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Information Transfer Capacity of Articulators in American Sign Language

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Abstract

The ability to convey information is a fundamental property of communicative signals. For sign languages, which are overtly produced with multiple, completely visible articulators, the question arises as to how the various channels co-ordinate and interact with each other. We analyze motion capture data of American Sign Language (ASL) narratives, and show that the capacity of information throughput, mathematically defined, is highest on the dominant hand (DH). We further demonstrate that information transfer capacity is also significant for the non-dominant hand (NDH), and the head channel too, as compared to control channels (ankles). We discuss both redundancy and independence in articulator motion in sign language, and argue that the NDH and the head articulators contribute to the overall information transfer capacity, indicating that they are neither completely redundant to, nor completely independent of, the DH.

Keywords

Sign language, articulator, information transfer, dominant hand, non-dominant hand

1 Quantitative measures of information throughput in biological systems

The goal of human communication is to transfer information. The information contained in the linguistic signal can be analyzed qualitatively (semantically) or quantitatively, using mathematical

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estimation of information contained in the signal (Shannon, 1948; Malaia, 2017). The present experimental work is concerned with quantitative analysis of information transfer capacity of articulators in American Sign Language (ASL).

When spoken and signed languages are compared, the superficial difference (that spoken languages produce an acoustic signal, while the signed ones produce a visual signal) is complicated by the fact that the visual signal contains the output of multiple articulators—head and two hands—that are all completely visible and capable of sending their own content. Quantitatively, the speech signal can be characterized by the physics of duration, frequency, amplitude, and internal frequency structure. In comparison, the characterization of the signed signal is only in its infancy. To produce a quantitative description of the sign language signal, the relevant parameters should include displacement of multiple articulators over time, from which duration, speed, acceleration, etc. can be measured and calculated. How can one quantitatively describe the visual linguistic signal as necessary and sufficient for communication? We approach this problem by analyzing the signals from separate articulators and their comparative information transfer potential; we focus on the two hands and the head.

In order to gain an intuitive sense of what this analysis could mean for individual signs, we need to go back to the goal of language: communication. The communicative intent behind utterances, such as those used for this analysis, is transmission of information between the signer and the recipient. Yet, if the transmitted signal is entirely predictable (e.g., consisting of the same sign repeated multiple times), then no new information (past that one sign, which is already known) is extractable from it by the recipient. New information would be available from a signal in which there is a lot of change (not just in motion, but handshape (HS), location, etc.). The signal that is entirely predictable carries no information. If the signal is repetitive, it is fully predictable. Entropy, as a mathematical construct, is the inverse of predictability of the signal (a measure of variability, or chaos, in the signal). A recent analysis of the visual complexity of the signal from everyday human motion vs. ASL observed from a video recording (Malaia, Borneman, & Wilbur, 2016) has indicated that the entropy of linguistic motion is higher than that of everyday motion across all temporal windows, suggesting a higher information transfer capacity of the visual stimuli in ASL. In the present analysis, we employ a measure of entropy (fractal complexity) for motion time series derived from motion capture recording of ASL narratives.

We further refer to entropy as a quantitative measure of information transfer capacity, because communication occurs between two entities, and we are only measuring the complexity of production, not perception. Information can be transferred only if the recipient has the means to interpret the signal. In this specific case, it would require knowledge of ASL: the ability to retrieve lexical tokens from semantic memory and interpret their compositionality in the signal using syntactic rules, etc. Thus, we do not know if the information is actually transferred in the act of communication if we do not assess the recipient. Since the present study deals only with production of sign language, as opposed to perception, we use the quantitative measure, entropy, as a proxy for potential information transfer (or information transfer capacity).

One of the features of complex systems, of which sign language production is but one, is that the signals they produce can have information at different levels of temporal and spatial resolution. In terms of sign language, one can think of information contained in the prosody, for example, compare emphasis-bearing increase in amplitude in speech to higher peak speed in stressed signs (Wilbur, 1999; Wilbur & Malaia, in press) with modified lexical information contained in the small repeated movement of the wrist in the sign “YELLOW-ISH.”

In order to assess fully the amount of information contained in the signal, we needed a measure of entropy that would be cross-cutting for available (recorded) levels of granularity, both in time and space. Fractal complexity is exactly such a measure, in that it quantifies entropy across multiple levels of granularity that are present in the signal. Given such a measure, however, it is important to note that the fractal complexity provides a meaningful measure of entropy only over larger units of connected discourse, rather than individual signs.

While the technique has not been previously applied to analysis of sign language motion, it has been widely used in kinesiology, for example, for analysis of motion in patients (cf. Borg & Laxåback, 2010; Wayne et al., 2013). The relevance of the present analysis lies mainly in the contribution that quantitative information transfer analysis makes to the long-standing debate on relevance of distinct articulators in sign language communication, and their relative importance to the message in the visual domain.

2 State of computational analysis of signing as compared to speech

Analysis of the speech signal is a well-developed field of computational linguistics, the roots of which can be traced back to the 19th century with the development of radio, talking movies, and television in the 20th century, and extensive development of cell phone technology in the 21st century. The signal components of duration, frequency, and amplitude are well known, their perceptual correlates well studied, and their information transfer capacity is crucial for modern communications (e.g., satellite technology). Speech-to-text and text-to-speech are now everyday commodities.

In contrast, quantitative analysis of the signed signal is still in its infancy. The only way to understand what information is contained in a video clip of sign language is to actually see it and know the language that is being transmitted—that is, by conducting qualitative analysis. There is no automated transcription or translation software, although attempts at developing automatic estimation and recognition software for sign language video data have increased during the last 10 years (see e.g., Benitez-Quiroz, Gökgöz, Wilbur, & Martínez 2014; Campr et al., 2010; Dreuw et al., 2010; Metaxas et al., 2012). It is only recently that the role of the signal components conveyed by the head/face/body (beyond the hands) has been recognized (Wilbur, 2000).

Algorithms for 3D motion analysis of sign language are also still in development. Despite the advances in avatar technology and animation, questions that still remain regarding signals with the complexity of sign language exceed those that have already been addressed by available methods. To date, we have only analyzed motion capture data coming from the right wrist for ASL and Croatian Sign Language verb types (Malaia & Wilbur, 2012a, b; Malaia, Wilbur, & Milković, 2013). Another team of researchers has taken on the challenge of analyzing finger shapes and movements (Keane, Brentari, & Riggle, 2015). The present report analyzes multiple motion capture channels, including dominant hand (DH), non-dominant hand (NDH), and the front of the head, in order to compare them both with each other and with non-meaningful sensors on the ankles. Our goal in looking at these sensors is to identify how the information-carrying capacities of these potentially independent channels are related, and how well the DH represents the whole signal.

These steps are part of a larger goal, which is to capture the structure of the signed signal itself. If we think about speech, we can meaningfully answer the question “what is the difference between a real sentence and a string of the same words produced as a mere list?” We can talk about the envelope and the frequency-domain structure of the speech signal. However, for signing, motion capture analyses have traditionally been done at the single sign level, either in isolation or in fixed carrier phrases (Mauk & Tyrone, 2012; Tyrone & Mauk, 2010). Only recently have motion capture data been collected and analyzed from continuous signing (see e.g., Jantunen, Burger, De Weerdt, Seilola, & Wainio, 2012; Puupponen, Wainio, Burger, & Jantunen, 2015; McDonald et al., 2016). We have recently (Wilbur & Malaia, in press) demonstrated that it is possible to use motion capture data from relatively more natural signing in longer narratives and still achieve results comparable to carrier phrase methods. From this, we can start looking at sentence position effects within narratives as a way of capturing notions of fluent signing beyond single signs in carrier phrases or single sentences.

3 Articulator motion in sign languages

Overall, in communicative signals, whether spoken or signed, there is both redundancy and independence/variability. Redundancy allows optimization of communication in noisy environments, and variability allows for potential transmission of information. A lot of attention has been paid to redundancy in sign language communication, especially between the DH and NDH articulators in lexical signs, due to a variety of types of symmetry, as explained below. At the same time, the NDH can contribute independent information, as, for example, in the minimal pair CAN'T-TOMATO, where the handshape of the NDH distinguishes the lexical meaning. The same critical role is true for the head articulator: a negative headshake changes the meaning of an entire sentence, regardless of what signs are produced by the hands. Below, we briefly discuss the variety among previously observed types of symmetry between DH and NDH articulators (Section 6.1) and DH/NDH and the head articulator (Section 6.2).

3.1 DH vs. NDH

Standard sign analysis in sign language linguistics posits four basic manual parameters of lexical signs ("words"): HS, orientation of the palm and fingers (O), place of articulation (POA), and movement (MOV). Lexical signs can be made with just one hand (DH)[1] or both hands. When a sign is made with both hands, there are constraints that govern possible movements given the sign's HS (Battison, 1978; Napoli & Wu, 2003). If only one hand moves (which is then considered the DH because it is moving), the NDH is often the location at which the sign is made. That is, the DH may move toward or away from the NDH, or along/above/below it. If both hands move, then their movement is either identical or a mirror image (expanded in Section 6.1.2). Thus, the DH is active in both types of two-handed signs while the NDH is (motion-)active only when it is symmetrical or a mirror image to the DH. As a result, there is an asymmetry in the roles of DH vs. NDH during signing that is reflected in the recorded movement.

Two constraints that govern possible movements of two-handed signs are the Symmetry Condition and the Dominance Condition (Battison, 1978). These constrain possible combinations of HS, POA, and MOV in lexical signs. The Symmetry Condition states that (a) if both hands move independently, then (b) both hands must have the same POA, HS, and MOV (simultaneously or alternating), and their orientation must be identical or symmetrical. This can be seen as a type of phonological complexity constraint: if the two hands differ on movement specifications, then other specifications are restricted. The Dominance Condition constrains movement if the HS specifications are different. In particular, while the DH articulates the movement, the NDH must not move and may only have one of a small restricted (unmarked) set of HS. These conditions form the basis for the explanation of our results with respect to the hands, and underlie our prediction that *more information complexity is to be found in the DH than in the NDH.*

3.2 Head articulator motion

The head/body/face nonmanuals (NMs), taken together, are considered a fifth sign structure parameter, although most signs do not have an associated required NM. Instead NMs are more likely to be present for syntactic, semantic, or morphological purposes; once present, their action is parallel to that of the hands and they are prosodically integrated into the overall phrasing.[2] To date, there has been noticeably more attention paid to grammatical articulations on the face than by the head. It is now clear that this lack of attention has missed many important functions. The head is capable of movement in all three planes (vertical up/down, and tilt; horizontal right/left; sagittal front/back) and can combine movement in more than one plane, so its movement is widely recruited for grammatical use in sign languages; their specific form and function are language-specific. Head movements used in sign languages include nod (down/up), nodding (multiple), turn, shake (multiple), tilt, thrust[3] (forward), and pull (back). Among the uses for head positions are: negative headshakes (or head back); head nods for emphasis, assertion, affirmation, existence, or focus (Liddell, 1980; Pfau & Quer, 2010; Wilbur, 2000); in ASL, nodding for hedging (Wilbur, 2000); head forward/back for questions or contrastive focus (Wilbur & Patschke, 1998); head/eye gaze direction for pronominal reference and possibly verb agreement; head shift for perspective taking ("role shift," quotative reporting); head thrusts for interrogatives (Pfau & Quer, 2010); and backward head movement for yes/no questions in British Sign Language (Sutton-Spence & Woll, 1999) and for marking negation in Turkish Sign Language (Gökgöz, 2011).

Our head data come from a sensor on the front of the head, which can register not only head movement itself, but also translation or rotation that might result from movement of the shoulders or whole body. Briefly, leans forward and back or side to side can be used to indicate contrast: such leans can offer options in a question, indicate correction to a prior utterance, denote inclusion/agreement (forward) with a group/position/statement, or exclusion/rejection/denial (back) (Wilbur & Patschke, 1998).

3.3 Foot motion in sign language

Signs are made within a signing space that extends from the top of the head to just below the waist/hip area on the vertical axis, while horizontally and laterally forming a "bubble" in front of the signer from right to left (an arc of ~180°). This space may be enlarged for bigger audiences ("louder") or reduced for more rapid signing or to be secretive ("quieter"). Few signs are made over the head, behind the ear, or below the waist (Lacy, 1974). Thus, the feet are not, in general, part of the signing space. Use of feet for communicative purposes has been reported in homesign (individually developed systems created by deaf children who are not otherwise exposed to any natural sign language) (see Hunsicker & Goldin-Meadow, 2013), and as a location (but not as an active articulator) in sign languages which are used for communication that generally takes place while sitting on the ground, as, for example, reported by Nyst (2007) for Adamorobe Sign Language (Ghana). Since sign viewers focus on the signer's face and use peripheral vision to perceive the hands in motion away from the face (Siple, 1978), using feet as articulators or locations in normal conversational situations (sitting or standing) would place an extra burden on both perceivers and producers of signs. Thus, we use the information from the sensors on the feet as our controls.

4 Materials and methods

Following the protocol established for the motion caption studies (Malaia et al., 2012; 2013; Wilbur & Malaia, 2008), 48 short (three-sentence each) narratives were elicited from a native deaf ASL signer communicating to another signer, who was sitting behind the video camera. The narratives used were scripted for an earlier study (Wilbur & Schick, 1987), and have been re-used in subsequent motion capture studies, in which it is shown that data from this one signer provides the same results as the previous study with multiple signers (Wilbur & Malaia, in press). Two examples are:

(1) a. SHOCK IX-1. DISCOVER GOOD FRIEND DIE. THINK HEART-ATTACK. NOT-KNOW … SEEM SICK IX-3, NOT-KNOW IX-1.
"I was shocked to discover that my good friend died. I think it was a heart attack but I'm not sure. Apparently he was sick but I didn't know."
b. POSS-1 FRIEND MARRY AGAIN. WIFE FIRST DIE LONG-AGO. NOW HAVE WIFE.
"My friend married again. His first wife died a long time ago. Now he has a wife again."

These stimuli are particularly appropriate for analysis of motion capture-based fractal complexity because they are narratives with communicative intent, and are larger than lexical items or single sentences. Therefore, the information transfer is not simply the sum of the semantics of the individual items in each, and each narrative is different lexically and intentionally. That is, we are not looking at information transfer from a semantic perspective but from the complexity of the signal itself.

The signer was right-handed, as determined by the Oldfield (1971) inventory. The DH and NDH labels were assigned to channels based on the results of the test. The signer produced the narratives facing the video camera while standing in a designated spot for motion capture. During recording, the signer wore a Gypsy 3.0 wired motion capture suit, and the data about the XYZ positions of all markers were collected at the rate of 100 frames per second by six ceiling-mounted cameras. The motion capture system defined the X, Y, and Z axes relative to a fixed external space, while the participant signed directly to another signer sitting with the video camera. The recorded positions of left (NDH) and right (DH) hands, ankles,[4] and front of the head in 3D were then triangulated to extract absolute velocity vectors over 12 narrative-long recording segments (36 sentences per segment), resulting in a total of four velocity vectors ("segments") per sensor (for details on triangulation method, see Wilbur & Malaia, 2008).

For each velocity vector (separately for each channel and segment) the Power Spectral Density (PSD) estimate of the absolute velocity was computed using MathWorks MATLAB's pwelch function with a hamming window of length N/2 and a sampling frequency parameter equal to motion capture recording frequency (100 Hz). The pwelch function uses Welch's averaged, modified periodogram method (Welch, 1967). This operation produced a vector for the spectral density of the motion versus frequency component for each channel (DH/NDH/head/right ankle/left ankle) and segment.

The velocity signal was then analyzed according to its fractal complexity. The function in equation (1) represents an arbitrary signal with variable fractal complexity, where M is the power spectral density profile of the signal, f is the frequency, α is the PSD magnitude, and β is a parameter for fractal complexity of the signal. Equation (2) is the same function in log/log space, where the PSD will be linear, and the fractal complexity (β) is the slope of the line.

$$M\left(f\right)=\alpha\,/\,f^{\beta} \tag{1}$$

$$\log\left[M\left(f\right)\right]=\beta\cdot\log\left(f\right)+\alpha \tag{2}$$

Therefore, equation (2) was fit to the PSD of the captured velocity in log/log space signal using an iterative nonlinear least squares method. The extracted slope (β) and x-intercept (α) of the linear fit give the fractal complexity and PSD magnitude offset, respectively.

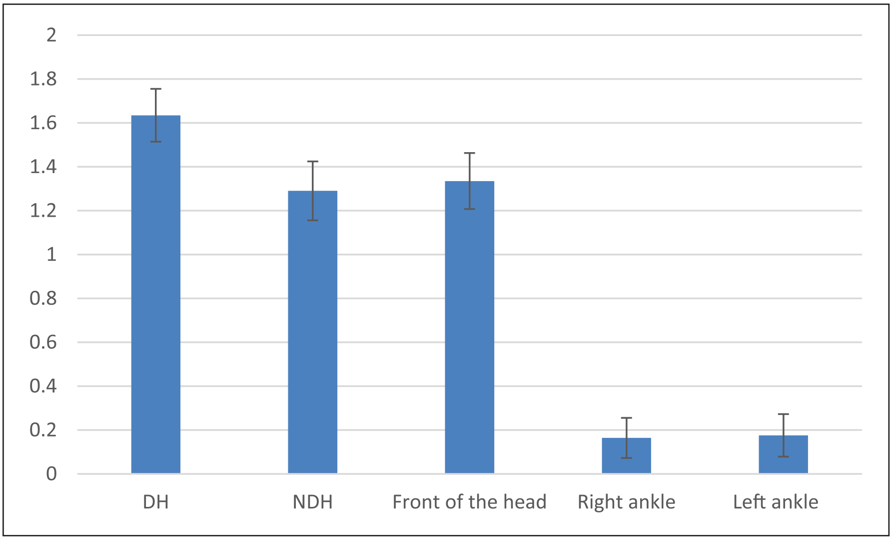

Figure 1. Means and SD of absolute values of fractal complexity parameter (β) for each of the five channels.

Table 1. Comparisons of fractal complexity parameters by articulator by paired samples *t*-test.

Motion vectors compared	*t*	*p*	*SE*	effect size
DH–NDH	–3.265	0.047	0.105	large
DH–head	–3.274	0.047	0.091	large
NDH–head	0.539	0.627	0.084	small
DH–right ankle	–21.029	< .001	0.085	large
DH–left ankle	–19.994	< .001	0.090	large
NDH–right ankle	–21.511	< .001	0.068	large
NDH–left ankle	–27.011	< .001	0.054	large
Head–right ankle	–70.711	< .001	0.021	large
Head–left ankle	–48.567	< .001	0.031	large
right ankle–left ankle	–0.679	0.546	0.015	small

Note: Student's *t*-test.
Note: DH (dominant hand); NDH (non-dominant hand).

5 Results

For each channel (DH, NDH, front of the head, and left and right ankles), the fractal complexity parameter (β) was determined to describe the fractal complexity of each velocity vector. The extracted absolute value of fractal complexity (entropy measure) for each channel is presented in Figure 1 and Table 1. The absolute value of the entropy measurement was the highest in the DH (right); NDH (left) was second highest in three out of four segments; in one segment, the entropy of head motion was higher than that of the NDH (but lower than that of the DH). The entropy parameter on the ankles was very low and, in fact, did not conform to a power law, but was instead indicative of asystematic noise.

Paired *t*-tests indicated that the DH was significantly different from both the NDH ($t = –3.265$, $p < 0.047$) and the head ($t = –3.274$, $p < 0.047$) but the NDH and head do not differ from each other

($t = 0.539$, $p = 0.627$). All comparisons with the right ankle are significant ($p < .0001$) except that the left ankle does not differ from the right ankle ($p = 0.546$). Likewise, all other comparisons with the left ankle are significant ($p < .001$). The Cohen's d for all significant comparisons was at least 1.6 (range 1.63–35.36) reflecting large effect sizes, whereas the two non-significant comparisons had Cohen's d of .3 reflecting small effects.

6 Discussion

The results demonstrate that, as predicted, the DH is instrumental in information transfer in signed narratives: the entropy measures were highest for the motion of the DH. Both the NDH and the head have a lesser role, given their abilities to be either redundant/predictable or independent channels. That is, our results show that the DH leads, and that the head and the NDH contribute significant information as well. Here, we address the implications of "redundancy" vs. "independence" for analysis of the sign language structure and the signal that carries it.

6.1 Redundancy and independence of information in NDH motion with regard to DH motion

Due to the constraints on two-handed sign formation mentioned earlier, the NDH motion can be largely predictable from the DH (such redundancy can be described as phonological in nature). However, these constraints on sign formation do not apply to sign sequences (phrases, sentences, and narratives, as in our data). At the levels beyond that of a single sign, the NDH can convey independent information (such information would be analyzed as morphological and/or syntactic in nature).

One could argue that some level of unpredictability exists even at the phonological level due to the existence of multiple types of symmetry constraints. Napoli and Wu (2003) generalized these multiple types of symmetry in a single Movement Symmetry Condition: when both hands move and have the same HS, the position of the hands on their respective paths is either **identical** or **inverse**. Thus, on one hand, NDH movement can be predictable (redundant), given specific constraints of the sign language in question. However, the choice of the type of symmetry (as well as symmetry axis) can vary, thus introducing a layer of unpredictability in the signal.[5] Let us illustrate this variability with some examples.

6.1.1 Examples of symmetry that can reduce fractal complexity of NDH. **Reflection symmetry.** For the reflection (mirror image) type of symmetry, there is a plane of symmetry between the two hands (Figure 2), and the DH and NDH are reflections of each other. Various planes can be used for reflection, with the one dividing the body into right and left (the midsagittal plane) being the most frequent, hence considered the default (unmarked) plane.[6]

Other reflection symmetry planes include (1) the one that divides the front of the body from the back (the "vertical wall"), usually tilted somewhat to avoid hand/arm/elbow stretch, for example, to the back for the NDH or to the front for the DH (PERFECT, Figure 3a), or (2) the horizontal plane (cutting the body into top/arms and bottom/legs), again with orientation not perfect due to ease of articulation. Neat symmetry is disrupted when the hands alternate movement, that is, their movement is out of phase. To see reflection symmetry, each hand's movement has to be viewed as an alternation over two times, for example, Mov_1 at the t_1 and Mov_2 at t_2. Napoli and Wu (2003) call this "inversion." Symmetry exists between DH_Mov_1 and NDH_Mov_2, and between DH_Mov_2 and NDH_Mov_1. This works for signs where both hands move (e.g., DESCRIBE, Figure 3b) and where only one hand moves but the hands alternate as to which one moves (COMFORTABLE, Figure 3c).

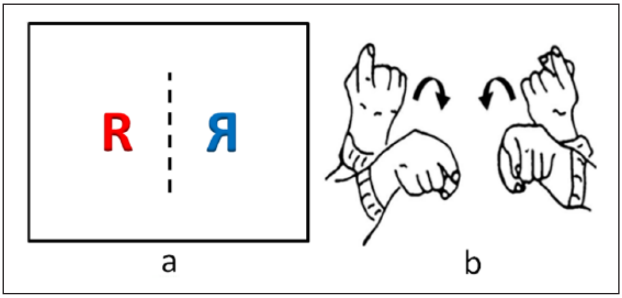

Figure 2. a. Reflection symmetry around midsagittal plane; b. the sign HAPPEN.[7]

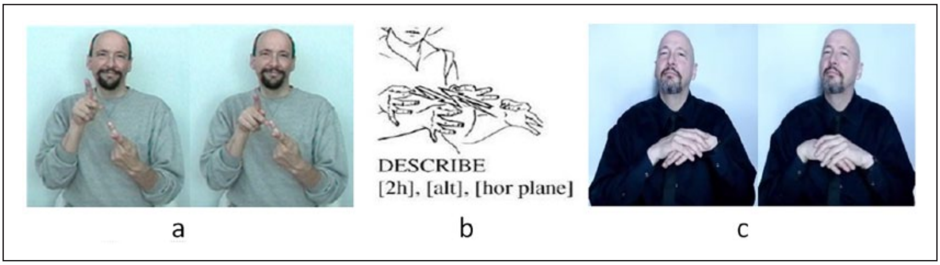

Figure 3. a. PERFECT, showing front–back plane symmetry; b. DESCRIBE, showing symmetry out of phase; c. COMFORTABLE, showing symmetry with hand alternation.

Figure 4. a. Rotation symmetry around a point; b. the sign CHANGE, showing rotation symmetry.

Rotation symmetry. Rotation symmetry involves a point around which objects rotate, rather than a plane (Figure 4). If the hands keep a relatively constant palm orientation with respect to the point, that is sufficient to define rotation for signing. Hand movement will display inversion, as the hands are displaced 180° from each other. As a general rule, such signs begin and end with contact between the hands. Napoli and Wu (2003) summarize these observations as the Rotation Condition: the hands must exhibit inversion and (almost) touch at points before and after the rotation movement.

Translation symmetry. Translation moves along a path on a mirror plane without any reflection or rotation (Figure 5).

Glide reflection. Glide reflection is complex symmetry with both reflection and translation (Figure 6). Because of this additional complexity, hand movement is more restricted; locations of

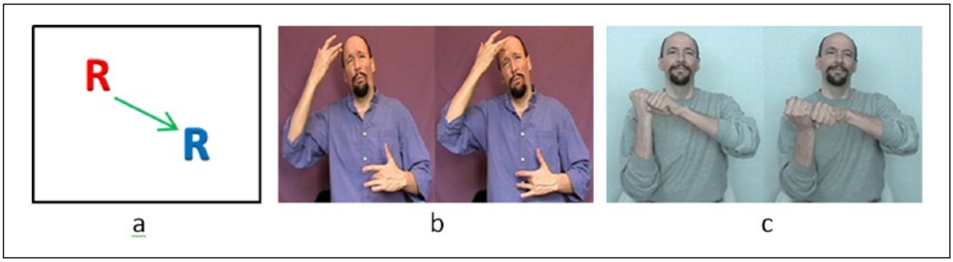

Figure 5. a. Translation symmetry; b. SICK (two-handed), translation symmetry; c. BASEBALL, translation symmetry with the hands in contact.

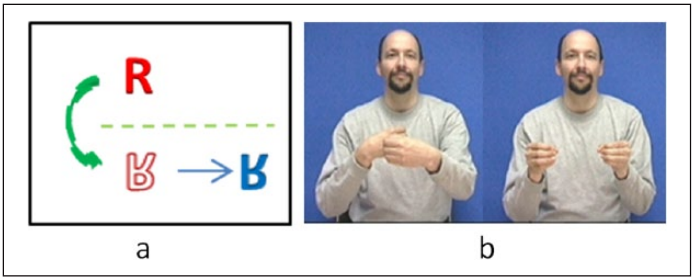

Figure 6. a. Glide reflection and translation; b. the sign OFFICE, showing glide reflection.

the hands on their respective paths must be the same at all times. When perfect symmetry is interrupted, there is a tendency for positions and movements to be semantically motivated, for example, when PLAY-CARDS looks like dealing cards.

In summary, in two-handed signs, if both hands move, there are constraints on symmetry, with reflections the most common, and the vertical midsagittal plane considered to be unmarked. Less frequent symmetry transformations include rotation around a point, translations along a path, and glide reflection, a combination of reflection and translation. Additional complexities, such as inversion and symmetry over time, are generally only possible with simple reflections.

6.1.2 Examples of NDH behavior that could increase fractal complexity. Given these constraints, for a large portion of the time only the DH is needed for recognition of two-handed signs, while the NDH is predictable (redundant). However, from the cross-linguistic standpoint (outside of known lexical items), the relative motion of the DH and NDH contains quite a bit of variability, which is unpredictable, for example, to a new learner of a specific sign language.

The cases when motion of the NDH relative to the DH is unpredictable (i.e., contains novel information) may nonetheless be redundant within the sentence even though not redundant within individual signs. For example, the phrasal-level phenomenon known as "non-dominant hand spreading" describes the cases in which the NDH functions as a referential landmark placeholder across syntactic constituents in longer narratives. The holding of the NDH signals that some semantic component of the sign at which the NDH spreading began is relevant to some later portion of the phrase. For example, in a translation of the English "He painted the chair red," an ASL signer will often sign CHAIR first, with the DH moving down to contact the NDH hand twice, then the NDH held in position until the sign PAINT, at which point the DH will perform the movement of PAINT on the held NDH from CHAIR, to mean "paint the chair."

Traditionally, spreading is considered to be a marker of a prosodic unit (phonological phrase), although there are indications that the spread may, in fact, continue over multiple sentences. In his summary of the domains over which the NDH may spread, Crasborn (2011) raises the question of whether such usage might constitute evidence for a discourse phrase, in which multiple units are joined by prosodic cohesion. We would suggest that from an information transfer perspective, the most likely specific function is semantic cohesion through maintenance of the NDH marker for a referent (individual or location) during the discourse, possibly as an aid to viewer memory in complex syntax. Under these circumstances, since the hand is not moving, it could be said that our complexity results, which are derived from movement, underestimate the contribution of the NDH, but we would note that once the sign where the spread begins is signed, the information conveyed by the held NDH should be largely redundant.

Another case of independent (unpredictable) motion of the NDH within a narrative can be observed when the referent of the NDH is represented by a classifier (group-level) HS. For example, in a story about a boy who wants to reach a doll on a high shelf, he gets a chair and piles boxes on it. Then the boy tries to climb up to reach the shelf. The signing at this point includes simultaneous production by the DH of CLIMB and a NDH classifier for the base (chair plus boxes) notated as NDH "cl-base" (Milković, Bradarić-Jončić, & Wilbur, 2007). Further examples in which both hands move separately are frequently observed in the telling of the "Tweety Bird" story, in which one hand is the cat trying to grab the bird and the other is the bird trying to get away. In such examples, there are two animate agents and both hands could be considered "dominant" as they are both moving. Thus, the redundancy in DH and NDH motion, which is determined by within-language phonological constraints, is counterbalanced by unpredictability, both in cross-linguistic variability in implementation of constraints, as well as in discourse-level phenomena (NDH spread and NDH classifier forms).

6.1.3 What our results show about the relationship between the DH and the NDH. First, our results show that the NDH is a linguistically meaningful signal (i.e., differs significantly from non-linguistic channels such as the ankles). Given the emphasis that has been placed on the NDH as a predictable signal due to symmetry constraints, it is conceivable that our results could have come out otherwise. Second, our results show that the NDH does carry information independent of the DH, in that their fractal complexities are significantly different, with the NDH being lower than the DH. Although no one has seriously discussed the possibility, it is conceivable that the NDH could have been equal to the DH if, in fact, the NDH was signing completely separate signs from those on the DH. That the brain and motor system do not favor such productions is not surprising. What we do see is an intermediate position: the NDH provides a meaningful signal that supports but does not compete with the DH, which leads the pair.

6.2 Relation of information carried on the head relative to the hands/DH

Like NDH motion, the head articulator motion can be redundant or independent with regard to DH motion.

6.2.1 Examples of head behavior that can reduce fractal complexity compared to the hands. Two kinds of **redundant relationships between the head and the DH** have been identified to date. The first is phonetic lowering (Tyrone & Mauk, 2016), in which the head (but not the torso) moves toward the hand to shorten the length of the path between them. In such situations, movement of the head is informationally redundant, in that it provides no additional information compared to the alternate situation where it would stay still and allow the hand to traverse the entire path trajectory

Figure 7. Head movement down follows hand movement down twice for CANCEL.

up to it. The second is echo phonology (Woll, 2001), in which the movement of the head follows the hands (Figure 7). In sign CANCEL, there are two (lexical) movements of the DH and, according to Wilbur and Petersen (1997), one transitional movement between them, one down, then a return up to the initial position, then down again. Likewise, the head moves down, up (to neutral), and down again. Again, in terms of information transfer, the movement of the head contributes no additional information.

6.2.2 Examples of head behavior that could increase fractal complexity compared to the hands. Studies of the **independent function of the head relative to the hands** have just started to provide insight into the types of information that may be communicated by the head in addition to the information transmitted by the hands. In a recent work on the topic, Puupponen et al. (2015) analyzed four head movements in Finnish Sign Language (FinSL)—nod, nodding, thrust, and pull—with regard to their linguistic function. They considered the following functions (our labeling in parentheses): emphasis (prosodic); phrasal boundary marking (prosodic); phrasal domain marking (syntactic); affirmation (pragmatic); interrogative (syntactic, pragmatic); copying the movement of the hands (echo); and indicating (pragmatic, syntactic). Their analysis indicated the following (again, our labeling in parentheses): (1) nods function as affirmation and positive feedback markers (pragmatic); (2) nodding provides positive feedback (pragmatic) or echo phonology (prosodic); (3) thrusts occur in interrogatives (syntactic), and emphasis (prosodic); (4) and pulls occur for emphasis (prosodic), contrast (semantic, prosodic), and exclusion (semantic). The most frequently occurring category for head movements was prosodic, which could easily be taken as support for an intonational/prosodic perspective on nonmanual marking, despite the fact that Puupponen et al. (2015) only looked at sagittal plane movements.

Of interest is the observation that each of these has a different movement trajectory shape: nods have a V-shape, indicating an abrupt change of direction (Figure 8a); thrust has more of a U-shape (Figure 8b); pull has an “upside-down J-shape” (Figure 8c); and nodding has a damped, oscillating shape (nodding not shown; trajectory is repetition of nod).

Thus, one can say that the shape of the head movement trajectory is a carrier of information that is independent of, and contributes to, the information carried on the hands.

Ichida (2010) analyzed a broader set of head behaviors in Japanese Sign Language, including five head movements: nod (down), nod (up), shake, thrust, and change of head position. These were combined with four possible chin positions: up, down, forward, and back. Twenty combinations of movement and position were, therefore, possible. His analysis suggested that headshakes with different chin positions have different interpretations (semantically), while different head positions and movements were used for different syntactic functions, such as separating conditional clauses from purposive clauses and embedded (subordinate) clauses, and relative clauses from simple clauses.

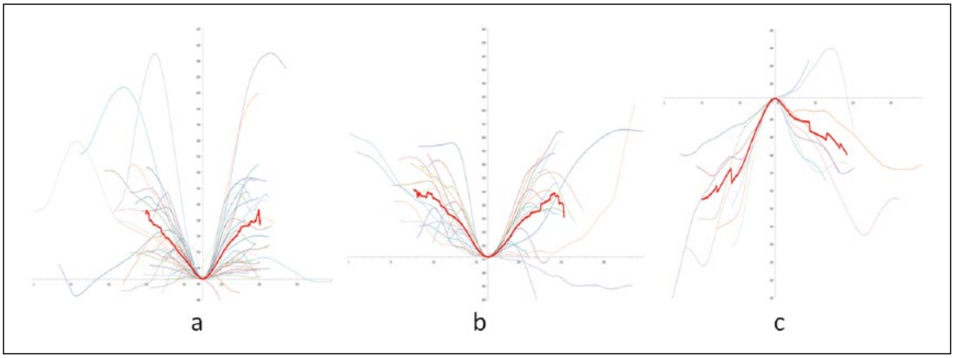

Figure 8. a. nod; b. thrust; c. pull.

6.2.3 What our results show about the relationship between the head and hands. Ichida's argument is supported by our findings that the head motion is equivalent to the NDH in fractal complexity and that both are significantly less than that of the DH. We interpret these results as evidence that the DH is in the lead, with the head and NDH as independent channels that both interact with the DH as well as being controlled by it.

7 Conclusion

Recent cross-linguistic studies in the function of motion across sign languages make it clear that there is much to the grammars of sign languages that have not yet been fully explored (Malaia & Wilbur, 2010). The results of quantitative analysis of articulator motion complexity are convergent with the evidence that the head motion in Finnish and Japanese sign languages is linguistically meaningful in ways that are much more intricate than generally assumed, along with the extensive evidence for both redundancy and independence of the NDH with respect to DH motion. The high information-carrying capacity of articulator motion in sign languages indicates that it is clearly not the case that they simply borrow existing co-speech gestures from the surrounding speech/cultural community. Rather, there has been grammaticalization of the available options into a learnable and linguistically adequate system to convey a full array of desired messages, contributing information and further complexity in as yet unknown ways. While our results indicate that the information-carrying capacity of head and NDH articulators are convergent with analyses of other sign languages, the lack of quantitative data beyond ASL (as well as a comparative analysis of co-speech gesture) is a limitation on the generalizability of results.

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Notes

1. May be either right or left, and may switch while signing despite signer's general preference for right or left handedness.

2. In-depth overview chapters on aspects of sign language structure can be found in Pfau, Steinbach, and Woll (2012).
3. Thrust motion, unlike nod, does not include head rotation.
4. The position of the ankles was recorded as a control. No full-body positional motion was necessary for the narrations; however, the participant had natural postural sway during the recording which was recorded as displacement over time by the motion capture system.
5. Unpredictability from the point of view of a new signer or a baby learning sign language, not from the point of view of a signer already familiar with specific lexical items.
6. A variant of this, rotated/tilted 45° to left or right, occurs rarely in the ASL lexicon. Likewise, the entire plane can be shifted away from the center of the body, for example to the shoulder, for an occasional sign.
7. Symmetry figures based on those available at Math Forum http://mathforum.org/sum95/suzanne/symsusan.html

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