brain activity in Nepali, where the object NP does not play this role. This comparison also allows us to 'factor out' other processing factors related to word order, morphology, and the thematic relations, which are controlled in the between-language comparison.

We present on the results of two parallel magnetoencephalography (MEG) studies in Hindi and Nepali. In our Hindi study, we find a pattern of activity during reading of the object NP and the subsequent verb that shows differential sensitivity to different agreement configurations. This activity localizes to the left temporo-parietal junction. Both languages show greater activation for accusative object NPs compared to bare object NPs in left anterior temporal and left inferior frontal regions. An exploratory analysis suggests that these brain regions also

play a key role in predicting the gender-marking on the verb in Hindi, across case and tense configurations.

1.1 Agreement Processing

Subject-verb agreement dependencies are extensively studied in psycholinguistics as a window into the memory operations that support language comprehension (Nicol et al. 1997; Badecker & Kumiak 2007; Wagers et al. 2009; Dillon et al. 2013), and as a window into the kinds of representations that are built in real-time (Bock & Miller 1991; Franck et al. 2002; Bhatia & Dillon 2022; Chacón 2022). Subject-verb agreement processing likely consists of at least two distinct stages; the first involves identifying possible agreement controllers and predicting likely morphosyntactic features of the upcoming verb (Eberhard et al. 2005; Wagers et al. 2009; Bhatia & Dillon 2022; Chacón 2022), followed by retrieval of the subject NP's features after the verb is encountered (Nicol et al. 1997; Bedecker & Kumiak 2007; Wagers et al. 2009; Dillon et al. 2013).

Electroencephalography (EEG) recordings demonstrate rapid detection of ungrammatical verbs vs. grammatical verbs, demonstrating rapid sensitivity to agreement features. (Hagoort et al. 1993; Friederici 2002; Nevins et al. 2007; Choudhary et al. 2009; Molinaro et al. 2011; Bhattamishra et al. 2021). Agreement violations, in which the verb and its argument mismatch in a feature, usually elicit a biphasic response, with a left anterior negativity (LAN) ~300ms post-verb onsent, followed by a P600. In a violation paradigm using MEG, Tucker et al. (2014) observed greater activity for grammatical verb forms compared to ungrammatical verb forms that mismatched the subject NP in number the left posterior superior temporal lobe, ~700ms post-verb onset.

Hemodynamic measures investigating agreement violations have implicated a variety of brain regions in agreement configurations, including the left inferior frontal lobe, portions of the left posterior and anterior temporal cortex, and the right and left inferior parietal regions. In an fMRI study investigating case and agreement violations in Basque, a language with ergative case and both obligatory subject-verb and object-verb agreement, Nieuwland et al. (2011) observed greater activation in the left and right inferior parietal lobules for object-verb agreement violations in which the object NP was marked with the wrong case or number. They also found

greater activation for object-verb mismatch in the left and right middle frontal gyri. In an fMRI study in Spanish, a language with obligatory gender- and number-agreement between nouns and modifiers, Carreiras et al. (2015) found greater activity in left inferior frontal areas for adjective-noun and determiner-noun pairs that mismatched in gender or number. They additionally found greater activation in right parietal areas for determiner- and adjective-noun pairs that mismatched in number. Finally, in an fMRI study in Japanese, a language with strict marking, Cui et al. (2022) found different patterns of activity for conventionality and status in left frontal regions, bilateral anterior temporal regions, and left inferior parietal lobule.

In direct neuron recordings, Sahin et al. (2009) found greater activity in the left inferior frontal gyrus when participants read English inflected verb and noun forms ~300ms after word-onset (*rock-s, rock*-ed) compared to uninflected forms. Similar findings were observed using production study using fMRI by Kielar et al. (2011). Using a similar paradigm in MEG with word production in English, Hauptman et al. (2021) observed greater activity in the left inferior frontal cortex and the left anterior temporal lobe corresponding to verb and noun inflection, approximately 300ms after the cue to begin speaking was provided.

However, due to the limitations of these methodologies, it has been difficult to draw firm inferences about which brain areas are responsible for which computations. EEG recordings have poor spatial resolution, meaning it is difficult to identify the locations for the measured activity. Inversely, hemodynamic measures afford poor temporal resolution, rendering it difficult to disentangle memory retrieval operations encountered at the verb versus pre-verbal computations. Finally, although direct neuron recordings and MEG recordings enjoy high spatial and temporal resolution, these studies have predominantly focused on processing of the verb, rather than relating the verb to its argument . Thus, little is understood about which brain areas support predicting agreement features, encoding agreement relations, or identifying the relevant controller NP in grammatical structures.

1.2 Split-Ergativity in Hindi and Nepali

Our study focuses on Standard Hindi and Nepali. Both languages are typically written in the Devanagari script and use a subject-object-verb (SOV) word order. Hindi nouns, verbs, and adjectives are marked for masculine or feminine gender (typically with *-ā* masculine singular, *-e*

for masculine plural, and -*ī* for feminine). Nepali animate nouns, verbs, and adjectives are marked for gender (typically -*ā* and -*o* for masculine and -*ī* and -*i(n)* for feminine), and verbs inflect for number. Inanimate nouns typically default to masculine in Nepali.

Both languages use a split-ergative case system. In the perfective aspect, the subject NP obligatorily ends in the ergative case suffix ने -*ne* in Hindi. In Nepali, the subject usually ends in the ergative suffix ले -*le*, although other factors can affect ergative case (Li 2007). In the imperfective aspect, the subject NP surfaces in the nominative case, which is morphologically unmarked.

Both languages also exhibit an object case alternation. Animate object NPs obligatorily surface with the accusative/dative case suffix को -*ko* in Hindi and लाई -*lāī* in Nepali. Inanimate object NPs may occur bare or with the accusative case. Inanimate object NPs that are marked with the accusative case carry a specific or definite interpretation. The variation in case of the subject NP and object NP are orthogonal, and do not appear to change their thematic interpretation or the grammatical relations between the NP arguments and the verb apart from agreement.

Hindi verb agreement is descriptively governed by what Bhatia (2019) calls The Hindi Agreement Generalization, based on Pandharipande & Kachru (1977): The verb agrees with the most prominent NP that is unmarked for case. This results in an interaction between ergativity/aspect marking and agreement. In the imperfective aspect (e.g., simple present), the subject NP does not end in ने -*ne*. The subject NP controls agreement in this configuration. However, in the perfective aspect, the subject must have the ergative suffix ने -*ne*. In this syntactic context, the subject does not control agreement due to the case marker. Instead, the next prominent NP must be considered. If the object NP is a bare, then the object controls agreement, since it is now the most prominent NP without case. However, if the object is marked with को -*ko*, then it also is not relevant for agreement. In this situation, with both NP arguments marked, the verb must surface as a third person, singular, masculine ‘default’ form. In Nepali, by contrast, verbs always agree with subject NP, regardless of case features. This is illustrated in Figure 1A.

More exhaustive studies on case and agreement in Hindi can be found in Butt and King (2004), Bhatt (2005), and Mahajan (2017).

Previous studies on the processing of Hindi/Urdu using EEG have revealed a similar rapid sensitivity to agreement violations as observed in other languages. In an agreement violation paradigm, Nevins et al. (2007) found that subject-verb agreement violations produced a greater 'P600', a positive amplitude beginning ~600ms post-verb onset, compared to grammatical controls. This was observed for verbs that mismatched in number, gender, and person with the subject NP, with the greatest amplitude difference corresponding to person mismatches. In a study leveraging the correspondence between subject NP case and verb tense/aspect, Choudhary et al. (2009) found distinct ERP patterns to verbs that mismatch in aspect with the expected case marker. Bare subject NPs followed by an ungrammatical simple perfective verb produced greater N400 amplitude post-verb onset compared to grammatical controls, and ergative subject NPs followed by an ungrammatical imperfective verb produced both greater N400 and P600 responses post-verb onset (see also Bickel et al. 2015). Bhattamishra et al. (2021) found an increase in P600 amplitude for gender agreement errors for animate subject NPs, but a negativity observed in posterior midline sensors for gender agreement with inanimate subject NPs (see also Gulati & Choudhary 2023 for Punjabi). Sauppe et al. (2021) show that neural signatures diverge before the utterance of sentences beginning with ergative vs. bare subject NPs. In behavioral measures, Bhatia & Dillon (2022) demonstrate that sensitivity to agreement violations is selective to syntactic context, parallel to the grammatical description above. They argue that Hindi comprehenders must explicitly consider the syntactic context and track which NP is identified as the agreement controller, as a key process in agreement processing. Taken together, these data show rapid integration of morphological features of the noun and verb, including case features, to construct agreement dependencies.

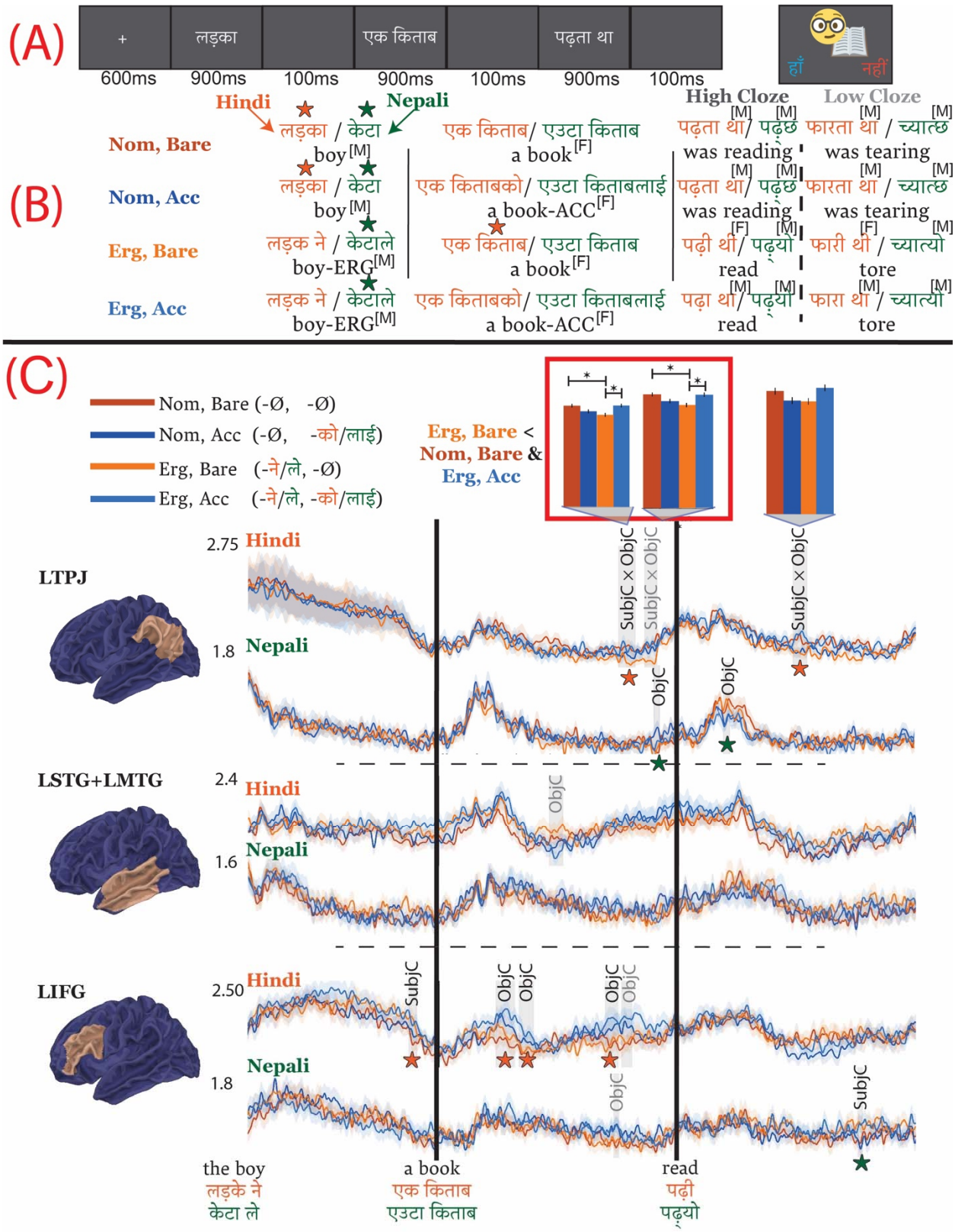

Figure 1. (A) Task structure. Participants saw a subject NP, object NP, and verb for 900ms each, followed by 100ms of blank screen. Then, they responded whether an image matched the sentence they just read. (B) Sample stimulus set. Conditions are Nom(inative)/Erg(ative) Subject; Bare/Acc(usative) Object; and High Cloze/Low Cloze.

Sentences are displayed both in Hindi (orange; left) and Nepali (green; right), with a gloss below each phrase. Superscript [M] marks morphologically masculine words, and [F] marks feminine words. Stars indicate which NP is the agreement controller. In Hindi, the subject NP in the Nominative subject conditions; the object NP in the Ergative Subject, Bare Object conditions, and no NP in the Ergative Subject, Accusative Object conditions. In Nepali, the subject NP. (C) Results of the ROI analysis. Brain plots show the ROI the activity of which was averaged, followed by the time course of this activity by condition for Hindi (top) and Nepali (bottom), averaging over the factor Verb Cloze Probability. Gray shading indicates temporal extent of clusters before correction of *p*-values for multiple comparisons. Stars indicate post-correction, statistically significant ($p < 0.05$) temporal clusters, and black text indicates the coefficient of the significant factor. Inset bargraphs show the averaged signal in the two significant temporal clusters in left temporo-parietal junction (LTPJ) in Hindi.

2. Methods

2.1 Participants

Twenty-five self-identified native speakers of Hindi and twenty-four self-identified native speakers of Nepali were recruited from the local community. All participants had normal or corrected-to-normal vision. The study was formally approved by the Institutional Review Board and all participants gave written consent.

2.2 Materials

We prepared fifty sets of items in both Hindi and Nepali. Each item set consisted of eight simple transitive sentences, in subject-object-verb word order, written in the Devenagari script. We manipulated the Subject Case (Nominative/Ergative), Object Case (Bare/Accusative), and Verb Stem Cloze Probability (High/Low), yielding a 2×2×2 design, in both languages.

The subject NPs were always animate nouns, and the object NPs were always inanimate nouns. This was done to ensure that the intended thematic relations between NPs were easily determinable, to ensure both bare and accusative object NPs were grammatically well-formed, and to make object-subject-verb (OSV) analyses less likely. The genders of the NPs were counterbalanced, such that the subjects were grammatically masculine in 50% of the items, and grammatically feminine in the other 50%. In Hindi, inanimate NPs are also marked for gender, so we ensured that the object NP and the subject NP had opposite gender marking. In Nepali, inanimate NPs are not grammatically marked for gender, and default to masculine. Thus, in Nepali, we counterbalanced the gender of the subject NP only.

The verb forms were grammatical in all trials. In Hindi, the verbs were marked with the past perfective endings if the subject was ergative, and with the past imperfective endings if the subject was nominative. In Hindi, tense surfaces as a separate auxiliary form, and aspect is marked with a verb stem suffix. Both tense and aspect markers agree with the subject in gender. In Nepali, the verbs were marked with the present perfective endings if the subject was ergative, and with the present imperfective endings if the subject was nominative. Due to orthographic conventions, the ergative and accusative case suffixes were written after a space in Hindi, and were written connected to the noun stem in Nepali. Because some masculine nouns in Hindi have the same form for the singular and plural, we also included the singular indefinite article एक *ek* 'one' before the object NP in Hindi, and the singular indefinite article एउटा *eu□ā* 'one' in Nepali to maintain parallelism between the languages.

Verb stems were chosen to ensure that the sentences all contained plausible thematic relations between the arguments and the verb. However, we varied the predictability of the verb stem as a factor in our design. This 'N400' manipulation was included as a verification of the design, to ensure that both participant groups attended to the stimuli, and that we could replicate an otherwise well-attested neural response. The N400 is a well-studied event-related potential (ERP) that is associated with predictability of a word given prior context (Kutas & Hilyard 1980; Lau et al. 2008; Kutas & Federmeier 2011). In EEG recordings, greater negative amplitude around 200–400ms is associated with less predictability given the context. The MEG correlate, the ‘M350’, and fMRI recordings localize responses to unpredictable words in the left temporal lobe (Baumgaertner et al. 2002; Halgren et al. 2002; Van Petten & Luka 2006; Pylkkänen & McElree 2007; Lau et al. 2008; Lau & Namyst 2019). We therefore expect to see a similar response that distinguishes between high-probability and low-probability verb stems around 200–400ms after verb onset in the left temporal lobe for both languages. We treat cloze probability as a binary factor, with levels High Cloze Probability and Low Cloze Probability.

Verb stem probability was estimated from an online sentence completion task (N = 76 for Hindi, N = 48 In Nepali). Subject and object NPs were presented in each case combination, distributed in a Latin Square design for an internet-based task. Participants were instructed to type a completion for the prompt, in either Devanagari or Roman script. Verb stems were identified by two linguists, one a native speaker of both Hindi and Nepali. The average High

Cloze Probability stems were produced 38.1±3.0% of the time for Hindi and 36.7±2.5% of the time for Nepali, and the average Low Cloze Probability stems were produced in 5.2±0.1% and 3.7±0.8% of the completions for Hindi and Nepali respectively. The stimuli are exemplified in Figure 1B.

2.2 Procedure

Participants were instructed about the task and signed a consent form electronically. After the participants arrived, we digitized the participant's head shape using a Polhemus FastScan II (Colchester, VA, USA). This digitized head shape was reduced to a basic surface for use in coregistration with MEG sensor data and MRI structurals. This included 8 fiducial points; 3 points on the forehead and 2 preauricular points approximately 1cm in front of the tragus for coregistration with MEG data, and the two tragus points and one nasion point for coregistration with MRI structurals.

After head shape digitization, participants laid supine in a dimly lit, magnetically shielded room (MSR; Vacuumschmelze, Hanover, Germany). Participants read sentences in Hindi or Nepali presented phrase-by-phrase (subject, object, verb) on a projected screen. The stimuli were presented in Devanagari script in the Devanagari MT font, printed in 36 point white font against a dark grey background. Each phrase was displayed for 900ms, followed by a 100ms blank screen before the next phrase. Each sentence was preceded by a fixation cross that lasted for 600ms. After 25% of trials, participants saw a stock photo image and were instructed to indicate whether the stock photo corresponded to the previous sentence using a button box. No feedback was provided to participants. Stimuli were presented in a pseudo-random order in eight blocks in a within-subjects design, such that one item per set was displayed per block. Participants were instructed to take a short break between each block, and the experimenter communicated with the participant during each break. Trial structure is exemplified in Figure 1A. All experimental procedures and communication with subjects were conducted in Standard Hindi or Nepali.

Brain signals were recorded using a whole-head 208 axial gradiometer (Kanazawa Institute of Technology; Nonoichi, Japan) at a rate of 1000Hz with a 0.1Hz high pass filter and a 200Hz low pass filter applied on-line. The participant’s head position was measured before and

after the experiment using the electrical marker coils attached to the two preauricular and three forehead fiducial points.

2.3 Data Preprocessing

MEG recordings were noise reduced using the CALM method within the MEG160 software (Adachi et al. 2001). All subsequent data analysis was done in MNE-Python (Gramfort et al. 2013) and Eelbrain (Brodbeck et al. 2023). The data were off-line low-pass filtered at 40Hz using the default settings in MNE-Python. We then used independent component analysis (ICA) to remove periodic neuromagnetic artifacts, including heart beats, saccades, and eye-blinks, and interpolated noisy and flat sensors. We then epoched the data from 200ms prior to the first phrase to the end of the sentence. We rejected all epochs that exceeded a 5 pT peak-to-peak threshold. Baseline correction was applied, using the 200ms pre-stimulus period as baseline.

We then projected the data from sensor space to source space. MEG data were coregistered with either a native T1 MRI structural image (N = 12 for Hindi; *N* = 7 for Nepali) or the FreeSurfer template brain 'fsaverage' (CorTechs Labs Inc., California, USA and 175 MGH/HMS/MIT Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts, USA). The fsaverage template brain was scaled to match the digitized headshape and fiducial markers. An ico-4 source space was then built with 2562 vertices per hemisphere using the minimum norm estimate algorithm (Hämäläinen & Ilmoniemi 1994). A forward solution was computed using the boundary element model (BEM; Mosher et al. 1999). Channel noise covariance matrices were estimated using the 200ms baseline period before each trial and regularized using the automated method (Engemann & Gramfort 2015). Combining the forward solution and the noise covariance matrices, an inverse solution was computed for each condition for each subject. For computing the inverse solution, we used a free dipole orientation. Finally, the signals were noise normalized in the spatial dimension, yielding a dynamic statistical parameter map (dSPM; Dale et al. 2000).

2.4 Data Analysis

We conducted two sets of analyses, both for Hindi and Nepali. The first analysis sought to identify effects of case morphology in Hindi and Nepali. This case morphology analysis was a region-of-interest (ROI) analysis. We chose to do an ROI analysis to permit a direct comparison between key brain areas in the two samples, identified in previous research on agreement processing. In this analysis, we averaged the brain response of three critical regions implicated in previous studies on case and agreement morphology – the left inferior frontal gyrus (LIFG), the left superior+middle temporal lobe (LSTG+LMTG), and the left temporo-parietal junction (LTPJ). These ROIs were defined as the left Brodmann Areas (BA) BA-44, BA-45, BA-46, and BA-47 (LIFG), BA-22 and BA-21 (LSTG+LMT), and BA-39 and BA-40 (LTPJ). Then, in each language, in each ROI, at each time point (ms), we conducted 2 × 2 ANOVAs with factors Subject Case (Ergative, Nominative) and Object Case (Accusative, Bare) in the two critical time windows (object NP, verb). For the subject NP time window, we conducted 1-way ANOVAs contrasting the levels of Subject Case (Ergative, Nominative), since the object NP had not been encountered yet. We then used a temporal cluster-based permutation test to identify significant clusters in each of the three ROIs (LIFG, LSTG+LMTG, LTPJ) and the three time windows, following the procedure described by Maris & Oostenveld (2007). First, we identified clusters of adjacent time points showing similar *F*-values produced from the ANOVAs. We constrained the clustering algorithm to time points that had uncorrected *p*-values < 0.10, with a minimum cluster size of 10ms. We excluded the initial 200ms of each phrase, to minimize the effects of orthographic features, i.e., the word length effects of the added case morphemes. We then conducted 10,000 permutation tests to identify significant clusters. For each coefficient of the ANOVA (Subject Case, Object Case, Subject Case × Object Case), we used the Benjamin-Hochberg method to correct for false discovery rate (FDR; Benjamini & Hochberg 1995). For FDR correction, we included all temporal clusters with *p*-value < 0.05. When we did not identify a significant cluster for a coefficient in the ANOVAs for some time window-ROI search, we either included in the FDR correction procedure the smallest non-significant cluster, or a *p*-value of 1.0 if no cluster was identified. The results of these ROI analyses in Hindi and Nepali are shown in Figure 1B.

Afterwards, we conducted three exploratory analyses. The first exploratory analysis replicated the 2 × 2 ANOVA analysis, examining the effects of morphological case. However, instead of a targeted ROI analysis, we explored the entire left-lateralized language network,

using a spatio-temporal clustering procedure. We constructed the left-lateralized language network by combining the *aparc* labels corresponding to the left temporal lobe (bankssts, fusiform, insula, inferior temporal, middle temporal, superior temporal, temporal pole, transverse temporal, lateral occipital, and entorhinal), inferior frontal cortex (pars opercularis, pars orbitalis, pars triangularis), temporo-parietal junction (inferior parietal, supramarginal), and ventromedial prefrontal cortex (frontal pole, medial orbitofrontal, lateral orbitofrontal, rostral middle-frontal). We conducted spatio-temporal cluster-based permutation tests as described above, including a cluster-formation threshold of 10 source points. We also conducted this exploratory analysis in two separate time windows, an early, 'N400/LAN' time window (300–600ms), and a later, 'P600' time window (600–900ms) in the object NP and verb time windows. The goal of this exploratory analysis was to determine whether we could identify candidate clusters in space-time corresponding to the findings from the ROI analyses, and whether their spatial and temporal extent were similar or different between the two languages. The results of this analysis are shown in Figure 2.

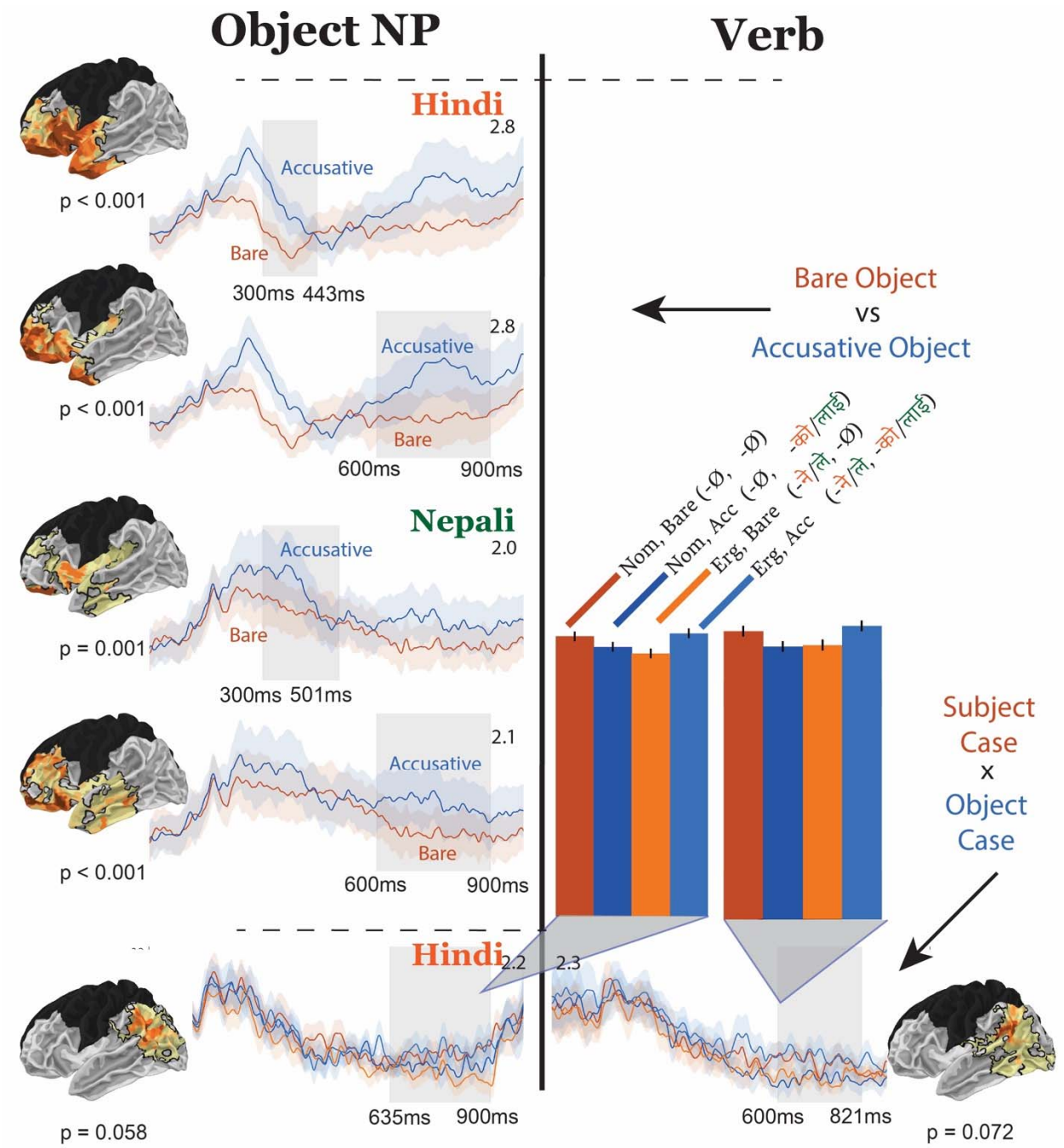

Figure 2. Results of exploratory spatiotemporal cluster-based permutation tests in Hindi (top) and Nepali (bottom) in the object NP (left) and verb (right) time windows for the 2 × 2 ANOVA. Brain plots show the spatial extent of the cluster – yellow indicates that the spatial coordinate was included in the cluster, and red shading indicates the *F*-value of the cluster at its peak. Time course shows the temporal extent of the clusters in gray shading. Top portion of the plot shows the Object Case clusters, and the bottom portion shows the Subject Case × Object Case interaction.

The second exploratory analysis sought to identify the neural correlates of processing verb gender. In languages like English and Nepali, the morphological features of the verb are dependent on the morphological features of the subject, in grammatical sentences. This means that a brain response to plural verbs might de difficult to distinguish from the brain response to retrieving or activating a plural subject NP, for instance. However, because of the split-ergative agreement system in Hindi, the morphological features of the verb in Hindi are not correlated directed with the morphological features of one noun across all sentence types. For this reason, we defined a *post-hoc* factor Verb Gender, with the levels Masculine and Feminine. Masculine consisted of Nominative/Bare and Nominative/Accusative sentences with a masculine subject NP and feminine object NP, Ergative/Bare sentences with feminine subjects and masculine object NPs, and all Ergative/Accusative sentences. All Ergative/Accusative sentences require a 3rd person, masculine verb, because this is the default form when all NPs are case-marked in Hindi. Verb Gender had the level Feminine for Nominative/Bare and Nominative/Accusative sentences with a feminine subject NP and masculine object NP, and Ergative/Bare sentences with masculine subjects and feminine objects. In Nepali, this factor was co-extensive with the gender features of the subject NP. This is shown in Table 1. Like the previous exploratory analysis, this analysis was conducted as spatio-temporal cluster-based permutation test, conducted in the left-lateralized language network, in the 'early' and 'late' time windows (300–600ms, 600–900ms) of the object NP time window. The goal of this analysis was to determine if there was a brain response corresponding to the prediction of an upcoming gender feature during the object NP before the verb, abstracted away from the morphological features of the nouns.

Finally, the last exploratory analysis targeted the factor Verb Stem Cloze. This analysis was also conducted in the left lateralized language network, but only in the verb time window. The results of these latter two exploratory analyses are shown in Figure 3.

Language	NP Genders (Subject/Object)	*Subject Case*	*Object Case*	*Verb Gender*
Hindi	Masculine Subject / Feminine Object	Nominative	Bare	Masculine
Hindi	Masculine Subject / Feminine Object	Nominative	Accusative	Masculine
Hindi	Masculine Subject /	Ergative	Bare	Feminine

	Feminine Object			
Hindi	Masculine Subject / Feminine Object	Ergative	Accusative	Masculine
Hindi	Feminine Subject / Masculine Object	Nominative	Bare	Feminine
Hindi	Feminine Subject / Masculine Object	Nominative	Accusative	Feminine
Hindi	Feminine Subject / Masculine Object	Ergative	Bare	Masculine
Hindi	Feminine Subject / Masculine Object	Ergative	Accusative	Masculine
Nepali	Masculine Subject	Nominative	Bare	Masculine
Nepali	Masculine Subject	Nominative	Accusative	Masculine
Nepali	Masculine Subject	Ergative	Bare	Masculine
Nepali	Masculine Subject	Ergative	Accusative	Masculine
Nepali	Feminine Subject	Nominative	Bare	Feminine
Nepali	Feminine Subject	Nominative	Accusative	Feminine
Nepali	Feminine Subject	Ergative	Bare	Feminine
Nepali	Feminine Subject	Ergative	Accusative	Feminine

Table 1. Assignment of the feature Verb Gender in Hindi and Nepali, as a function of the language, the genders of the subject and object, the subject case, and the object case.

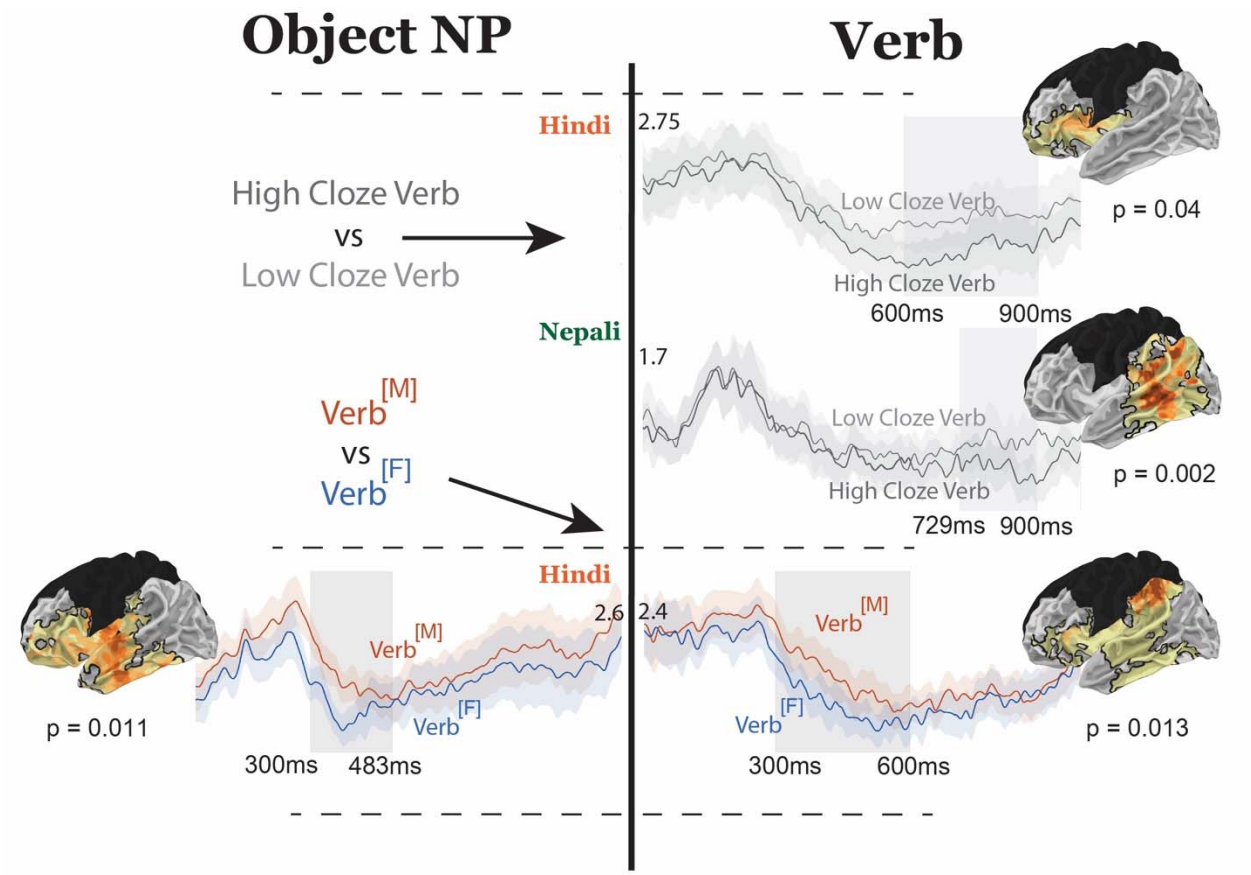

Figure 3. Results of exploratory spatiotemporal cluster-based permutation tests in Hindi (top) and Nepali (bottom) in the object NP (left) and verb (right) time windows for one-way ANOVAs of Verb Stem Cloze Probability and Verb Gender. Brain plots show the spatial extent of the cluster – yellow indicates that the spatial coordinate was included in the cluster, and red shading indicates the *F*-value of the cluster at its peak. Time course shows the temporal extent of the clusters in gray shading. Top portion of the plot shows the Verb Stem Cloze Probability clusters, and the bottom portion shows the Verb Gender clusters in Hindi.

3. Results

Behavioral Results

For behavioral results, we fit a logistic liner mixed effects model in R (R Core Team 2021) to the accuracy and a linear mixed effects model to the reaction times on the trials with the picture matching task. We fit two separate models to the Hindi and Nepali data, because models including a factor of Language did not converge. All models had a structure including Subject Case, Object Case, Verb Stem Cloze Probability, and participant as a random effect. For the Hindi participants, we found that responses to sentences with accusative objects were less accurate than their bare counterparts ($\beta = -0.55$, SE = 0.17, $z = -3.2$, $p = 0.001$), and similarly for

sentences with low probability verbs compared to high probability verbs ($\beta = 0.39$, SE = 0.17, $z = -3.2$, $p = 0.001$). There was a marginal three-way interaction, suggesting less accurate responses for sentences with ergative subjects, accusative objects, and low cloze probability ($\beta = -0.59$, SE = 0.33, $z = -1.7$, $p = 0.08$). Sentences with accusative objects were responded to marginally more quickly than bare objects ($\beta = -0.65$, SE = 0.37, $t = -1.7$, $p = 0.07$). There was also a two-way interaction, showing greater response times for accusative objects and low cloze verbs ($\beta = 1.29$, SE = 0.52, $t = 2.5$, $p = 0.01$). For the Nepali participants, responses to sentences with ergative subjects were less accurate than to bare subjects ($\beta = -0.59$, SE = 0.16, $t = -3.7$, $p < 0.001$), and to accusative objects than to bare objects ($\beta = -1.24$, SE = 0.17, $z = -7.3$, $p < 0.001$). This is tempered by the two-way interactions showing greater response accuracy for sentences with ergative subjects and accusative objects ($\beta = 1.15$, SE = 0.24, $z = 4.8$, $p < 0.001$), and ergative subjects and low cloze verbs ($\beta = 1.14$, SE = 0.24, $z = 4.7$, $p < 0.001$). Finally, there was a three-way interaction suggesting lower response accuracy for ergative subjects, accusative objects, and low cloze probability verbs ($\beta = -2.30$, SE = 0.36, $z = -6.5$, $p < 0.001$). For response times, sentences with low cloze probability verbs were slower than high cloze probability verbs ($\beta = 0.52$, SE = 0.25, $t = 2.1$, $p = 0.03$). Two-way interaction showed slower response times for sentences with ergative subjects and accusative objects ($\beta = 0.78$, SE = 0.38, $t = 2.0$, $p = 0.04$). A marginally significant two-way interaction suggested slower response times for sentences with ergative subjects and low cloze verbs ($\beta = -0.71$, SE = 0.36, $t = -1.9$, $p = 0.051$). The mean acceptability and response times are shown in Figure 4.

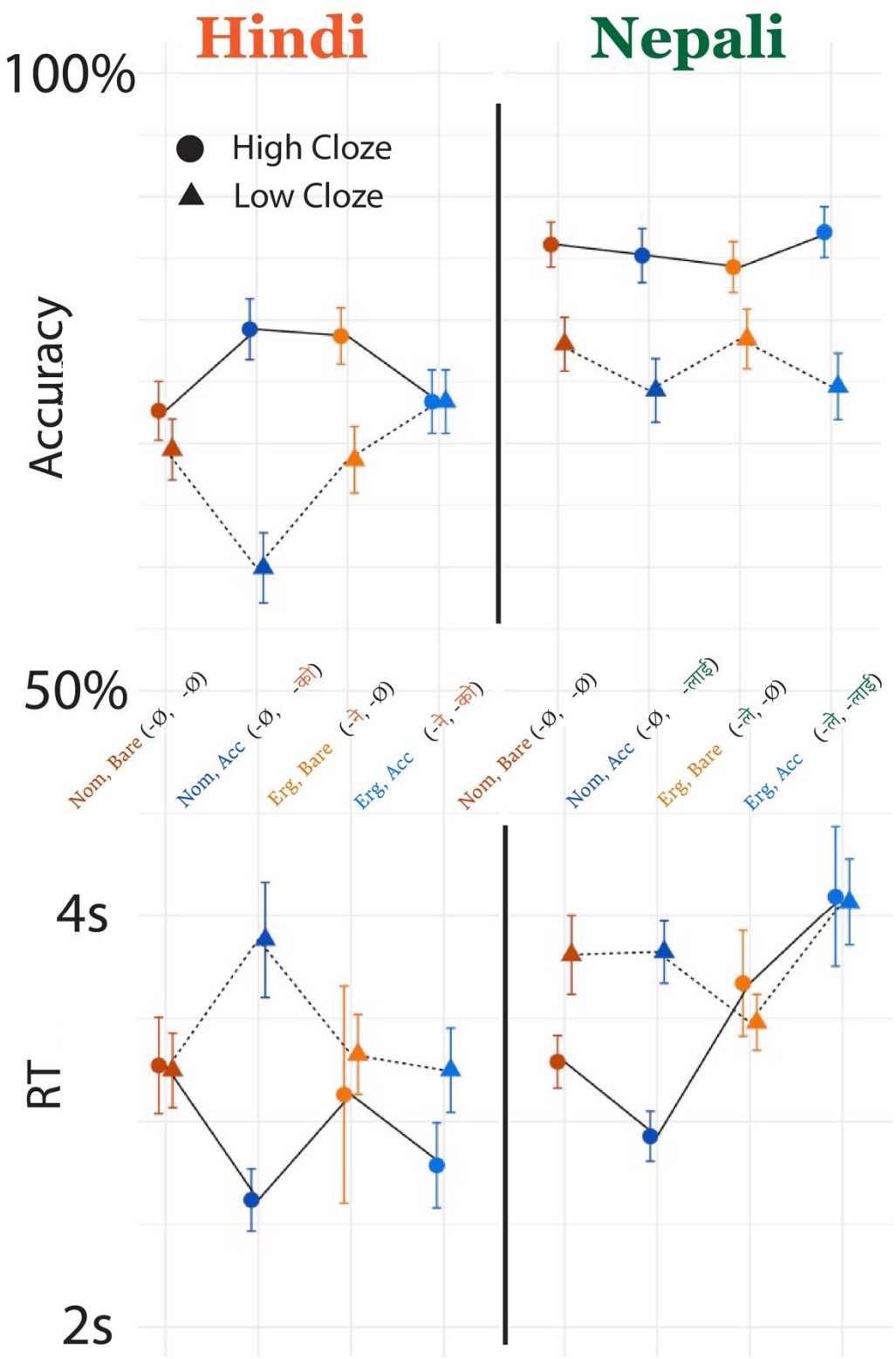

Figure 4. Accuracy and response time by condition for the behavioral task. The x-axis shows the condition, collapsing over the factor of Verb Stem Cloze Probability. Circles with solid lines show the High Cloze conditions and the triangles with dashed lines show the Low Cloze conditions.

Case Morphology ROI Analysis

Prior to FDR-correction, across the three time windows (subject, object, and verb) and three ROIs (LTPJ, LMTG+LSTG, LIFG), there were one Subject Case cluster, five Object Case clusters, and three Subject Case × Object Case clusters in Hindi, and one Subject Case and three Object Case clusters in Nepali. Time courses with temporal clusters are given in Figure 1C.

Post-correction, in Hindi, there was one cluster corresponding to Subject Case in the left inferior frontal gyrus, from 876–908ms after subject NP onset (corrected $p = 0.03$). This cluster showed greater activity for ergative subjects compared to nominative subjects. In the subsequent object NP time window, there were three significant clusters corresponding to Object Case in the left inferior frontal gyrus, each showing greater activity for accusative case. The first occurs 241–330ms post object NP onset (corrected $p = 0.003$), the second occurs 338–397ms (corrected $p = 0.02$), and the third occurs from 697–761ms (corrected $p = 0.03$). Around the same time, from 757–825ms, there is an interaction of Subject Case × Object Case in the left temporo-paterial junction (corrected $p = 0.01$). This temporo-parietal junction cluster shows greater activity for Nominative/Bare and Ergative/Accusative conditions compared to Nominative/Objects and Ergative/Bare conditions. In the verb time window, this is followed by a similar pattern in the left temporo-parietal junction 479–537ms post verb onset (corrected $p = 0.02$).

In Nepali, post-correction, we identified an Object Case cluster in the left temporo-parietal junction from 912–934ms post object NP onset (corrected $p = 0.03$). Like in Hindi, this cluster showed greater activity for accusative object NPs compared to bare object NPs. In the subsequent verb time window, there was a cluster 202–231ms post stimulus onset (corrected $p = 0.02$) that showed greater activation for bare object NPs compared to accusative object NPs. This was followed by a cluster of Subject Case in the left inferior frontal lobe 740–759ms post verb onset, showing greater activity for sentences with ergative subjects compared to nominative subjects (corrected $p = 0.03$).

Case Morphology Exploratory Analysis

In the exploratory spatio-temporal analysis, we identified a biphasic response for Object Case in the left inferior frontal lobe and the left anterior temporal lobe in both Hindi and Nepali. In the Hindi data, we identified a cluster 300–433ms ($p < 0.001$) and 600–900ms ($p < 0.001$) showing greater activity for accusative object NPs compared to bare object NPs. In Nepali, we identified clusters 300–501ms ($p = 0.001$) and 600–900ms ($p < 0.001$), showing greater activity for accusative objects compared to bare objects. In Hindi, we also identified two marginally-significant clusters in the left temporo-parietal junction in the object NP time window and the verb time window. Like the ROI analyses, these clusters showed greater activity for Nominative/Bare and Ergative/Accusative conditions compared to Nominative/Accusative and Ergative/Bare. These clusters were found 635–900ms post-object NP onset ($p = 0.058$) and 600-821ms ($p = 0.072$) post-verb onset. No significant clusters or marginally significant clusters were identified for subject case in Hindi or Nepali, or the interaction term in Nepali.

Verb Gender Exploratory Analysis

In the exploratory analysis of Verb Gender, we identified a cluster in Hindi in both the object NP and the subsequent verb time window. Both clusters showed greater activation for (predicted) masculine verbs over (predicted) feminine verbs. The cluster observed in the object NP time window was centered on the left inferior frontal lobe and the left anterior temporal regions, 300–483ms post-object NP onset ($p = 0.011$). The cluster observed in the verb time window was centered on the left temporo-parietal junction, 300–600ms post-verb onset ($p = 0.013$). No clusters were identified for Nepali Verb Gender in this exploratory analysis.

Verb Cloze Probability Exploratory Analysis

In the exploratory analysis for verb cloze probability, we did not find any difference between Low Probability Verb Stem and High Probability Verb Stem conditions in the expected N400 time window. Instead, in Hindi, we found a cluster in the left inferior frontal gyrus 600–

900ms post-verb onset (p = 0.04. For Nepali, the cluster was located in posterior temporal cortex, 729–900ms (p = 0.002).

4. Discussion

In both Hindi and Nepali, we found a consistent profile implicating the left inferior frontal lobe and portions of temporal cortex as correlating with NP case morphology. This was robustly observed in the Hindi ROI analysis and reflected in the exploratory spatiotemporal analysis in both Hindi and Nepali. In Hindi, we also observed an interaction effect, demonstrating lowered activity for Nominative Subject, Bare Object and Ergative Subject, Accusative Object in the left temporo-parietal junction. This was observed both during processing of the object NP and during the verb. Furthermore, we observed that these regions correlated with the morphological gender of the verb, both before the verb was encountered in the left inferior frontal lobe and anterior temporal regions, and at the verb in the left temporo-parietal junction. No similar effect was observed in Nepali.

The Verb Cloze manipulation localized to different cortical regions in Hindi and Nepali. Both the source localization of the Hindi and Nepali results are consistent with the broad network of regions that underlie N400 effects (Lau et al. 2008). However, the delayed response is somewhat surprising. This may have been due to the increased complexity of the stimuli, since entire phrases were displayed one-by-one, or due to additional complexities introduced by the Devanagari writing system.

Interpretation of LIFG effects

In both Hindi and Nepali, we observed greater activation in the left inferior frontal lobe for ergative subjects while processing the subject NP, and in the left inferior frontal lobe and portions of the left anterior temporal lobe for accusative case while processing the object NP. These findings could in principle reflect computations corresponding to representing ergative and accusative NPs, respectively. However, both cases are ‘marked’, in the sense that there is an additional, overt morpheme. For this reason, the increased activity in the left inferior frontal gyrus could reflect additional morphosyntactic computations corresponding to the visual stimuli,

instead of any abstract linguistic computation. Alternatively, the ergative case and accusative case provide additional semantic information about the interpretation of the sentence that may be relevant for predictive processing. In both languages, the ergative case implies that the sentence will terminate with a simple past tense verb. The accusative case assigns a definite or specific interpretation to the object NP, which may require updating a discourse representation. Thus, the left inferior frontal cortex activity could correspond to top-down predictive processes of morphological features, discourse-related processes, or both.

The left inferior frontal cortex is implicated in many processes in language comprehension. Much attention has been paid to the correlation between the left inferior frontal activity and general processes assisting in sentence comprehension (Stromswold et al. 1996; Ben-Shachar et al. 2003; Bornkessel et al. 2005; Hagoort 2005; Friederici 2018). More recent proposals highlight the role of the left inferior frontal gyrus is its role in supporting retrieval from short term memory (Fiebach et al. 2005; Novick et al. 2005; Caplan et al. 2008; Leiken & Pylkkänen 2014). Case and agreement information are crucial cues for identifying the relations between verbs and their argument NPs. Thus, this activity may reflect differential uses of case information to identify the participants of an event. Different case configurations may differentially guide the retrieval of previously-encountered NP arguments for identifying possible semantic or syntactic relations between them, which could result in case morphology affecting the left inferior frontal lobe differently.

One key to interpreting the left inferior frontal and the left anterior temporal cortex activity is that the same brain regions appear to index case information and predict verb features. The left inferior frontal lobe may assist in morphosyntactic processing and morphological decomposition (Sahin et al. 2006; Marslen-Wilson & Tyler 2007; Regel et al. 2017). Thus, the left inferior frontal lobe activity may correspond to identifying the relevant morphological cues, i.e. noun gender and number, and maintaining a representation of the verb’s expected morphological structure. This latter possibility is supported by findings that the left inferior frontal lobe may support syntactic predictions (Matchin et al. 2017). If this is the correct interpretation, then this suggests that agreement processing may require a mechanism of prediction before the verb is encountered (Eberhard et al. 2005; Chacón 2022), despite much of the attention in psycholinguistics focusing on memory retrieval processes that unfold after the verb is encountered.

Interpretation of LTPJ effects and the Psycholinguistics of Agreement

The effects observed in the left temporo-parietal junction are arguably more theoretically novel. This effect was only observed in Hindi during processing of the object NP and the subsequent verb. Crucially, the sentences in our experiment are virtually identical in terms of their syntactic structure, and the case morphemes in both languages serve virtually identical semantic and syntactic functions in the two languages, apart from their relevance for agreement. Thus, the processes that are correlated with the different case morphemes are controlled for between the two languages, and cannot be the explanation for this activity. Thus, we argue that the unique effect observed in this brain region in Hindi likely reflects the specific processes of selecting an agreement controller.

The left temporo-parietal junction appears to have a wide range of functions (Seghier 2013). In language processing, the left temporo-parietal junction is usually thought to be key to understanding event representations (Binder et al. 2009, Binder & Desai 2011) or semantic and thematic relations (Lewis et al. 2015; Thompson et al. 2007; Thothathiri et al 2012, Williams et al. 2017). However, although agreement is a helpful cue in identifying the relations between an event and its participants, it's not clear how to relate this line of research to the selection of a verb agreement controller, a purely functional syntactic relation. Outside of language processing, bilateral temporo-parietal junction activity corresponds to attention shift (Corbetta & Shulman 1998; Singh-Curry & Husain 2009; Seghier 2013), especially attending to task-relevant "bottom-up" features (Ciaramelli et al. 2008).

We propose that agreement controller selection in object agreement constructions can be conceived of as requiring a shift in attention. In Hindi, the generalization is that the most structurally prominent, morphologically bare is the agreement controller. This requires participants to attend to the morphological properties of both the subject NP and the object NP, relate them to the syntactic analysis, and then select one as relevant for agreement computation. Since the object NP canonically follows the subject NP, participants must first attend to the morphosyntactic properties of the subject, and then the object NP. In the critical object-agreement constructions, this necessitates processing the morphosyntactic features of the subject

NP, then shifting and attending to the morphosyntactic features of the object NP, then determining which set of features is relevant for the task of predicting verb features.

We suggest that the directionality of the effect may support in this interpretation. The interaction effect in the left temporo-parietal junction shows an reversal of activation for the two object NP cases given the prior subject NP cases. After a nominative (bare) subject NP, a bare object NP shows greater activation than an accusative (marked) object NP. Conversely, after an ergative (marked) subject NP, an accusative (marked) object NP shows greater activity than a bare object NP. Put differently, there is a reduction in the left temporo-parietal junction activity if there is one bare NP, but there is greater activity if there are zero or two. If we interpret this interaction through the lens of attention, then we could suggest that the reduced activity for Nominative Subject, Accusative Object and Ergative Subject, Bare Object is due to the decreased demand in identifying a potential agreement controller, as there is only one candidate NP without a case suffix. However, in the Nominative Subject, Bare Object and Ergative Subject, Accusative Object, it is not the case that there is a morphologically unambiguous cue to the agreement controller. In the former condition, there are two bare NPs, and thus the comprehender must examine the syntactic properties of the entire sentence to identify the intended controller, i.e., they must determine which bare NP is the most prominent, as per Bhatia's (2019) generalization. In the latter case, both NPs are marked, and thus participants must retrieve a default rule, in which a 3rd masculine singular form of the verb is selected, rejecting both NPs as potential agreement controllers.

If this is the right approach, our findings appear to conflict with Bhatia & Dillon's (2022) behavioral findings. Bhatia & Dillon find that, using an agreement-attraction paradigm (e.g. (Wagers et al. 2009), Hindi speakers' agreement attraction errors are not sensitive to bare NPs. Instead, they find that agreement processing in Hindi only shows susceptibility to attraction effects if there are additional agreement controllers. Put differently, morphological features are not sufficient for rendering an NP as a potential attractor. However, their findings crucially depend on processes occurring during or after the verb, whereas we report on evoked responses at the preverbal object NP. It is possible that Hindi speakers may initially evaluate an NP as a 'candidate' agreement controller based purely on morphological features, yielding the evoked responses we report here, and then subsequently reject it based on syntactic features, rendering it invisible to attraction later. We leave reconciling these findings to future work.

Finally, the interpretation we propose here rests crucially on the generalization that only bare NPs are eligible for agreement controlling, and that Hindi speakers rely on this morphological cue. Other Indo-Aryan languages with split ergativity do not follow this generalization. For instance, Gujarati exhibits a nearly-identical case system as Hindi and Nepali. Like Hindi, the verb agrees with the object in the simple past, and this is cued by the presence of an ergative case suffix on the subject. However, unlike Hindi, the simple past agrees with the object regardless of whether it is bare, i.e., an accusative case suffix on the object does not 'block' object-verb agreement (Mistry 1997). If our interpretation of the Hindi data is correct, then we would expect an interaction of case features in Gujarati. However, we would not predict that the pattern of activity would be the same, since accusative case features do not have the same relevance for identifying agreement controllers as in Hindi.

5. Conclusion

The human brain is capable of learning and representing any natural human language. Yet, different grammatical rules may require that comprehenders store, attend to, or predict different features, processes which must be supported by the brain. By careful cross-language comparison, we can refine theories that relate psycholinguistic models of language comprehension with brain activity. Specifically, we found that Hindi comprehenders exhibit an interaction of subject and object case features in the left temporo-parietal junction activity, and we failed to find a similar pattern in Nepali comprehenders. We suggest that this demonstrates the selective deployment of attention systems to identify a verb agreement controller. We also found that the left inferior frontal and the left anterior temporal lobe activity showed near-identical effects of case morphology in Hindi and Nepali, and that this region may facilitate the prediction and encoding of the verb's gender morphology before the verb is encountered. Our findings validate the utility of carefully controlled, cross-language experiments in the cognitive neuroscience of language, and the importance of research in less-studied languages for psycholinguistic models in general.

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To be completed upon completion.

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