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What sign languages show

Neurobiological bases of visual phonology

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The chapter presents analysis of the motion properties of the environment that humans use to parse natural scenes, and the kinematics of articulator (hand) motion in American and Croatian Sign Languages, asking whether the kinematic distinctions between linguistic categories in sign languages are important to phonological and syntactic systems in sign languages. Based on motion capture and neuroimaging data from native signers and sign-naïve non-signers, we propose that sign languages grammaticalize perceptual features already available from the human visual system for the phonology-syntax interface.

1. Introduction

Human languages differ from all other stimuli in the natural environment in that they rely on rapid spectral changes over varying time intervals (Poizner 1981; Zatorre & Belin 2001). Perception of this type of input is supported by the neurons in the visual and auditory system, which are individually sensitive to specific ranges of spectral information change over time (as characterized by their spectral-temporal receptive fields, or STRFs), which adapt to match the sparsely distributed, informative components of the natural world to make processing informationally and metabolically more efficient (Theunissen et al. 2001; Vinje & Gallant 2000). The features extracted from linguistic input are further processed for extraction of what can be currently construed as linguistic information at the phonological, semantic, and syntactic levels.

While the exact mechanisms of cortical tuning are not yet completely understood, there is more known about the abstract level of visual and auditory processing. For example, both visual and auditory systems activate distinct cortical networks for processing of different sources of signal, such as hands vs. face information in the visual stream, living vs. non-living sound sources in the auditory system (Engel, Frum, Puce, Walker & Lewis 2009; Thompson, Hardee,

Panayiotou, Crewther & Puce 2007). At least since Poizner (1981, 1983), sign language researchers hypothesized that kinematic properties of hand articulator movement in sign languages might carry phonological information in sign languages, although high-resolution quantitative kinematic and neuroimaging data were not available until recently. In this chapter, we will review some of the insights gained from the recent inquiries into the question of how perceptual-kinematic properties of the hand articulator motion can be processed as phonological distinctions by signers.

2. Visual adaptation to the processing of sign language

The adaptations of the signers' visual system due to the processing requirements of sign language has been extensively investigated using behavioral, neurophysiological, and neuroimaging methods. ERP and fMRI studies show that ASL signers (both Deaf and hearing) are much faster and more accurate in identifying direction of motion in the right visual field (processed by the left hemisphere), as compared to hearing non-signers, and show increased left hemisphere activation during a motion detection task (Bosworth & Dobkins 1999; Neville & Lawson 1987). Deaf[1] participants are also faster than hearing ones in detecting information in peripheral vision (Loke & Song 1991; Parasnis & Samar 1985; Reynolds 1993). Motion similarity judgment studies (Poizner 1981, 1983) show that movement and cyclicity in dynamic stimuli are more salient for ASL signers than for non-signers, likely due to the fact that cyclicity is an important feature in ASL (Klima & Bellugi 1979; Wilbur 2009).

The adaptations in the signer's visual system can also point to informationally dense (as well as, possibly, linguistically relevant) features of sign language input. In an experiment by (Klima et al. 1999), Deaf signers and hearing non-signers were shown dynamic point-light displays of Chinese pseudocharacters being drawn 'in the air', and asked to repeat them. Deaf signers were much better at distinguishing transitions from stroke components: i.e. while hearing participants were more likely to draw the entire trajectory of the point-light, Deaf signers identified discrete movement strokes, and were less likely to include transitional movements into their representations of the stimuli. Even though earlier research has already shown that lexical identification in sign languages coincides with movement identification, and that handshape change within the sign coincides

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1. Use of capital D in Deaf is an indicator of cultural affiliation, including use of sign language as primary means of communication.

with the end of movement whereas between signs it can be completed at any time (Brentari & Poizner 1994), the kinematic markers of transitional vs. linguistic motion are still under-investigated.

3. Kinematic features in sign language phonology

Kinematic features of motion in dynamic scenes, such as velocity and deceleration of actor limb movements, appear to play the leading role in segmentation of scenes into discrete events (Speer, Swallow & Zacks 2003; Zacks et al. 2001; Zacks, Kumar, Abrams & Mehta 2009; Zacks, Swallow, Vettel & McAvoy 2006). Sign languages (SLs) as linguistic interfaces of perceptual and non-speech motor behaviors can provide unique insights into the neurobiological substrate of motion processing. In sign language linguistics, articulator movement is considered to be the core of a syllable, comparable to vowels in spoken language. In (Brentari 1998) phonological model of sign language, sign movements are dynamic prosodic units with autosegmental status similar to tones in contrastive tonal languages. From this perspective, syllables in American Sign Language contain distinctive features which are accessed by phonological rule only in terms of their tiers and syllabic positions (syllable initial, final) without further subdivision or organization (Wilbur & Allen 1991). The segments in the syllable are timing slots (x_1, x_2), onto which phonological features are mapped (cf. Figure 1).
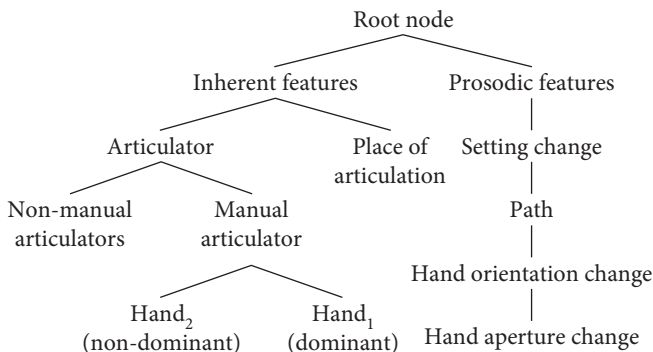
Figure 1. Brentari (1998) Prosodic Model of SL phonology

In Brentari's theory of sign language phonology, telic and atelic ASL verb signs differ in the phonological features which unfold sequentially over time (i.e. dynamic, or prosodic features), and in their syllable structure (Brentari 1998). Specifically, atelic verb signs have the same handshape and orientation specifications for the initial and final positions of the sign, and thus simple syllable

structure; telic ASL signs have a more complex syllabic structure, as they always employ one of the following dynamic changes: (1) change of handshape aperture (open to closed, or closed to open); (2) change of handshape orientation; and (3) arc or circular movement orthogonal to the plane of articulation, with an abrupt stop at a location in space (Wilbur 2008). Within Brentari's (1998) Prosodic Model of sign language phonology, telic and atelic signs thus fall into distinct phonological classes, as shown in Figure 2.
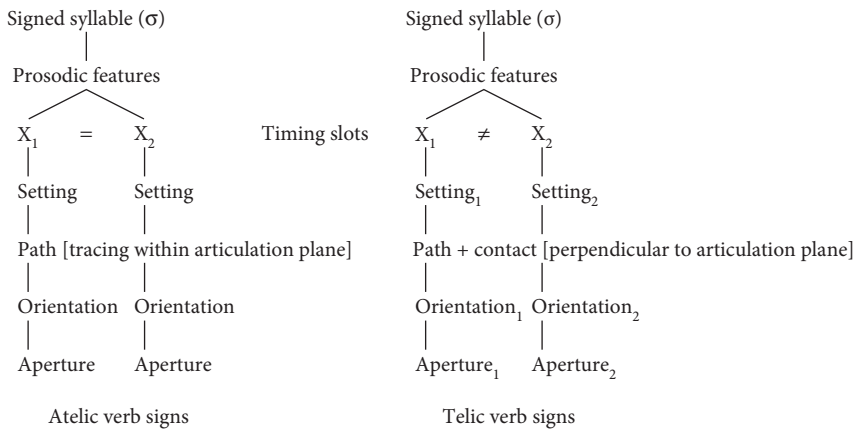

Figure 2. Phonological differences between telic and atelic verb signs

(Wilbur 2003, 2008, 2010) proposed that semantic classes of ASL verbs could be kinematically (and phonologically) marked, formulated as the Event Visibility Hypothesis (EVH). Specifically, internally complete, or telic events (those denoting a change of state, such as *throw, fall*) would have a higher deceleration in their end-motion, reflecting the semantic end-state of the affected argument, as compared to signs denoting atelic events (which typically denote homogenous activities, such as *swim, walk*). This hypothesis was investigated using motion capture method (Malaia & Wilbur in press-a, in press-b), which allows recording the location of the moving hand (articulator) at 60 frames per second in three dimensions. The data was recorded for the dominant (right) hand position during the signing of ASL and Croatian Sign Language (HZJ) verbs in the vocabulary form, in a phrase (SIGN X AGAIN), sentence-medially (SHE X TODAY), and sentence-finally (TODAY SHE X). At the processing stage, the displacement profiles of dominant hand motion, as well as first and second derivatives (velocity and acceleration) were computed for each sign.

Both ASL and HZJ demonstrated the effect of Phrase Final lengthening, whereby the duration of the sign increased significantly in Phrase-Final position (Figure 3). This suprasegmental variable was included in order to filter out

spurious kinematic features: as the signers have no difficulty comprehending the signs regardless of their place in the sentence, only kinematic features robust to Phrase-Final lengthening could be phonologically distinctive.
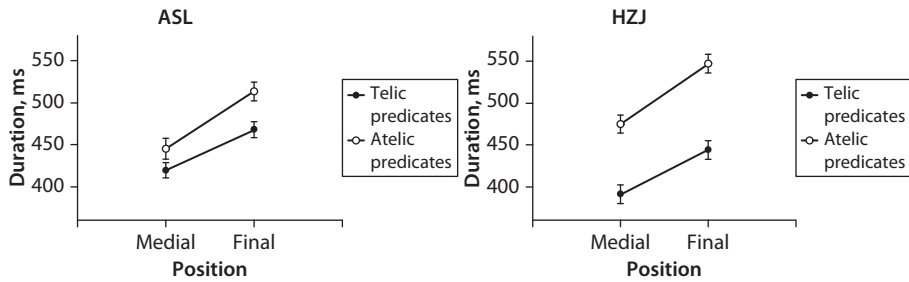

Figure 3. Sign duration in ASL and HZJ, demonstrating effect of Phrase Final Lengthening

Multivariate analysis of variance was conducted to determine the effect of each independent factor (Predicate, Position) and their interaction (Predicate × Position) on each of the dependent kinematic variables. In ASL, the instantaneous deceleration, as well as the overall slope of deceleration within the sign were statistically significant markers of predicate type, unaffected by the sign's position in the sentence. In HZJ, the peak velocity achieved within the sign was similarly significant, and robust to Phrase Final Lengthening (Table 1).

Table 1. Kinematic features significantly different between telic and atelic signs, and not affected by phrase final lengthening, in ASL and HZJ

Kinematic variable	ASL			HZJ		
	$F_{(1,916)}$	$p<$	η_p^2	$F_{(1, 1170)}$	$p<$	η_p^2
Peak velocity				641.448	.001	.354
Instantaneous deceleration	52.614	.001	.054			
Slope of deceleration from peak velocity to the minimum velocity at the end of the sign	29.645	.001	.031			

Overall, the motion capture data on sign production in ASL and HZJ showed that the second slot (x_2) of syllables in predicate signs denoting bounded (telic) events is marked by a rapid deceleration at the end of the sign, made even more prominent by higher peak velocity, as compared to verb signs denoting unbounded (atelic) events (Figure 3), with distinctions of syllable structure being robust to the effect of Phrase Final Lengthening. Signers of both ASL and HZJ mark transitions to end-states within events by articulating them with a higher peak velocity and deceleration, supporting the theoretical proposal that more complex phonological

representation of telic vs. atelic verb signs is represented by kinematic features of the dominant articulator – specifically, its velocity and deceleration. The differences between the statistical results of the kinematic feature analysis in the two languages suggest a possibility that neural adaptations to the input of different sign languages might differ somewhat (although not as much as the visual systems of a signer and a non-signer).

4. Neurolinguistic processing of visuo-kinematic markers

Recent neuroimaging studies demonstrate that abstract, modality-independent features extracted from sensory linguistic input (in either spoken or sign language) are processed in the temporal lobe (Bornkessel, Zysset, Friederici, von Cramon & Schlesewsky 2005; MacSweeney et al. 2004; McCullough, Emmorey & Sereno 2005; Shetreet, Palti, Friedmann & Hadar 2007). The question one can pose with regard to motion-related features is then: are kinematic distinctions between telic and atelic verb signs, produced during signing, processed as abstract, phonological features?

The fMRI study based on the video recordings of the signs produced during the motion capture experiment addressed this question (Malaia, Ranaweera, Tamer, Wilbur & Talavage 2009). The 12 Deaf participants were presented with the videos of telic and atelic verb signs in a blocked paradigm, and were asked to identify whether each action was more likely to occur inside or outside the house (ensuring semantic processing). Analysis of brain regions which were more active during semantic processing of telic, as compared to atelic predicates, showed that Deaf participants exhibited highly focused right-lateralized activation in superior temporal gyrus (p < 0.05, FDR-corrected), as well as trend-level (p < 0.001, uncorrected) activations in the precuneus, and right cerebellum (Figure 4). No brain regions were more active in semantic processing of atelic, as compared to telic, signs.
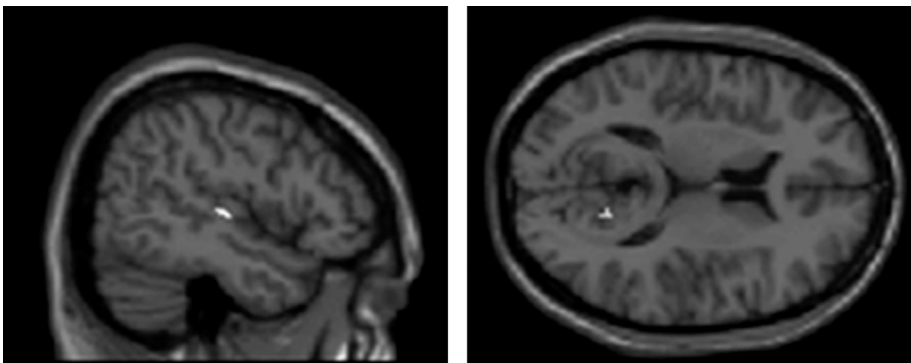

Figure 4. Cortical areas activated by viewing of telic > atelic ASL predicates in Deaf signers: precuneus and STG activation clusters visible (p < .001, uncorrected)

Prior sign language research has demonstrated that STG activation is related to representation of abstract phonological representations (Emmorey et al. 2003; Emmorey, Mehta & Grabowski 2007; MacSweeney et al. 2004; Petitto et al. 2000). Thus, higher activation of STG in response to telic verb signs appears to reflect higher complexity of the phonological structure of telic verbs, compared to atelic ones. Trend-level activations in the current data (cluster level p < 0.05, uncorrected) also support the hypothesis that telic and atelic verb signs elicit differential phonological processing in Deaf signers. Cerebellar activation, as seen in the telic > atelic contrast, has been previously shown to play a role in linguistic-cognitive processing in both signed and spoken languages (Corina, Jose-Robertson, Guillemin, High & Braun 2003). Right cerebellum has been suggested to modulate activity in the parts of the brain to which it is reciprocally connected, i.e. left language-dominant dorsolateral and medial frontal areas (Marien, Engelborghs, Fabbro & De Deyn 2001); the extent and strength of the activation in the cerebellum was shown to be modulated by the difficulty of the task (Xiang et al. 2003). The right cerebellar-left mediofrontal network has been implicated in various linguistic processing tasks for spoken languages, such as subvocal rehearsal mechanisms of verbal working memory, concatenation of syllable strings into coarticulated sequences (Ackermann, Mathiak & Riecker 2007), and facilitation of phonological processing (Stoodley & Schamahmann 2009). The possibility that the cerebellum is involved in low-level processing of linguistic stimuli is of special interest in the present study. In sign language linguistics, movement is considered to be the core of a syllable, comparable to vowels in spoken language. Thus, more complex kinematic signatures of telic predicates correspond to a more complex phonological representation, as compared to that of atelic signs: the distinction is parallel to complex and simple syllables of spoken languages (Wilbur 2008, 2010, 2011). It is thus possible that the right cerebellar activation seen in cortical response to telic as compared to atelic signs reflects preattentive processing of velocity contour changes within sign-syllables. A similar effect has been observed in the speakers of tonal languages for native tone perception (Krishnan & Gandour 2009), whereby language experience was shown to 'tune' the brainstem to the processing of linguistically-relevant dimensions of native (and only native) pitch changes. Other neuroimaging studies of spoken languages also associated higher syllable complexity with more extended patterns of hemodynamic responses in the language-processing network including the cerebellum (especially its right hemisphere), bilateral opercular/insular junction, left posterior IFG and left parietal cortex (Riecker, Brendel, Ziegler, Erb & Ackermann 2008; Bohland & Guenther 2006).

The telic > atelic contrast also demonstrated increased activation of the precuneus at the trend level. Perceptual studies requiring segmentation of continuous

video into discrete events (Zacks et al. 2001; Zacks et al. 2006), as well as studies of event segmentation in text narratives (Speer, Zacks & Reynolds 2007) show increased activation of precuneus at event boundaries. The higher activations of precuneus by telic, as compared to atelic, verbs in the present study may indicate indexing of event boundaries triggered by the semantics of telic predicates, although comparison of neural activations in Deaf signers and hearing non-signers should be made with caution (Meyer et al. 2007). In summary, the fMRI data supports the motion capture studies, by showing that telic ASL signs, which differ from atelic ones by higher deceleration toward the end, are processed as more phonologically complex than atelic signs.

5.   Conclusion

The studies on ASL verb sign production and neural activity during comprehension show that signers process the dynamic (velocity and acceleration) properties of articulator motion as abstract phonological features. The precise motion-related features which entail abstract (phonological) processing might differ among unrelated sign languages, and are still under investigation. It is, however, clear, that the processing of spectro-temporal patterns inherent in natural sign languages requires adaptation from the visual cortex, for which a sufficient amount of non-degraded input is necessary during the critical period.

From a biolinguistic perspective, we see naturally-evolved sign languages perfectly adapted to the human visual system. Grammaticalization of distinctions in physical/action characteristics for lexical purposes enables learners to use existing visual system capabilities and fine-tune them through experience with signed input, thus permitting rapid and early neural, cognitive, and linguistic development to proceed on schedule despite the use of the visual modality.

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