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Article

# Kinematic Parameters of Signed Verbs

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**Purpose:** Sign language users recruit physical properties of visual motion to convey linguistic information. Research on American Sign Language (ASL) indicates that signers systematically use kinematic features (e.g., velocity, deceleration) of dominant hand motion for distinguishing specific semantic properties of verb classes in production (Malaia & Wilbur, 2012a) and process these distinctions as part of the phonological structure of these verb classes in comprehension (Malaia, Ranaweera, Wilbur, & Talavage, 2012). These studies are driven by the event visibility hypothesis by Wilbur (2003), who proposed that such use of kinematic features should be universal to sign language (SL) by the grammaticalization of physics and geometry for linguistic purposes. In a prior motion capture study, Malaia and Wilbur (2012a) lent support for the event visibility hypothesis in ASL, but there has not been quantitative data from other SLs to test the generalization to other languages.

**Method:** The authors investigated the kinematic parameters of predicates in Croatian Sign Language (*Hrvatskom Znakovnom Jeziku* [HZJ]).

**Results:** Kinematic features of verb signs were affected both by event structure of the predicate (semantics) and phrase position within the sentence (prosody).

**Conclusion:** The data demonstrate that kinematic features of motion in HZJ verb signs are recruited to convey morphological and prosodic information. This is the first crosslinguistic motion capture confirmation that specific kinematic properties of articulator motion are grammaticalized in other SLs to express linguistic features.

**Key Words:** sign language, predicate, prosody, morphology, velocity, acceleration, phonology, Deaf

The process of parsing continuous reality into discrete events is an automatic component of human visual perception (Baldwin, Baird, Saylor, & Clark, 2001; Speer, Zacks, & Reynolds, 2007; Zacks & Swallow, 2007). Research in perceptual psychology has demonstrated that humans rely on velocity and acceleration patterns of an actor's motions to identify event boundaries in visual scenes (Zacks, Kumar, Abrams, & Mehta, 2009; Zacks & Tversky, 2001).

Perceptual features of events further appear to be reflected in linguistic inventories. Languages label observable events in a conceptually restricted manner, commonly described as event structure (Dowty, 1979; Pustejovsky, 1991; Vendler, 1967). The structure of events as denoted by linguistic predicates has been of interest to linguistic theorists as the source of possible conceptual primitives —the building blocks of semantics (Dowty, 1979; Jackendoff, 1991; Pustejovsky, 1991; Ramchand, 2008; van Hout, 2001; Van Valin, 2007; Vendler, 1967; Verkuyl, 1972). One such basic semantic element, which by now has been identified in the majority of languages, is event *telicity* (also known as event completion, boundedness, or internal/lexical aspect). The verbs that describe events as involving a change (e.g., *fall, break*) are termed *telic*. The verbs describing events as homogenous, such that any part of the event can be referred to using the same verb as that describing the event itself (e.g., *swim, walk*) are termed *atelic*.[1]

Linguistic means of expressing telicity vary among languages. In English, telicity can be expressed at the lexical level (e.g. *fall, break*), or at the level of the verb phrase (VP) or the entire predicate, by quantifying the internal argument (e.g., *eat the cake*), or otherwise "measuring out" the event, such as providing it with a bounded path (e.g., *run a mile, swim to the shore*). In Japanese, event types are marked phonologically, with non-low vowels corresponding to verbal telicity: telic verbs have /e/ or /u/, atelics have /i/ or /o/, and speakers display sensitivity to these correspondences

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[1]We limit the discussion of linguistic event structure to the concepts used in the present experiment: the basic telic/atelic dichotomy. More complex models of event representation include other types of conceptual primitives. Pustejovsky's logical model (1991, 1995), built on the primitive of *dynamicity,* used two types of subevents—static (S) and process (P)—to construct event typology. Van Lambalgen & Hamm (2005) used the notion of force (F), and so on.

even in nonce verbs (Fujimori, 2012). In many Germanic languages, event types may be marked grammatically, by the choice of *haben* ("to have") versus *sein* ("to be") in the formation of the perfective (van Hout, 2001).

Recent SL research has shown that the event structure of signed verbs affects their morphosyntactic behavior in American Sign Language (ASL; Brentari, 1998; Wilbur, 2005, 2008). Crosslinguistic quantitative investigation into event structure expression in SLs is needed to provide insight into the interface between the perceptual/phonological cues of event structure used in SLs and the linguistic systems of (unrelated) SLs. In light of recent claims of SL iconicity (Thompson, Vinson, Woll, & Vigliocco, 2012), one might inquire whether the same kinematic features are used in different SLs and whether event markers are coded by different kinematic features across languages. The present study focuses on these questions using kinematic (motion capture) data from Croatian Sign Language (HJZ).

## *Relevant Aspects of SL Structure*

Prior analyses of event structure in ASL focused on the mapping between semantics and phonological structure; therefore, a short exposition of SL phonology is necessary to clarify the design used in the present motion capture experiment. For SLs in general, a fully formed sign contains at least one articulated handshape, a specific orientation of the handshape, place of articulation, and movement.[2] Linguistic constraints on possible combinations of handshape, location, orientation, and movement permit modeling of the phonology for each SL (Brentari, 1998). Movement within a sign is constrained in ways that clearly distinguish it from movement between signs, referred to as *transitions*. Each SL has constraints as to which features may change within a well-formed (i.e., phonotactically appropriate) sign. (However, these constraints can be violated in transitions.) Movement within a sign can consist of a change in handshape (aperture), a change in orientation, a change in setting (small change within a plane), or a change in place of articulation (path; see Figure 1A).[3] It is possible for a change of place of articulation to occur with one of the other movements, but no other multiple movement combinations are permitted within a sign (see Figure 1B).

Brentari (1998) postulated two timing slots per syllable (as opposed to a sequence of consonant and vowels in spoken language syllables), onto which the movement change is mapped. The movements described above (e.g., change of handshape, orientation, setting, etc.) involve two different timing slots in a single signed syllable.[4]

The critical distinction between telic and atelic signs in ASL is based on how the movement maps onto those timing slots. It is possible for a movement to be specified in a way that essentially spreads the single movement over the two timing slots (e.g., tracing, alternating, trilled movement), or there can be a distinct specification for the second timing slot different from the first one (e.g., changes of handshape, orientation, place of articulation or setting). Critically, the ability for the second timing slot to have different specifications than the first allows verbs that denote telic events to have a second-slot specification that reflects marking for the end state of the telic event.[5]

For SLs, the mapping between semantics and phonological forms represents a systematic recruitment (i.e., grammaticalization) of features of the physical world for conceptual, hence morphological, semantic, and syntactic purposes (Wilcox, 2007). The linguistic system depends on the visual perceptual system to process the necessary distinctions. Because the resources are universally available, they may be used in hearing culture gestures and in mime. However, to be morphemes in an SL, they must be grammaticalized beyond gestural or mimetic use and, therefore, must be explicitly learned as part of learning a SL.

Wilbur (2003) made the linguistic observation that ASL lexical verbs could be analyzed as telic or atelic, based on their form: telic verbs (for activities and accomplishments) appeared to have a sharper ending movement to a stop, reflecting the semantic end state. Schalber (2004) reported similar results for Austrian Sign Language. The observation that semantic event structure is visible with certain phonological profiles was formulated as the event visibility hypothesis (EVH; Malaia & Wilbur, 2010a, 2012b; Wilbur, 2003, 2008, 2010; Wilbur & Malaia, 2008a). In Brentari's terms, telic verbs are defined by different sets of phonological features associated with each of the two timing slots, whereas atelic signs are characterized by spreading of the phonological features between the two slots.

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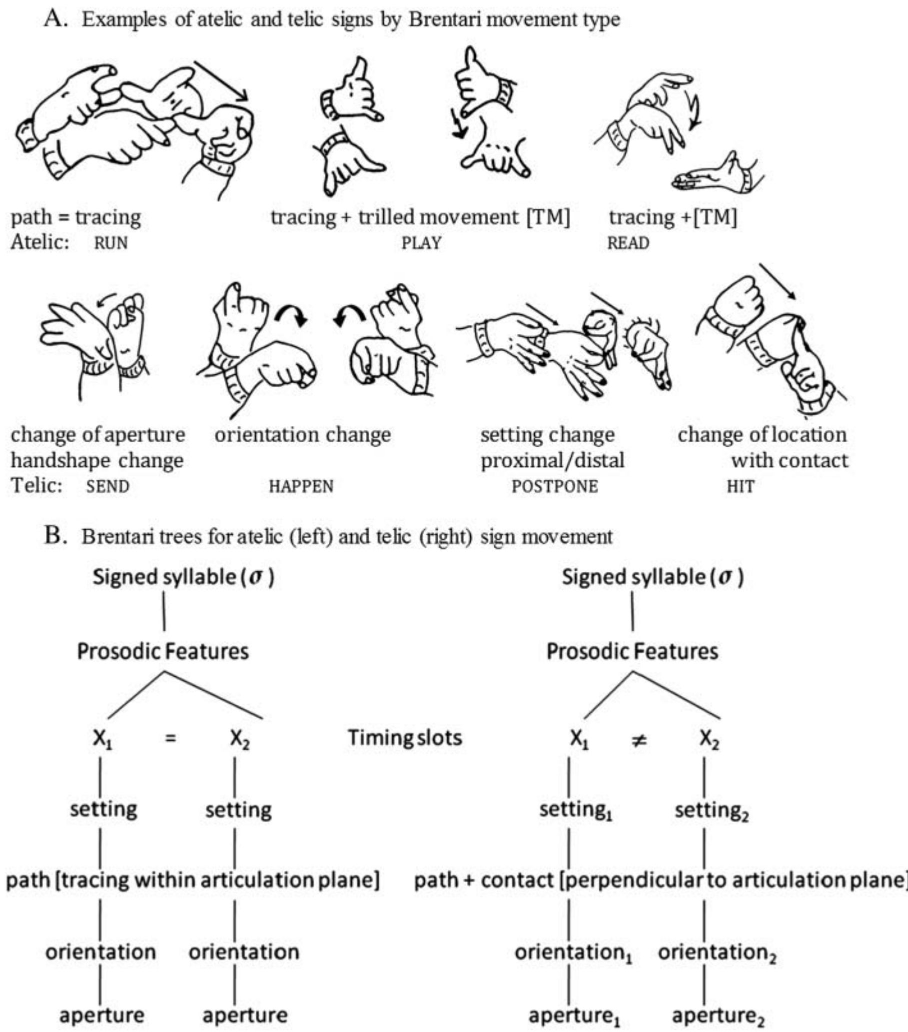
[2]Some signs also require specific nonmanual markings (e.g., positions of facial, head, or body articulators).

[3]Brentari (1998) argued that path movement involves contact either at the beginning or at the end of the movement and that the contact may be with a body part or with a plane—that is, in neutral space. Although initial contact—and its loss as movement starts—does play a role in event structure (Wilbur, 2003, 2008), only final contact is relevant to the issue being considered here, namely marking of end state.

[4]Some types of movement are analyzed as spreading over the two timing slots so that the feature specifications for timing slot 1 and timing slot 2 are identical. These include *trilled* movement (e.g., small uncountable changes of handshape, orientation, etc.), and *tracing* movement. Tracing can take different shapes (e.g., lines, arcs, circles, and irregular outlines), but always moves within the plane of articulation defined based on the designated hand part (e.g., face of the palm, back of the hand, or fingertip; see Brentari, 1998, Chapter 4, for full elaboration). *Path* movement differs from tracing movement in that it is based on a restricted set of possible shapes and involves motion perpendicular to the main articulation plane.

[5]This end state marking could be thought of as being like a suffix that combines with the verb in the same way that the past tense shows up on English verb *walk,* which, although written "walked," is pronounced /walkt/—that is, as a single syllable. The addition of the end-state suffix in telic verb forms does not make a second syllable but simply joins the existing syllable at its end.

**Figure 1.** In Brentari's (1998; see also Wilbur, 2011) phonological model, atelic and telic verb signs in ASL differ in whether the two timing slots in sign syllables contain the same or different setting, orientation, aperture, and directionality of the movement path.




### *Prior Motion Capture Analysis of Verb Kinematics in ASL*

There are few kinematic motion capture studies of SLs because the development of the technology and analytical software is relatively recent.[6] For linguistic purposes, considerable preprocessing is necessary to achieve the desired data extraction from the recorded kinematic stream, resulting in a protocol that uses carrier phrases (with the target sign embedded between easily identified preceding and following movements), multiple recordings of stimuli (aimed at within-signer variance), and a small number of signers (between one and five). Techniques for normalizing sign data to permit absolute value comparison across signers are under development (Grosvald, 2009; Russell, Wilkinson, & Janzen, 2011).

Malaia & Wilbur (2012a) conducted a motion capture study of ASL that was innovative in a number of respects. There were 40 different target signs, 24 telic and 16 atelic.[7] These were produced by six deaf right-handed native signers

[6]Wilbur (1999) reported motion capture results of a study of stressed and unstressed target signs. A number of experimental studies, some with motion capture equipment, focused on hand position, determining whether the hand reaches its target location (Cormier, 2002) or whether the height of the preceding or following sign in the carrier phrase affects the target sign's place of articulation (i.e., phonetic lowering; Mauk & Tyrone, 2008, 2012). Signing rate has been found to have a general phonetic lowering effect (Tyrone & Mauk, 2010). Cheek (2001) used similar methodology to determine the impact of the handshape of preceding or following signs on the target sign handshape. Emmorey, Gertsberg, Korpics, & Wright (2009) used motion capture to track how restricted vision, blindfolding, and level of formality affected sign production.

[7]As will become apparent in the discussion of HZJ verbs, ASL does not allow a single stem to alternate between telic-looking and atelic-looking forms, and it was not possible to provide matched pairs for ASL like those that were used for the HZJ.

in four conditions: in isolation, in a carrier phrase SIGN X AGAIN, in sentence-medial position SHE X TODAY, and in sentence-final position TODAY SHE X, for a total of 160 productions per signer. Data were analyzed across subjects by predicate type (e.g., telic/atelic) and position (e.g., medial/final)[8] for five kinematic variables: duration, maximum velocity, percent of elapsed duration when the peak speed within the sign is reached, the slope of the change from the peak velocity to the next minimum velocity, and the peak instantaneous deceleration. Compared with the group of atelic signs, the telic signs had significantly higher peak velocity, greater instantaneous deceleration, shorter sign duration, steeper decelerating slope, and later percent of elapsed time to peak velocity. To interpret this result, it is necessary to note that position was also significant for peak velocity, duration, and percent of elapsed time to peak velocity. If there is a kinematic difference that specifically cues telic versus atelic, it would have to be visible regardless of position; only decelerating slope and peak instantaneous deceleration meet this criterion.

What these results tell us is that there is a change in how the telic signs come to an end, namely they are end marked with sharper deceleration, as compared with atelics. This fits with the theoretical phonetic model of telic verb signs as having a different phonological specification on their second timing slot, whereas atelic verb signs have the same specification spread from the first timing slot to the second.

## *Linguistic Analysis of HZJ Verb Types*

A series of linguistic analyses have been conducted on HZJ exploring various aspects of its phonology (Šarac Kuhn, Alibašić Ciciliani, & Wilbur, 2006), syntax (Alibašić, 2003; Alibašić Ciciliani & Wilbur, 2006; Dukić, 2011; Hrastinski, 2010; Milković, 2005; Milković, Bradarić-Jončić & Wilbur, 2006; Milković & Malaia, 2010; Šarac, 2003; Šarac Kuhn & Wilbur, 2006), and information structure (Milković, Bradarić-Jončić, & Wilbur, 2007).

Most recently, investigation of verb behavior parallel to those for ASL and Austrian Sign Language has been conducted by Milković (2011). Looking at 200 temporal-aspectual pairs of verbs (= 400 total verbs), Milković found that they formed three major groups. The largest group was comprised of verb pairs based on the properties of sign movement: Telic (perfective) signs in this group were formed by using shorter, sharper movement, as compared with atelic-imperfective roots (examples include all the stimuli given in the Appendix). The second group did not allow alternation of telic (perfective) signs and atelic-imperfective signs from the same roots but instead constructed phrasal sequences of several types: verb plus a separate aspectual sign, quantification of the internal argument, or use of verbal complements. For example, the Croatian verb *gorjeti* ("to burn") forms a telic/perfective *izgorjeti* ("to burn entirely"), whereas HZJ does not, combining instead the signs GORJETI ("burn") + SVE ("all") to express perfective meaning. Similarly, the perfective counterpart of the Croatian verb *boriti-se* ("to fight/strive") and *izboriti* ("to win") is conveyed in HZJ as a combination of the signs BORITI ("fight/strive") and DOBIT ("defeat"). The third group displayed pairs using suppletive stems parallel to ASL. As an example, the Croatian imperfective-perfective pair *buditi* ("wake someone") and *probuditi* ("awaken someone") is conveyed in HZJ by a sign BUDITI made with both hands using a fist handshape and a back-and-forth motion in the space in front of the signer versus a different two-handed sign PROBUDITI-SE made with an opening-L handshape (from closed fist to extended index and thumb) with the hands located on each side of the head. These findings are based on two experimental tasks. In the first, verbs were presented in pairs, one pair at a time, in Croatian print on PowerPoint slides to eight deaf native HZJ signing subjects, who were asked to translate the verbs into HZJ. Each of these eight subjects was presented with a different subset of 25 pairs, which makes a total of 200 different verb pairs; these were videorecorded for subsequent linguistic analysis. For the second task, a subset of 25 pairs were taken from the larger list and put into short narratives which each contained both members of a pair (1).

(1) *Moja prijateljica jako voli* ***putovati****. Jučer je ponovno* ***otputovala*** *u Francusku.* ("My friend really loves to **travel**. Yesterday she again **went** to France.")

These paragraphs were then translated into HZJ and signed by a hearing native signer to serve as stimuli. Nine deaf native HZJ signers were shown all 25 HZJ stimuli paragraphs and asked to reproduce them as well as answer questions about the meaning of the paragraphs, the grammaticality of the sentences, whether they would sign it that way, and if not, how they would sign it. These procedures and the data thereby obtained allowed us to proceed with confidence to the current study.

As a result of Milković's study, we know that HZJ differs from ASL in providing a regular morphological process, seen in the majority of verbs (first group), that permits a single stem to alternate between occurring in an end-marked form, denoting a telic-like interpretation of *perfective,* or in a non-end-marked form, denoting an atelic-like interpretation of *imperfective*. These derived telic/perfective atelic/imperfective pairs in HZJ allow for construction of matched-pair experimental stimuli to investigate motion kinematics, addressing questions such as, What kinematic features can be recruited to mark grammaticalized temporal-aspectual verb types in HZJ? How would the kinematic parameters recruited for verb type marking in HZJ interact with the prosodic effects on sign motion contributed by different sentence positions?

We designed the present motion capture experiment to study the effects of sign phrase position and event structure marking on the kinematic parameters of predicate signs in HZJ. We compared duration, peak velocity, minimal acceleration (peak deceleration), overall slope of deceleration, and the elapsed duration of the sign to the peak velocity in perfective and imperfective HZJ predicates produced in phrase-final and medial position. This 2 × 2 predicate type

[8]Medial included carrier phrases and sentence-medial signing; final included isolation and sentence-final.

by position parametric design allowed us to investigate the effects of prosodic and event structure marking individually as well as in interaction and to compare the results with our prior findings on ASL.

## Materials and Methods

Thirty HZJ temporal-aspectual sign pairs (= 60 signs) were chosen for further investigation using motion capture recording (see the Appendix). Following the protocol established for the ASL study, the signs were elicited from a native bilingual hearing HZJ signer in the four conditions: each sign in isolation, each sign in the carrier phrase SIGN X AGAIN, each sign sentence-medially SHE X TODAY, and each sign in sentence-final position TODAY SHE X. The signer produced the HZJ predicates as translations of spoken Croatian stimuli; she signed facing the video camera while standing in a designated spot for motion capture. This procedure was repeated on 5 separate days (in total, 240 productions from the signer each day for 5 days). During recording, the signer wore a Gypsy 3.0 wired motion capture suit, and the data about the XYZ positions of all markers in millimeters were collected at the rate of 100 frames per s 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 the video camera. The hand motion was thus recorded in relation to the body as well as to an external fixed point. Because we are not attempting to determine the absolute location of the hands or the distance between them or between them and the body, whatever artifactual body movements may have been present during the data collection are not relevant to the analysis that we conducted, and in any event, the differences that we report are likely to be larger than any such body movement artifacts.[9]

A simultaneous video recording at 30 frames per s rate was made with a National Television System Committee (NTSC) video camera on a tripod outside the motion capture recording field. The positional data from the marker on the right wrist, tracking the movement of the dominant signing hand, was used for the analysis.[10] Both the video and the 3D positional data were imported into ELAN annotation software (Max Planck Institute for Psycholinguistics, www.lat-mpi.eu/tools/elan), and aligned using the audio marker and T-pose (the signer standing with arms extended to the sides at shoulder level) at the beginning and end of each recording. The video was annotated in ELAN by another HZJ signer, who marked the beginning and end of each target sign following procedures established by Green (1984), assuming the first frame of recognition of the sign-initial handshape as the beginning of each predicate and either the point of contact—or maximal distance traveled by the hand—as the end of the sign, using both video and high-resolution XYZ displacement data (but without access to other kinematic variables). The time points for the beginning and end of each sign were extracted from ELAN annotation of the video data, and processed in MATLAB to extract the speed and acceleration profiles for each predicate from the recorded kinematic files.

### *Data Analysis*

The predicates whose maximal speed occurred on the last or next to last frame were discarded from analysis (= 66 signs, or 5.3% of cases, including 49 imperfective and 17 perfective signs, of which 31 were in phrase-final position); these were the cases where contact occurred at the end of the sign, but both hands kept moving together briefly after contact. This situation resulted from using Green's definition for determining the sign end, which perhaps cuts the end short. These cases were eliminated because the calculation of one variable, the slope of deceleration, would have been skewed by this short time: If the maximal speed occurs on the last frame of the sign, the slope would need to be calculated with a divisor of 0; if it occurs on the next to last frame, the divisor is 1. For the rest of the predicates, the following kinematic metrics were calculated:[11]

1. the duration of the predicate in ms (duration);
2. the peak instantaneous speed achieved within each predicate (maxV);
3. the percent of sign movement elapsed to the moment where peak speed occurred (% elapsed), which is also the point at which deceleration starts,
4. the minimum instantaneous acceleration (i.e., maximal deceleration) within each predicate (minA);
5. the slope of deceleration, calculated as the difference between maxV and the following local minimum, divided by the number of ms over which it occurred. The slope measured the overall steepness of the deceleration from maxV to minV, whereas minA measured the maximum instantaneous negative acceleration (deceleration).

## Results

We used a multivariate analysis of variance (MANOVA) to investigate the effect of two independent variables (i.e., predicate type and phrase position) on five dependent kinematic variables, which include sign duration, peak speed

[9]Formulae for computational processing follow procedures described previously (Malaia, Borneman, & Wilbur, 2008; Wilbur & Malaia, 2008b).

[10]Our procedure thus follows Mauk (2003) and mostly parallels Cormier (2002), except that the latter author used the outside of the pinky base. In order to simplify the kinematic analysis, for this study we avoided signs with handshape change, which eliminated the need to analyze individual fingers.

[11]Because we are not studying position effects such as sign lowering, we do not calculate the position of the hand with respect to any reference marker, body part, or absolute location, as displacement is only calculated for purposes of deriving velocity. Wilbur (1999) reported that displacement varies in order to permit phrase position to affect duration and stress/prominence to affect peak velocity—that is, given that $v = d/t$, $v$ is controlled by stress and $t$ is controlled by position, which leaves displacement to vary as needed (see also Wilbur & Martínez, 2002).

of dominant hand within the sign, maximum deceleration, overall slope of deceleration, and the location of peak speed within the sign. As in our previous work on ASL, the isolation condition overlapped with sentence-final condition, allowing them to be collapsed, and the carrier phrase overlapped with sentence-initial condition, so they were collapsed. Thus, phrase position analysis was conducted as medial vs. final. The results of the MANOVA are summarized in Table 1.

*Effects of predicate type on kinematic variables.* Predicate type (e.g., telic/atelic) significantly affected all calculated kinematic variables: sign duration, maximum velocity within the sign, minimum acceleration and overall slope of deceleration, and percent of sign elapsed to peak speed, as shown in Table 1.

*Effects of predicate phrase position on kinematic variables.* Phrase position (e.g., medial/final) significantly affected sign duration, minimum acceleration and overall slope of deceleration, and percent of sign elapsed to peak speed, as shown in Table 1. Peak velocity within the sign was not significantly affected by sign phrase position, $p > .5$.

*Interaction effects of predicate type and phrase position on kinematic variables.* Only the overall slope of deceleration was affected by the interaction of phrase position and predicate type, $F(1, 1170) = 4.58$, $p < 0.033$, $\eta_p^2 = .004$.

### Individual Kinematic Variables

The effects of predicate type and phrase position on each kinematic parameter are described below.

*Sign duration.* Sign duration was affected by both predicate type and phrase position. Figure 2 shows these effects such that signs in phrase-final position were longer than those in medial position, and that in final position, telics were significantly shorter than atelics (telics, medial $M = 0.391$ s, final $M = 0.444$ s; atelics, medial $M = 0.475$ s, final $M = 0.547$ s).

*Peak speed.* Peak speed was affected only by the predicate type. Figure 3 shows this effect such that telic signs had significantly greater peak speed than atelic ones regardless of phrase position of the predicate sign in the sentence (telics, medial $M = 2.28$ m/s, final $M = 2.31$ m/s; atelics, medial $M = 1.35$ m/s, final $M = 1.37$ m/s).

*Minimum instantaneous acceleration (deceleration).* Minimum instantaneous acceleration was affected both by predicate type and phrase position. Figure 4 shows those effects such that telic signs had greater peak instantaneous deceleration than atelic signs regardless of phrase position; however, telic signs in the final position were characterized by smaller instantaneous deceleration than telic signs in medial position (telics, medial $M = –30.4$ m/s$^2$, final $M = –33.2$ m/s$^2$; atelics, medial $M = –18.4$ m/s$^2$, final $M = –17.6$ m/s$^2$).

*Elapsed percent of sign movement to time of peak speed.* Elapsed percent of the sign movement from the movement origination to the moment of achieving peak speed was greater in telic predicates as compared with atelic ones—that is, the peak speed occurs later in the sign for the telic predicates. In both predicate types, peak speed was reached significantly earlier in phrase-final position compared with medial. Figure 5 illustrates these effects (telics, final $M = 50.3\%$, medial $M = 54.6$ %; atelics, final $M = 42.7\%$, medial, $M = 49.6\%$).

*Deceleration slope.* The overall slope of deceleration from the peak speed to the local minimum speed was significantly affected by phrase position in telic predicates only (yielding an interaction effect in the overall model). It was significantly steeper in telic signs as compared with atelic ones (telics, final $M = –0.016$, medial $M = –0.019$; atelics, final $M = –0.009$, medial, $M = –0.01$), as shown in Figure 6. Note that in this case, the slope marker is still a reliable indicator of telicity in either position: As the means show, the slope of telics is roughly twice that of atelics regardless of position.

### Summary of Findings

Predicate type had a significant effect on peak speed, instantaneous deceleration, the overall slope of deceleration within the sign, sign duration, and percent of sign elapsed to peak speed. Phrase position affected sign duration, instantaneous deceleration and the overall slope of deceleration within the sign, and the point in the sign where peak speed was achieved. There was also a significant Predicate Type × Phrase Position interaction effect on the overall slope of deceleration. This interaction was due to the fact that the phrase position effect was significant only in telic predicates. We take the robustness of velocity and deceleration to phrase position effects as evidence that the semantic information marked on telic predicates by deceleration is not washed out by phrase final lengthening, which would possibly lead to ambiguity of how to interpret the status of the event.

## Discussion

### Kinematic Results for HZJ as Compared With ASL

As demonstrated by statistical analysis, both predicate type and phrase position showed effects on the kinematic

**Table 1.** Significant effects of predicate type and position on kinematic variables.

| | Predicate type | | | Position | | | Predicate Type × Position | | |
|---|---|---|---|---|---|---|---|---|---|
| Kinematic variable | $F$(1, 1170) | $p$ | $\eta_p^2$ | $F$(1, 1170) | $p <$ | $\eta_p^2$ | $F$(1, 1170) | $p$ | $\eta_p^2$ |
| Duration | 68.375 | <.001 | .055 | 31.292 | <.001 | .026 | | | |
| maxV | 641.448 | <.001 | .354 | | | | | | |
| % elapsed | 28.925 | <.001 | .024 | 22.288 | <.001 | .019 | | | |
| minA | 356.863 | <.001 | .234 | 6.522 | <.011 | .006 | | | |
| Slope | 306.2 | <.001 | .207 | 8.886 | <.003 | .008 | 4.58 | <.033 | .004 |

Figure 2. Predicate duration in telic and atelic predicates in phrase-medial and phrase-final position.

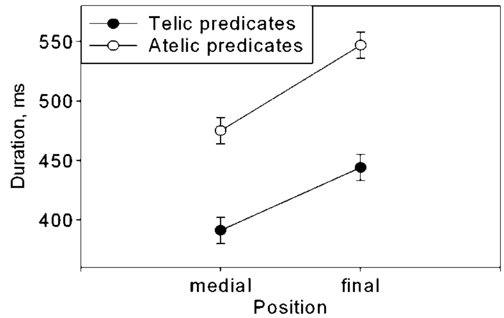
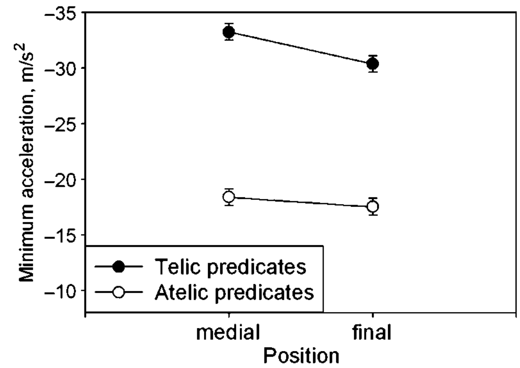



Figure 4. Minimum instantaneous acceleration (i.e., maximum deceleration) in telic and atelic predicates in medial and final phrase position.




variables. Here, we further discuss these results in the context of previous research on the kinematics of ASL. The ASL results confirmed that event structure differences in the meaning of the verbs are reflected in the kinematic formation: In telic verbs, the endpoint of the event is marked by significantly greater deceleration as compared with atelic verbs. This kinematic marker was robust to position of the verb (e.g., medial vs. final), whereas other measures (e.g., duration and peak speed) were affected by the prosodic process of phrase final lengthening. our study provided the first kinematic confirmation that event structure is expressed in movement profiles of ASL verbs, up to then only supported by apparent perceptual distinctions. Comparing the present results on HZJ with the prior findings on ASL, we note both similarities and differences.

One clear similarity between the two languages was the kinematic feature of *instantaneous deceleration.* Telic-perfective HZJ verbs were characterized by larger absolute values of instantaneous deceleration in both medial and final phrase position, as compared with atelic-imperfective ones. This observation supports the EVH claim that the endpoint in event structure is kinematically manifested as end-marking in sign production, whether such marking is unique to each sign root (i.e., lexical), as in ASL, or used productively throughout the verbal paradigm, as in HZJ.

Another similarity is seen with respect to duration and percent of sign duration elapsed to peak speed. The prosodic effect of phrase final lengthening was evident in increased duration of both types of HZJ predicates in final phrase position, which is parallel to what has been shown for ASL (Wilbur, 1999). In both languages, the difference in duration of both predicate types in final position results mainly from the lengthening of the portion of each sign following the peak speed as evidenced by the lower (hence, earlier) values of percent of sign elapsed to peak speed in final phrase position as compared to medial.

One clear difference between the two languages is peak velocity. For HZJ, the peak velocity was greater in telic-perfective signs as compared with atelic ones, and the effect of phrase position was not significant. In contrast, in ASL peak velocity was affected both by predicate type and phrase position. One possible interpretation of this difference between the two SLs is that grammaticalization of event structure in HZJ makes the parameter of peak velocity robust to prosodic

Figure 3. Peak velocity in telic and atelic predicates in medial and final phrase position.

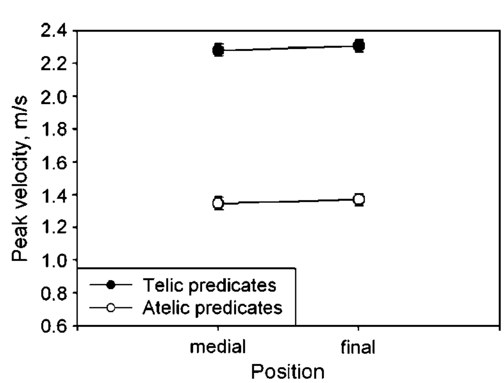



Figure 5. Percent of sign elapsed until peak velocity is reached in telic and atelic predicates in medial and final phrase position.

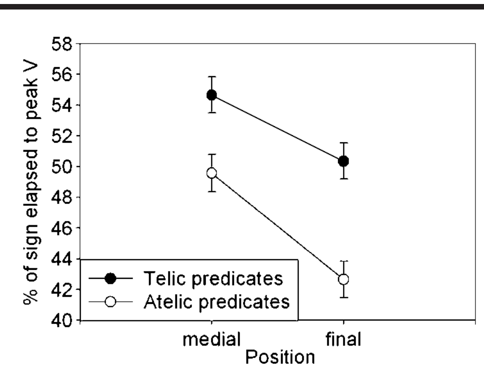
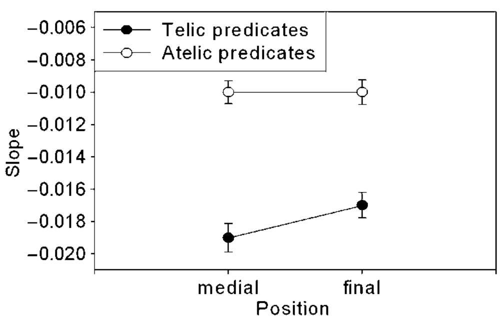


**Figure 6.** Gross slope of deceleration from peak velocity to the following minimum in telic and atelic predicates in medial and final phrase position.




effects. A related possibility is that in ASL, peak velocity is already used to indicate stress (Wilbur, 1999), whereas there is no information available concerning the marking of stress in HZJ, which may use a different motion variable or other type of marking (face/head/body). Further research is required to fully understand this kinematic difference between the two languages, as well as to determine whether individual kinematic variables can carry more than one linguistic distinction in a single language.

One less-clear difference between the two languages is the slope of deceleration. In HZJ, the overall slope of deceleration was affected by the interaction of phrase position and predicate type, meaning that the behavior in telics differed by position, but that of atelics did not. In ASL, the overall slope of deceleration was affected only by the predicate type, being significantly steeper in telic signs as compared with atelics. In both languages, the slope for telics is larger than for atelics. However, a comparison of the ratios of telic slope to atelic slope reveals that the HZJ telics are close to twice those of atelics (final telic to atelic: –.016/–.009 = 1.78; medial telic to atelic: –.019/–.010 = 1.9), whereas for ASL, the difference is much smaller (final telic to atelic: –.011/–.007 = 1.57; medial telic to atelic: –.010/–.008 = 1.25). Whether this is a language difference cannot easily be determined. One reason is the fact that the HZJ data represent only one signer, albeit on 5 different days and in more than 240 productions per day. The ASL sample included both teachers and nonteachers whereas the HZJ signer was a teacher, which may have led to unconscious hyperarticulation that affected the magnitude of the kinematic values, leading to the present result. Another reason is that at this stage of our understanding of the grammar of SLs it is not clear what other functions might be marked by the kinematic variables being investigated and, thus, what alternate explanation we could supply if this difference between ASL and HZJ is shown to stand up.

Overall, the kinematic parameters of articulator motion during production of HZJ verbs demonstrate significant differences between telic-perfective and atelic-imperfective signs, which are reflective of the grammaticalized event structure marking in HZJ. HZJ appears to map the linguistic distinctions between temporal-aspectual verb types by means of peak velocity and maximum deceleration of articulator motion within the sign. The prosodic effect of phrase-final lengthening affects the parameters of sign duration and deceleration slope between sign pairs; however, the distinctive difference in peak velocity is maintained despite this effect, constituting a resilient marker of endpoint in the predicate's event structure. These results are consistent with the cross-linguistic EVH model of event structure representation in the visual modality (Wilbur, 2008).

## *Neural Bases of Kinematic Feature Recruitment*

The recruitment of kinematic features into SLs, specifically the use of velocity/deceleration cues for marking verb types, is likely based on a general human ability to utilize perceptually salient motion for monitoring the environment. According to event segmentation theory (Zacks & Tversky, 2001), humans continually use perceptual data to make predictions about what will happen next (Zacks, Speer, Swallow, Braver, & Reynolds, 2007). Sensory cues, such as visually perceived velocities and acceleration/deceleration of objects, contribute to event perception along with the inferences about actors' goals (Zacks et al., 2009). In the event segmentation theory model, the selection and maintenance of an event model in working memory are supported by event schemata—memory representations with abstract features of previously encountered events. Event schemata are accessed when a perceptual event boundary is encountered. The neural region likely responsible for the retrieval of event schemas from episodic (i.e., long-term) memory is the precuneus/posterior cingulate (Brodmann area 7/23, Montreal Neurological Institute (MNI) coordinates [19 –66 24]), which is active during visual processing of event boundaries (Zacks et al., 2001).

The relevance of telic verbs for discourse processing lies in the fact that they provide a temporal boundary for events (Jackendoff, 1991; Van Lambalgen & Hamm, 2005). Comparison of neural activations during processing of sentences with English telic and atelic verbs has also been shown to elicit differential processing in the precuneus/PCC (MNI [20 –56 16]) during a reading experiment (Malaia & Newman, submitted), suggesting that both perceptual and conceptual (i.e., linguistic) event boundaries can trigger access to event schemata. A neuroimaging study of ASL also revealed higher activation of the precuneus/PCC (MNI [18 –54 10]) during comprehension of telic verbs, as compared with atelic (Malaia et al., 2009, 2012), despite the fact that telicity representation is not morphologically productive in ASL.

We suggest that the overall perceptual and neural salience of environmental velocity and acceleration cues for event segmentation would make those kinematic parameters available for recruitment into SLs as conceptual triggers from event schema access. However, language-specific implementation of kinematic cues in SL phonology would depend on the interaction between all modules of the linguistic system in the particular language (e.g., the fact that velocity is a cue for stress in ASL may affect its availability for other purposes). Further neuroimaging research on HZJ, or systematic analysis of currently emerging SLs, might help further substantiate this possibility. As signed languages are underrepresented in experimental linguistics research, it is also important to collect larger samples in order to distinguish individual differences (due to accent, dialect, etc.) from crosslinguistic differences.

Behavioral and neurophysiological studies of verbal event structure in spoken languages demonstrate that telic verbs, which license the internal argument, prime the patient theta role during online comprehension, facilitating the processing of complex syntactic structures (Malaia, Wilbur, & Weber-Fox, 2009, 2012; O'Bryan, 2003). For example, the correct assignment of thematic roles in reduced relative clauses with atelic verbs (e.g., "The infant bathed by the mother cried loudly") is more difficult compared with reduced relative clauses with telic verbs (e.g., "The infant changed by the mother cried loudly"). This psycholinguistic data confirm that telicity, a property of the verb reflecting its lexical semantic complexity, is also a key component in the interface linking syntactic structure and conceptual representation in human languages.

### *Linguistic Systematization of Kinematic Features*

These results provide further support for the EVH by showing that available kinematic resources are recruited to convey important semantic distinctions. They also show that two SLs can differ in which resources are used for a specific purpose: ASL uses deceleration and slope of deceleration; HZJ uses peak velocity for distinguishing telic/atelic. This difference may possibly be related to the manner in which stress is marked in the two languages: We know that ASL uses peak velocity, but we do not yet know how HZJ conveys stress. Further linguistic research on this aspect of HZJ will be necessary before any experimental design can be constructed to test it.

These results also support our contention that SLs evolve by a process that takes perceptually and productively distinct motion characteristics and grammaticalizes them into distinct units that convey lexical or functional meanings. Both the vocabulary and the structural processes that construct sentences are overlaid on the physical and geometrical substrata. End-marking is an example of the grammaticalization of physics (e.g., deceleration) for linguistic purposes. That these resources are grammaticalized into SLs is further supported by the fact that these kinematic factors, such as velocity and deceleration, are not used consistently in prelinguistic gesturing systems such as that used in Nicaragua among deaf children before Nicaraguan Sign Language emerged, even though the meaning is conceptually available (Kegl, Senghas, & Coppola, 1999; Senghas & Coppola, 2001). Thus, the route from the basic conceptual nature of the meanings expressed to the forms required to express them is neither direct nor continuous, indicating grammaticalization into abstract linguistic systems of SLs (Casey, 2003; Malaia & Wilbur, 2010b; Rathmann & Mathur, 2008).

Finally, given that the physical resources (e.g., physics, geometry) are universal, it is expected that SLs will recruit these options and assign them various meaningful functions. The difference in telicity marking between ASL and HZJ both linguistically and kinematically suggests that the form/function relationships are not universal. But the fact that both languages recruit kinematics for this distinction may provide the fundamental similarity that makes SLs resemble each other more than spoken languages do (Newport & Supalla, 2000).

Another interesting question that is raised by these results is whether there is a borrowing effect from spoken Croatian onto HZJ with respect to how telic–atelic marking is achieved. Although it is not likely that the recruitment of velocity (as opposed to deceleration in ASL) would have been directly affected, there is a reasonable possibility that the linguistic coding that permits the same root to alternate between telic and atelic may have been so influenced.[12] Croatian is a member of the Slavic language family: The same verb may appear with a prefix to indicate telic/perfective/resultative or with a suffix to indicate atelic/imperfective (Arsenijević, 2004; Malaia, 2004). The possibility that telicity marking on verbs in HZJ was influenced by the surrounding superstrate of Croatian also suggests that the absence of systematic alternation of telic–atelic marking for single roots in ASL may be related to the absence of such marking in the surrounding superstrate of English.

## Conclusion

In the present study, we demonstrated that SLs may grammaticalize different available kinematic cues for specific linguistic purposes. As a result, the kinematic features used by different linguistic modules (e.g., syntax, morphology, phonology, lexicon) have to be clearly distinguishable: A single kinematic parameter (e.g., sign duration) cannot be used as a phonological marker of phrase-final lengthening and also as a morphological marker of telicity or aspect within a single linguistic system. The pervasiveness of phrase-final lengthening would overshadow the aspectual semantic distinction on verbs perceptually, so if such a system did arise, it would be quickly lost and presumably replaced with a different but clear kinematic feature.

This is the first study to supply quantitative data that allow the comparison of how the phonological feature of velocity is employed by unrelated SLs. It appears that the use of velocity in ASL versus HZJ is equivalent to the use of nasalization as a feature in spoken French versus Pech (in Honduras; Holt, 1999) or Akan (in Ghana; Schachter & Fromkin, 1968). In French, nasalization is predictable from the phonological environment, whereas in Pech, nasalization

[12]Although we have no direct evidence in this regard, there is evidence of Croatian influence on HZJ with respect to question formation (Šarac Kuhn & Wilbur, 2006). In that study, we see use of an optional question sign JE-LI that is not integrated with the peak intensity of the nonmanual markers and, thus, is clearly an adjunct. This sign was introduced into HZJ through the pedagogical signed version of spoken Croatian—that is, from signed Croatian.

is used to express negation in the present tense (i.e., the phonological feature of nasalization is the only overt expression of the morpheme of negation) and in Akan for negation of many verbs regardless of tense. Similarly although peak velocity is a phonological feature of ASL that serves at least to mark stress, in HZJ it serves, concurrent with acceleration, as a morphemic marker of event structure/aspect.

Kinematic features of HZJ verbs in the present study were affected both by the temporal-aspectual verb type and by their phrase position within the sentence in a regular manner. The motion capture analysis of HZJ sign production demonstrated regular kinematic distinctions between temporal-aspectual verb classes, with the peak velocity and maximal deceleration parameters being robust to the prosodic effect of phrase-final lengthening. The findings show that event visibility in kinematic parameters, first demonstrated at the lexical level in ASL verbs, can also be productive in SLs. HZJ allows formation of temporal-aspectual verb classes from the same sign root, such that rapid deceleration following peak velocity constitutes a morphemic affix similar to those observed for various aspectual purposes, e.g. different types of reduplication (Wilbur, 2005, 2009). Alternation of roots has been argued to exist in ASL at the level of deriving nominals from a restricted set of activity verbs (Brentari, 1998; Supalla & Newport, 1978); thus, it is a language-specific difference that HZJ alternates roots for temporal-aspectual pairs and ASL does not. Through our experiment, we also demonstrated independent and interactive effects of grammar and prosody on kinematic parameters of HZJ predicate signs, providing crosslinguistic confirmation that physical properties of articulator motion are recruited into SLs to express linguistic features. This is instrumental in understanding how kinematic features can be employed by different components of the linguistic system, such as the use of sign duration to indicate phrase-final lengthening and peak velocity (unaffected by sign duration in HZJ) to indicate predicate type.

The interesting difference between the use of kinematic features in ASL and HZJ to indicate semantic verb type arises due to the fact that verb type in ASL is not systematically constructed: Although all verbs with telic meaning have the marking of deceleration in their second timing slot, ASL has no regular morphological process to produce an alternation between two forms of a verb with one stem. Alternatively, HZJ uses a phonologically expressed morphological process to consistently produce verb pairs with different event structure, which leads to stringent restrictions on the type of kinematic feature used for the purpose. There is no information on whether the formation of temporal-aspectual verb pairs is the result of contact and continuous interaction of HZJ with spoken Croatian. Given the bilingual environment and education of Croatian signers and the communicative pressures that lead to constant language contact and creolization of SL, this is a possibility. It is also possible that a developing SL might form a regular grammatical pattern with temporal verb pairs on its own, such as standard Indonesian (Son & Cole, 2008); the historical development of grammaticalization pattern in kinematics merits further investigation.

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## Appendix

Verb forms in English and Croatian.

| Imperfective | English translation (continuous meaning) | Perfective | English translation |
|---|---|---|---|
| *buditi* | wake up | *probuditi* | wake up |
| *putovati* | travel | *otputovati* | take off |
| *putovati* | travel | *doputovati* | arrive |
| *gledati* | look at | *ugledati* | spot |
| *gurati* | push | *gurnuti* | push |
| *brisati* | wipe | *obrisati* | wipe off |
| *crtati* | draw | *nacrtati* | draw |
| *češljati* | comb | *počešljati* | comb |
| *čistiti* | clean | *očistiti* | clean-up |
| *čitati* | read | *pročitati* | read |
| *dijeliti* | share | *podijeliti* | split |
| *brijati* | shave | *obrijati* | shave |
| *bježati* | flee | *pobjeći* | run away |
| *disati* | breath | *udahnuti* | breathe-in |
| *dizati* | lift | *dignuti* | pick up |
| *dolaziti* | come | doći | show up |
| *donositi* | bring | *donijeti* | bring |
| *dopuštati* | allow, tolerate | *dopustiti* | allow |
| *dovoditi* | bring | *dovesti* | bring |
| *dovoziti* | drive something/someone | *dovesti* | drive |
| *govoriti* | speak | *reći* | tell |
| *gristi* | bite | *ugristi* | bite |
| *gubiti* | lose | *izgubiti* | lose |
| *iskorištati* | exploit | *iskoristiti* | take advantage of |
| *oblačiti-se* | dress | *obući-se* | put clothes on |
| *odgovarati* | respond | *odgovoriti* | answer |
| *prodavati* | sell | *prodati* | sell |
| *propadati* | decay | *propasti* | fail |
| *birati* | choose | *izabrati* | pick |
| *grmjeti* | thunder | *zagrmjeti* | thunder |