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Sign lowering and phonetic reduction in American Sign Language

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ABSTRACT

This study examines sign lowering as a form of phonetic reduction in American Sign Language. Phonetic reduction occurs in the course of normal language production, when instead of producing a carefully articulated form of a word, the language user produces a less clearly articulated form. When signs are produced in context by native signers, they often differ from the citation forms of signs. In some cases, phonetic reduction is manifested as a sign being produced at a lower location than in the citation form. Sign lowering has been documented previously, but this is the first study to examine it in phonetic detail. The data presented here are tokens of the sign WONDER, as produced by six native signers, in two phonetic contexts and at three signing rates, which were captured by optoelectronic motion capture. The results indicate that sign lowering occurred for all signers, according to the factors we manipulated. Sign production was affected by several phonetic factors that also influence speech production, namely, production rate, phonetic context, and position within an utterance. In addition, we have discovered interesting variations in sign production, which could underlie distinctions in signing style, analogous to accent or voice quality in speech.

1. Introduction

Studies of phonetics and phonology in signed languages can illustrate commonalities and differences between sign and speech. Signed languages are natural languages used by Deaf[1] communities around the world. This study focuses on American Sign Language, which is used by Deaf people in the United States and Canada. Research has shown that ASL and other signed languages are organized similarly to spoken languages, i.e. they have semantic, syntactic, morphological and phonological systems (Klima & Bellugi, 1979; Sandler & Lillo-Martin, 2006). The terms phonology and phonetics are used in sign language research to describe the sign modality's analogs of the phonological and phonetic aspects of spoken languages. More specifically, sign language phonetics is the study of the physical transmission of ideas through the manual–visual channel by the movement of the arms, hands and fingers. The basic phonological parameters of signs are movement, handshape and location (Stokoe, 1960). Minimal pairs in a signed language result from differences in movement, handshape and location, just as minimal pairs in a spoken language result from differences in consonants and vowels. See Liddell and Johnson (1989) and Brentari (1998) for descriptions of phonological phenomena in ASL and Crasborn (2001) for a discussion of current models of sign phonology.

The location of a sign refers to the spatial location of the hands during that sign, which is often a location on the body that the hands contact (Klima & Bellugi, 1979). The phonological distinctiveness of location values is demonstrated by the minimal pairs in Fig. 1. The signs FATHER, MOTHER and FINE are all articulated with the same handshape and involve repeated movement toward the body and contact with the thumb tip. These signs differ solely in the location parameter: forehead for FATHER, chin for MOTHER and torso for FINE. Stokoe (1960) distinguishes 12 contrastive locations for ASL, 11 of which are body locations.

The study of sign phonetics has been limited primarily to special populations of signers. There is a rich literature on sign production by Deaf infants (Conlin, Mirus, Mauk, & Meier, 1999; Marentette, 1996). In addition, several kinematic and descriptive studies have focused on signers with aphasia, apraxia, Parkinson's disease, and other neurogenic movement disorders (Brentari & Poizner, 1994; Loew, Kegl, & Poizner, 1995; Poizner, Klima, & Bellugi, 1987; Tyrone & Woll, 2008).

Few studies have examined the phonetic variation that occurs in the typical production of sign location. Signs can rise in emphatic (Wilbur & Schick, 1987) or child-directed signing (Holzrichter & Meier, 2000) and in shouting (Crasborn, 2001; Mauk, 1999). Similarly, signs can lower in whispering (Crasborn, 2001). Mauk (2003) found that signing rate and phonetic environment affected variation in ASL sign locations.

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[1] In this paper, we will use the term Deaf to describe members of the community of sign language users, as distinct from deaf, which refers to clinical hearing loss.

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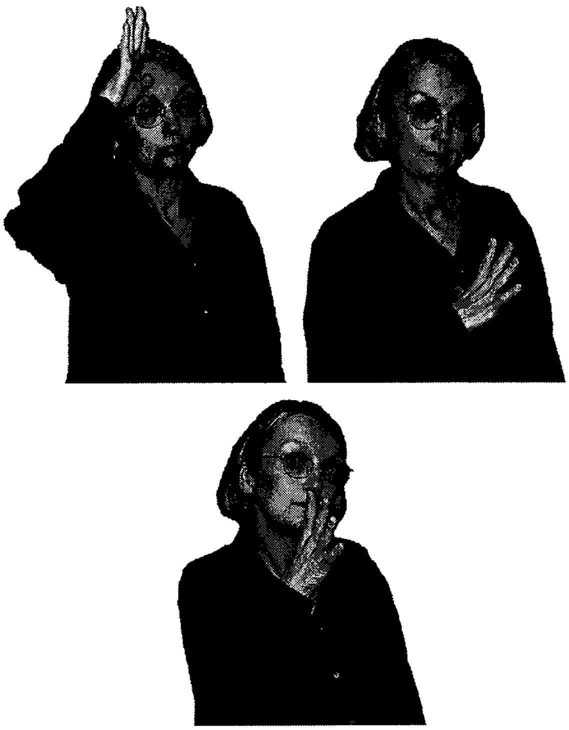

Fig. 1. ASL minimal pairs based on location: FATHER, MOTHER, FINE. Meaning distinctions between these signs rely on differences in the location of the signs.

Given that reduction in spoken languages is affected by factors like production rate and phonetic environment (Kelso, Vatikiotis-Bateson, Saltzman, & Kay, 1985; Moon & Lindblom, 1994), we are investigating to what extent similar factors affect reduction in sign production. Because sign production, like speech, is affected by the biomechanical constraints of its articulators, we hypothesize that movements that occur on the periphery of the movement space are more likely to be affected when the spatial or temporal demands of the production task are heightened. Thus, signs with locations that are high in the signing space may be more apt to move down, or lower, at fast signing rates or in low sign contexts. Because the forehead is near the upper bound of the space in which signs occur, signs at that location should be more likely to be lowered than to be reduced along another dimension. The lowering of forehead-located signs has been examined in terms of phonology (Liddell & Johnson, 1989) and sociolinguistics (Lucas, Bayley, Rose, & Wulf, 2002; Schembri et al., 2009). However, no previous study has examined sign lowering as an articulatory phenomenon or attempted to measure it precisely. This study examines sign lowering as an articulatory phenomenon that may be affected by factors such as signing speed, phonetic environment, and utterance position.

Liddell and Johnson (1989) suggested that phonetic environment affected lowering of forehead-located signs, but no data were presented. Lucas et al. (2002) found that grammatical category was the strongest predictor of the downward shift of forehead-located signs, with function words (e.g., prepositions) the most likely to shift and adjectives the least likely. Location of the preceding sign was also found to have an effect: relative to forehead variants, cheek variants were more likely to be preceded by a lower sign. Lucas et al.'s results suggest that phonetic context affects variation for some ASL locations; however, they used qualitative coding and did not control for potentially confounding variables such as signing speed. We are expanding upon these studies by looking at sign lowering in controlled environments and rates and by using high resolution data capture. We expect the occurrence and degree of lowering to be increased by placing signs in phonetic environments that require large movement trajectories (e.g. vertical distances of approximately 30 cm or more) and by asking participants to sign at faster rates.

Most studies of sign production have collected data via standard video, which unfortunately does not allow the type of precise measurements necessary for detailed phonetic analyses of sign production. Recently, optoelectronic systems, which track light-emitting or light-reflecting markers attached to a subject's articulators, have become more prevalent. Unlike video, optoelectronic systems allow points on the body to be tracked in three dimensions simultaneously. The Optotrak system (Northern Digital) uses a set of infrared sensitive cameras to record the location of infrared light-emitting diodes (IREDs) that are attached to a signer's body. By comparing the locations of the IREDs over time, it is possible to track movement in three dimensions. Optoelectronic systems such as Optotrak have been used to study sign-specific phenomena such as verb morphology (Poizner, Newkirk, & Bellugi, 1983), emphasis (Wilbur, 1990), fingerspelling (Wilcox, 1992), sign shouting (Mauk, 1999), handshape coarticulation (Cheek, 2001), indexic signs (Cormier, 2002), and undershoot of handshape and location (Mauk, 2003).

2. Methods

As part of an on-going study, we looked at the ASL sign WONDER shown in Fig. 2. To make this sign, a signer positions her hand in front of her forehead with the index finger pointing upward and the palm of the hand facing toward her. The signer moves the hand in small circles either in the horizontal plane or in the vertical plane that runs lateral to the body. This sign does not normally involve contact between the hand and the forehead. While WONDER has not been described specifically as a member of the set of signs that may be lowered, it fits the general category of forehead-located signs.

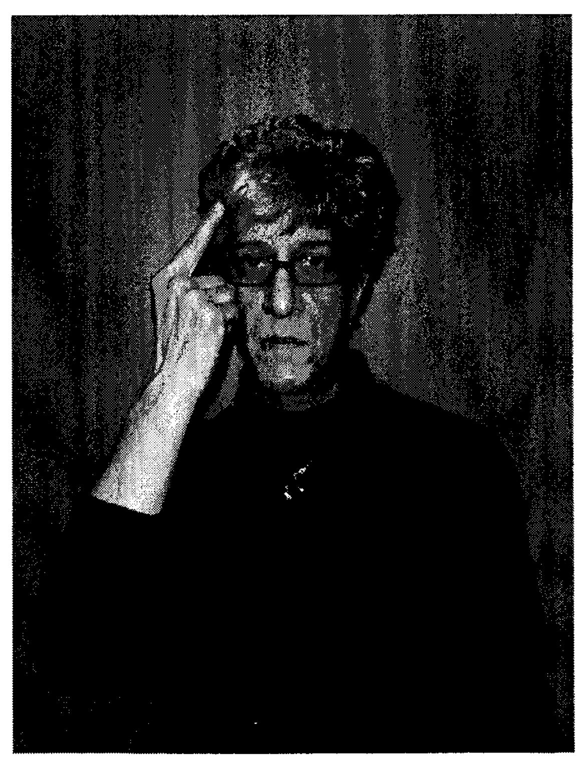

Fig. 2. ASL sign WONDER.

Fig. 3. ASL signs BITTER (left) and ME (right).

Phonetic environment of the sign WONDER was manipulated such that it was adjacent to either the ASL sign BITTER or the ASL sign ME. BITTER is formed by bringing the index finger to contact the chin, while the palm of the hand faces the signer. The sign ME is formed in an identical way, except that the hand moves toward contact with the center of the torso. Each sign is shown in Fig. 3.

The two utterances elicited from the signers were WONDER BITTER WONDER and WONDER ME WONDER. Notice that in each utterance the handshape and palm orientation are constant throughout. The signer must simply move the hand from the forehead location to either the chin or the torso and then back to the forehead. While these utterances are not meaningful in ASL, all two-sign combinations in these utterances are possible in larger ASL sentences.

2.1. Participants

The data presented here are from six signers: two male and four female. All were native Deaf signers of ASL who were living in Connecticut at the time of data collection. The group ranged from 19 to 65 years of age. Five of the signers were right handed and one was left handed.

2.2. Procedure

Participants were asked to produce these utterances at three signing speeds. For the first speed, the signer was asked to sign at a normal conversational speed. Then the signer was asked to sign faster, being careful not to sign as fast as possible, since that would be the final signing speed. Signers were allowed to set their own pace based on these instructions and were not coached more specifically on how fast they should sign. The participants in the study found these directives easy to interpret and follow.

Signers produced 15 tokens of each WONDER ___ WONDER sequence for each of the signing speeds, and these productions were collected as a single data trial.[2] For each trial, we excluded the first full WONDER ___ WONDER sequence. We often found that this sequence was produced in a qualitatively different way, in that it tended to be produced substantially more clearly than later sequences. Similarly, the final sequence or final two sequences of a trial were often substantially reduced. For these reasons, only the 10 sequences that immediately followed the first one were analyzed for each signing speed category, for a total of 120 productions of the target sign WONDER per participant. Productions in which IREDs were occluded were excluded from analysis.

2.3. Data collection and analysis

Sign movements were recorded with Optotrak Certus and Optotrak 3010 systems. IREDs were attached to participants' sign articulators and tracked by three cameras at a sampling rate of 60 Hz. Five IREDs were attached to a device which maintained a fixed position on the head (Fig. 4), thereby allowing us to track the head's movements in three dimensions and to compare its location to the hand's location. The head device was built on an ophthalmic headband, which is adjustable to any participant. Additional IREDs were attached to the tip of the dominant index finger and to the dorsal side of the dominant hand, at the midpoint of the third metacarpal bone.

Reference scans were performed at the start of each session, during which participants held their right index finger in place at the chin. The purpose of this scan was to allow the creation of a rigid body transformation in Matlab, with the head device and chin location as the fixed components of a rigid body. When the IREDs at these locations are treated as a single rigid body, it is then possible to compare the hand's location to the head's location in three dimensions across entire trials. All movements were analyzed in this head-centered coordinate scheme, analogous to local coordinate schemes used for tongue movement from X-ray microbeam data during speech production, for example (cf. Westbury, 1994). While the forehead was the phonological location we examined, the chin was used as the zero value along each of the X, Y, and Z axes for all movements, because the data were collected as part of a larger study in which multiple target locations were examined. However, no special significance was assigned to the value zero in our analyses.

The head-centered coordinate scheme allows us to control for participants' gross adjustments in body location across the testing session, and to control for small modifications of head position during the execution of individual signs. Without this

[2] Though the multiple utterances of the same sequence of signs were collected as a single trial, no list effect was apparent, neither an overall rise nor an overall fall across successive tokens.

transformation to a head-centered coordinate scheme, if a signer, for example, began to slouch more over the course of a trial or session, the measure of sign location would be confounded. In addition, measuring all movements relative to the head makes our data more directly comparable to those of Lucas et al. (2002) or Schembri et al. (2009), who discuss lowered sign variants in terms of where they are located on the head or face.

Fig. 4. Head markers.

The IRED at the third metacarpal bone was used to represent the hand's location in the signing trials. Extensive piloting of the data collection procedure indicated that this IRED's position could be captured more reliably than the position of the IRED at the fingertip for the signs we are examining here.

Maxima in the trajectories along the vertical dimension were identified and taken to represent the vertical location of the sign WONDER. Fig. 5 shows the vertical position of the right hand for three tokens of WONDER BITTER WONDER at the normal signing speed, as produced by signer KM. The chin is used as the zero point for all measures of displacement and speed, so negative values on the vertical axis indicate that the hand marker is below the chin. At the beginning of the trial, her hand is resting in her lap, and so it is low on the vertical axis. Next, she raises her hand to a high position such that the index finger is in front of the forehead to produce the sign WONDER. Then she lowers it slightly for the sign BITTER, and she raises it again for the second production of WONDER before returning her hand to her lap. Because the sign WONDER includes a circular movement, there are often two vertical peaks for each production of the sign. The higher peak for each production was used as the measure of the sign's vertical location.

We estimated signing rate by examining the duration of each signed utterance. This duration was measured by finding the difference between the time of the first instance of WONDER and the second instance of WONDER in each utterance. Time points were taken at vertical maxima during each instance of the sign WONDER. The difference between the times of the vertical maxima corresponding to the location measurement during the first and second WONDER was taken to approximate the duration of the utterance.

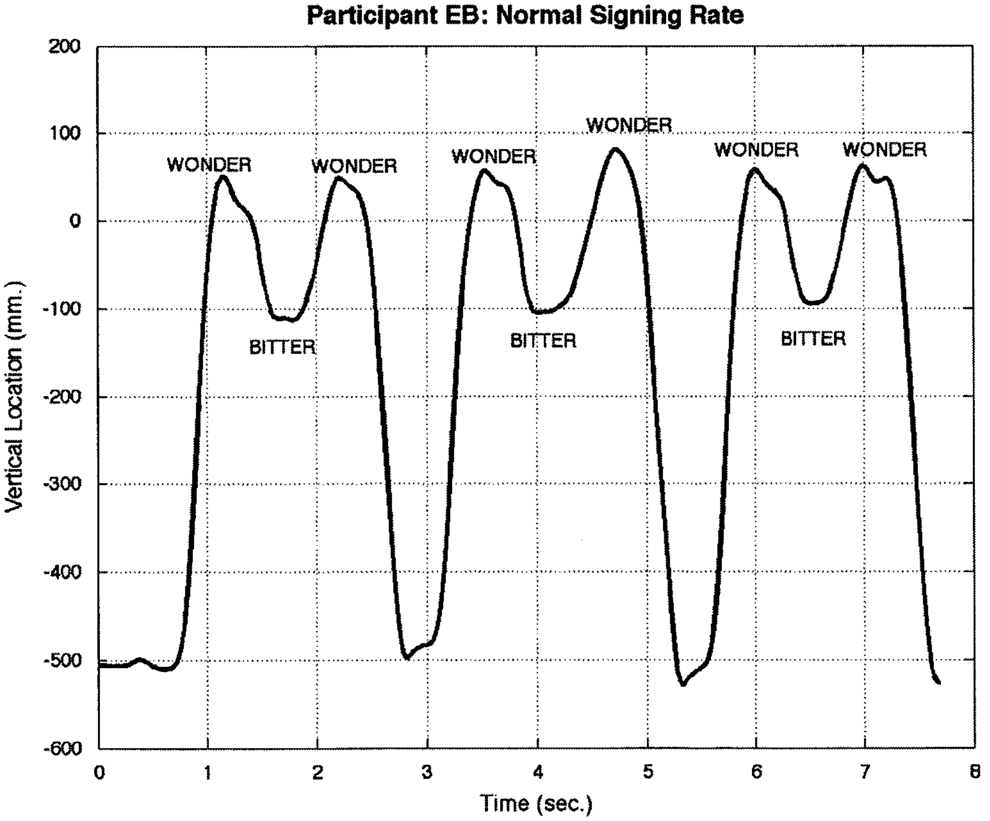

Fig. 5. Example of vertical displacement of the hand for three productions of the utterance: WONDER BITTER WONDER.

Table 1
Results of linear regressions: one for each combination of phonetic context and utterance position, comparing the vertical placement of the hand during the sign WONDER with the duration of the sequence of signs.

Phonetic context	Utterance position	Vertical placement mean (SD) in mm	Duration mean (SD) in ms	Regression equation	R^2
DP					
BITTER	Initial	73.4 (20.3)	927.8	$y=0.0461x+30.662$	0.5172
	Final	84.1 (11.1)	(316.42)	$y=-0.0001x+84.251$	0.00002
ME	Initial	73.0 (19.4)	866.1	$y=0.0364x+41.437$	0.7159
	Final	81.9 (18.1)	(451.5)	$y=0.0304x+55.555$	0.5762
DSM					
BITTER	Initial	−4.2 (51.7)	1054.0	$y=0.0829x-91.576$	0.8876
	Final	−2.0 (59.3)	(587.1)	$y=0.0796x-85.891$	0.6213
ME	Initial	7.4 (35.8)	1086.4	$y=0.0559x-53.354$	0.7697
	Final	34.8 (32.9)	(561.7)	$y=0.0443x-13.275$	0.5730
EB					
BITTER	Initial	64.3 (12.7)	1027.2	$y=0.0288x+34.693$	0.4378
	Final	68.3 (13.2)	(290.9)	$y=0.0317x+35.764$	0.4864
ME	Initial	64.0 (14.4)	1082.2	$y=0.0325x+28.823$	0.5037
	Final	66.9 (10.8)	(315.1)	$y=0.0158x+49.851$	0.2101
JP					
BITTER	Initial	−5.3 (47.1)	721.7	$y=0.2157x-160.98$	0.6756
	Final	−23.4 (41.4)	(179.6)	$y=0.1428x-126.42$	0.3828
ME	Initial	−0.4 (46.0)	767.8	$y=0.1394x-107.49$	0.6643
	Final	−5.6 (36.8)	(268.6)	$y=0.1115x-91.191$	0.6626
KM					
BITTER	Initial	1.9 (13.6)	851.1	$y=0.023x-17.654$	0.3092
	Final	5.3 (22.9)	(328.7)	$y=0.0385x-27.482$	0.3050
ME	Initial	−1.4 (23.0)	871.1	$y=0.0449x-40.505$	0.2311
	Final	−6.1 (22.6)	(245.8)	$y=0.0504x-49.971$	0.3000
RD					
BITTER	Initial	114.2 (21.7)	687.8	$y=0.0267x+95.765$	0.1086
	Final	96.8 (32.0)	(267.5)	$y=0.0323x+74.607$	0.0727
ME	Initial	107.2 (18.6)	603.3	$y=0.0642x+68.507$	0.5423
	Final	100.3 (25.3)	(213.1)	$y=0.0506x+69.758$	0.1819

Data were not pooled across the participants because the data patterned differently from one participant to the next, perhaps indicating different approaches to the experimental conditions (see Section 4.2). The statistical significance of the location measure of WONDER across the different conditions was determined via separate Multiple Linear Regressions for each participant with duration, phonetic context (adjacent to the chin-located sign BITTER or adjacent to the torso-located sign ME) and utterance position as independent variables and the vertical placement of the hand marker during the sign WONDER as the dependent variable (cf. Mauk, 2003). The independent variables as well as three two-way interaction terms and one three-way interaction term were entered into the statistical model in a stepwise fashion. Terms were included in the model if their contribution were significant at the $p=0.05$ level or better. Over the course of building the model, if the contribution of a variable already included lost significance beyond the $p=0.10$ level, the variable was removed from the model. Since stepwise multiple linear regressions may at times over-estimate the importance of one or more factors, multiple linear regression models where all terms were included were performed for each participant. For five of the signers, this new model provided no special added insight. However, for signer DP, the new model was substantially different from that produced by the stepwise model. After consideration, we chose to include the new model in our results in lieu of the stepwise model for signer DP. Both models had interpretable results, but the results of the non-stepwise model were more clear cut.

Table 2
Results of a series of multiple linear regressions, one for each participant, on the vertical placement of the hand during the sign WONDER.

Signer	Significance of model	Significant factors	
DP	$R^2=0.577$	Phonetic context	$t(1,112)=-2.647$, $p=0.009$
	$F(7, 112)=21.786$	Dur. × context	$t(1,112)=2.570$, $p=0.011$
	$p<0.001$	Cont. × utterance pos.	$t(1,112)=3.287$, $p=0.001$
		Dur. × cont. × pos.	$t(1,112)=-3.274$, $p=0.001$
DSM	$R^2=0.743$	Phonetic context	$t(1,107)=-1.938$, $p=0.055$
	$F(4, 107)=77.310$	Dur. × context	$t(1,107)=16.334$, $p<0.001$
	$p<0.001$	Utterance position	$t(1,107)=3.484$, $p=0.001$
		Cont. × utterance pos	$t(1,107)=-2.671$, $p=0.009$
EB	$R^2=0.415$	Duration	$t(1,117)=8.945$, $p<0.001$
	$F(2, 117)=41.506$	Cont. × utterance pos.	$t(1,117)=2.292$, $p=0.024$
	$p<0.001$		
JP	$R^2=0.585$	Duration	$t(1,117)=11.220$, $p<0.001$
	$F(2, 117)=82.500$	Dur. × utterance pos.	$t(1,117)=-2.651$, $p=0.009$
	$p<0.001$		
KM	$R^2=0.281$	Duration	$t(1,117)=6.388$, $p<0.001$
	$F(2, 117)=22.873$	Context	$t(1,117)=2.651$, $p=0.016$
	$p<0.001$		
RD	$R^2=0.200$	Duration	$t(1,117)=4.573$, $p<0.001$
	$F(1, 117)=14.653$	Utterance position	$t(1,117)=-2.896$, $p=0.005$
	$p<0.001$		

Table 3
Results of linear regressions, one for each participant, comparing the vertical placement of the hand during the sign WONDER with the duration of the sequence of signs.

Signer	Regression equation	R^2 value
EB	$y=0.0266x+37.837$	0.3888
KM	$y=0.0363x-31.335$	0.2444
RD	$y=0.0397x+78.977$	0.143

3. Results

Table 1 reports the regression analyses comparing the vertical location of the hands during the sign WONDER with signing rate represented by utterance duration.[3] Regression equations show a positive slope in all cases but one. A positive slope indicates that as signing rate increases (and duration decreases), the location of WONDER lowers in the signing space. In the one case of a negative

[3] For these data, one duration was measured for each pair of WONDER tokens, one in utterance-initial position and the other in utterance-final position. As a result, all other variables held constant, duration means matched with utterance-initial and utterance-final positions are identical. In the table, only one duration mean is reported for each set of utterance-initial and utterance-final data.

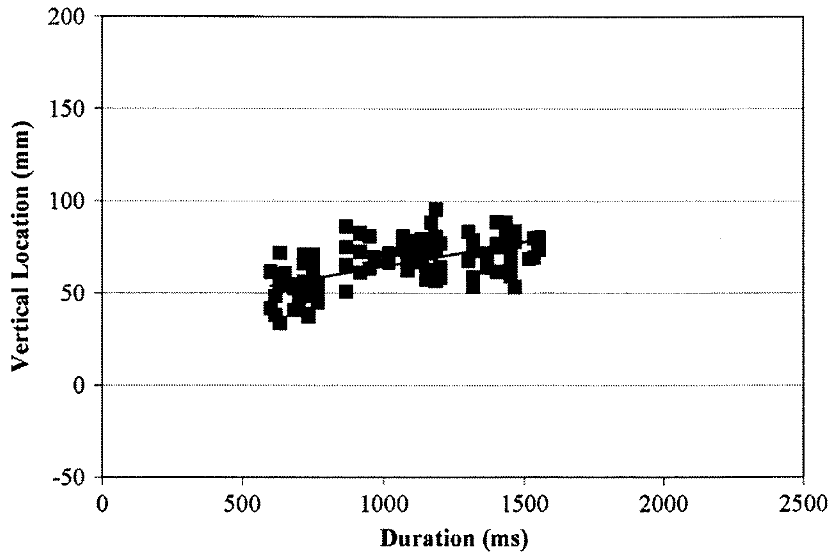

Fig. 6. Vertical placement for WONDER during the sequence WONDER ___ WONDER compared with the duration of the sequence for signer EB.

slope, that slope is almost zero, indicating no relationship between signing rate and location for that segment of the data.

When examining the results of the multiple linear regressions, the primary finding is that signing rate had a significant effect on the vertical position of the hands during the sign WONDER for all participants either as a main effect or through an interaction term. For each participant, the location of WONDER was significantly higher in slower signing than in faster signing. The specific details of these analyses are discussed in the following sections. Table 2 summarizes the final model for each signer.

3.1. *Effect of signing rate*

As described in Section 2, signing rate was quantified via a measure of duration between the two instances of WONDER in each utterance. This duration measure was found to be a significant predictor of the location measurement of WONDER for all signers. For three signers, EB, KM and RD, duration was significant only as a main effect without an interaction with one of the other variables. Table 3 lists the regression equations for the relationship between duration and location for each of the three signers. Fig. 6 is a scatter plot demonstrating this relationship for Signer EB. With this signer as with the others, as signing rate increased (and duration decreased), the location of the sign WONDER lowered.

For signer JP, the effect of duration was influenced by the position of WONDER within the sequence of signs (i.e. as the initial item in the sequence or the final item). Table 4 provides the regression equation for each utterance position. The slope of the regression line is steeper for WONDER in utterance-initial position than in utterance-final position, indicating that the effect of increased signing speed was stronger in the utterance-initial position rather than the utterance-final position. Fig. 7 shows that during slower signing, WONDER in utterance-initial position is higher than WONDER in utterance-final position, but as signing rate increases, WONDER in either utterance position lowers and the difference between WONDER in the two utterance positions disappears.

For signer DSM, the effect of duration on vertical location was affected by the phonetic context (adjacent to BITTER vs. adjacent to ME). As demonstrated by the regression equation in Table 5, the effect of increased signing rate was stronger in the BITTER context than in the ME context. The graph in Fig. 8 shows that the location values in slower signing are similar across the two contexts. As signing rate increases, WONDER in the BITTER context lowers to a greater degree than WONDER in the ME context. This result was unanticipated in that based on general principles of coarticulation, we expected that the effect of rate would be stronger when neighboring signs were farther apart (e.g. WONDER and ME) rather than closer together (e.g. WONDER and BITTER).

Table 4
Results of linear regressions, one for each participant and in each utterance position, comparing the vertical placement of the hand during the sign WONDER with the duration of the sequence of signs.

Signer	Utterance position	Regression equation	R^2 value
JP	Initial	$y=0.1624x-123.8$	0.6403
	Final	$y=0.1239x-106.77$	0.5009

The three-way interaction of duration, phonetic context and utterance position was significant for only one signer: DP. Regression equations are shown in Table 6 for each combination of phonetic context and utterance position, and the regressions are shown in Fig. 9. Notably the regression for WONDER in the BITTER context in utterance final position had a slope close to zero, indicating that the location of WONDER did not vary. The other three regressions are very similar.

3.2. *Effect of phonetic context*

The sign WONDER appeared in two phonetic contexts: one where it was adjacent to the sign BITTER, which is articulated at the chin, and another where it was adjacent to the sign ME, which is articulated at the chest. For only one signer, KM, phonetic context was included as a main effect without a related interaction term. Fig. 10 shows the mean values and standard deviations of the location of the sign WONDER in the two phonetic contexts.[4] In this case, the sign WONDER is lower in the context of the sign ME than in the context of the sign BITTER. The difference in the means is quite small, however, only approximately 7 mm.

[4] Standard deviations in Figs. 10–12 reflect not only variation related to phonetic context, but also variation related to signing rate.

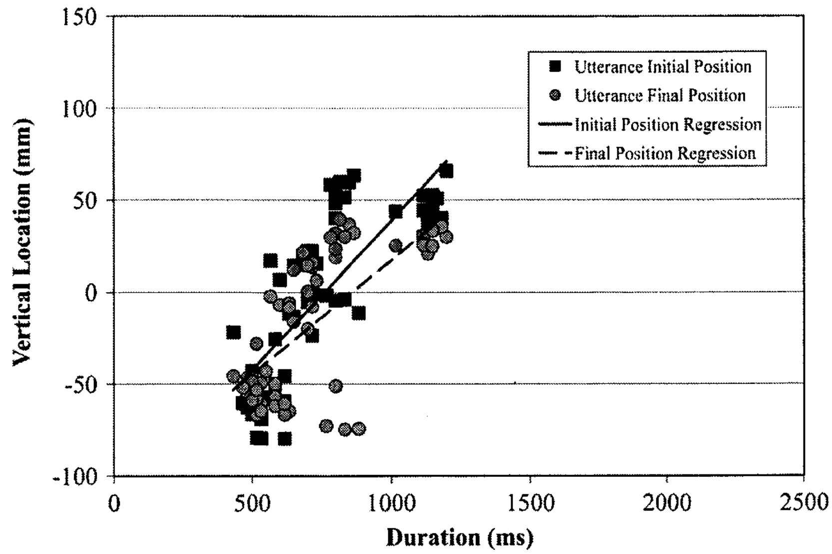

Fig. 7. Vertical placement for WONDER during the utterance WONDER ___ WONDER compared with the duration of the sequence for signer JP. The data are separated by utterance position and regression lines are shown for each.

Table 5
Results of linear regressions for signer DSM, one for each phonetic context, comparing the vertical placement of the hand during the sign WONDER with the duration of the sequence of signs.

Signer	Phonetic context	Regression equation	R^2 value
DSM	BITTER	$y=0.0812x-88.734$	0.7358
	ME	$y=0.0501x-33.314$	0.5755

For three signers, the effect of context interacted with another independent variable. The interactions between phonetic context and duration for signers DSM and DP are discussed above in Section 3.1. In the data for signers DSM and EB phonetic context interacted with utterance position. In utterance-final position data for DSM, the sign WONDER was around 37 mm higher in the ME context than in the BITTER context (see Fig. 11). Further, in the ME context, WONDER in utterance-final position was higher than in utterance-initial position by around 28 mm. Though the interaction of phonetic context and utterance position was significant for signer EB, no difference in means across these categories was apparent.

3.3. *Effect of utterance position*

While we did not have any specific predictions, we did anticipate that the utterance position of the sign WONDER within the sequence of signs might have an effect on its location value. In the sections above we have already seen that utterance position had a significant interaction with signing rate (Section 3.1) and phonetic context (Section 3.2). One additional signer, RD, showed a main effect for utterance position without an associated interaction term. For RD, WONDER in utterance-initial position was around 12 mm higher than in utterance-final position as shown in Fig. 12.

3.4. *Summary of results*

Lowering of the sign WONDER was evident through comparisons of different signing rates with the sign relatively high at slower speeds and lower at faster signing speeds. For only two signers was signing rate a relevant factor without an associated interaction with one or both of the other independent variables. However, it was never the case that the sign WONDER rose as signing rate increased.

For three signers, phonetic context was relevant to their productions of WONDER. For one signer, KM, instances of WONDER were produced higher in the signing space when adjacent to the chin-located sign BITTER than when adjacent to the torso-located sign ME, regardless of the rate of signing. Fundamentals of coarticulation led us to anticipate that this would be the typical result. For signer DP, the statistical model revealed a complex interaction of all three independent variables. WONDER for DP lowered with increased signing rate in the ME context for both utterance positions, and lowered with increased signing rate in the BITTER context, but only in the utterance-initial position. Finally, one signer showed a pattern that was unexpected. Signer DSM showed significant interactions between phonetic context and utterance position as well as between phonetic context and signing rate. WONDER was higher when adjacent to a torso-located sign than when adjacent to a chin-location sign, though only in utterance-final positions and only at a relatively slow signing rate.

Utterance position was also a significant factor for three signers. For signer RD, the sign WONDER in utterance-initial position was higher than in utterance-final position. Signer JP's data showed a similar pattern, though the difference between the two utterance positions was lost as signing rate increased. However, for signer DSM, WONDER was higher in utterance-final position than in utterance-initial position, but only in the context of the torso-located sign, not in the context of the chin-located sign. In sum, two signers showed a preference for the initial sign to be higher than the final sign and one signer showed a preference for the reverse.

4. Discussion

This study has explored sign lowering as a form of phonetic reduction—that is to say, modification of the phonetic form of a word that occurs in the normal process of language production, as an effect of factors such as phonetic context, production rate, and utterance position. As this study and previous studies have demonstrated, phonetic reduction occurs in the sign as well as

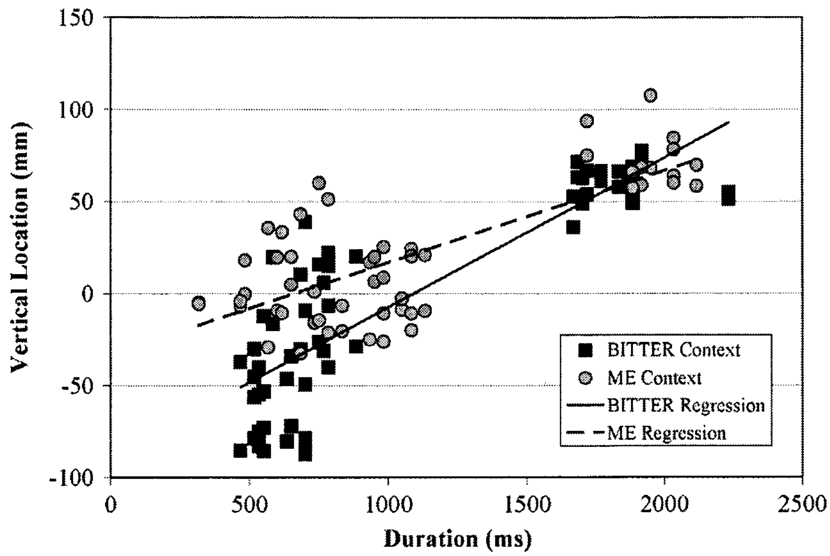

Fig. 8. Vertical placement for WONDER during the sequence WONDER ___ WONDER compared with the duration of the sequence for signer DSM. The data are separated by phonetic context and regression lines are shown for each.

Table 6
Results of linear regressions for signer DP, one for each combination of phonetic context and utterance position, comparing the vertical placement of the hand during the sign WONDER with the duration of the sequence of signs.

Signer	Phonetic context	Utterance position	Regression equation	R^2 value
DP	BITTER	Initial	$y=0.0461x+30.662$	0.5172
	ME	Final	$y=-0.0001x+84.251$	0.00002
		Initial	$y=0.0364x+41.437$	0.7159
		Final	$y=0.0304x+55.555$	0.5762

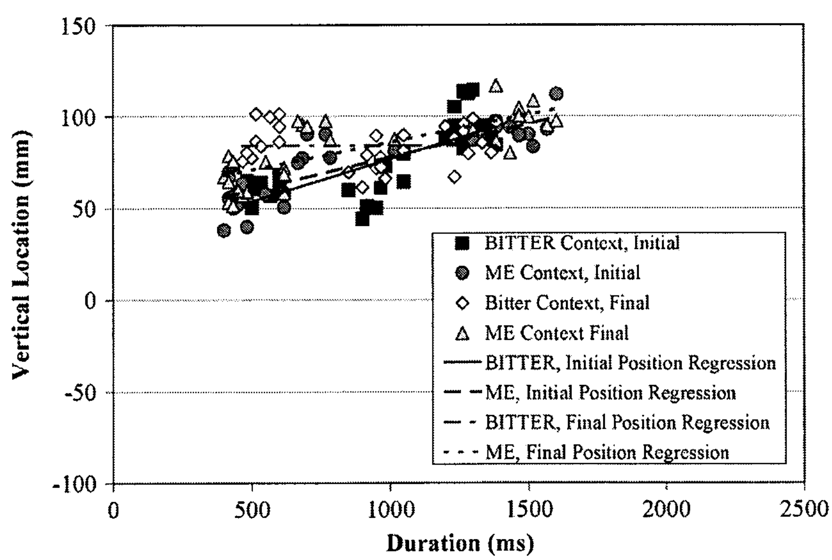

Fig. 9. Vertical placement for WONDER during the sequence WONDER ___ WONDER compared with the duration of the sequence for signer DP. The data are separated by phonetic context and utterance position and regression lines are shown for each combination.

the speech modality. Moreover, phonetic reduction in the sign modality is affected by many of the same phonetic factors that affect reduction in articulatory speech gestures (cf. Flege, 1988; Recasens, 2004; Shaiman, 2001). This finding is relevant to previous studies of sign language, which have examined the lowering of high signs primarily as an effect of grammatical and sociolinguistic factors (Lucas et al., 2002; Schembri et al., 2009). The focus of this study was on signs that are high in the signing space, so our prediction was that reduction of these signs would primarily take the form of a vertical shift downward. Future studies might examine phonetic reduction of signs along other spatial dimensions.

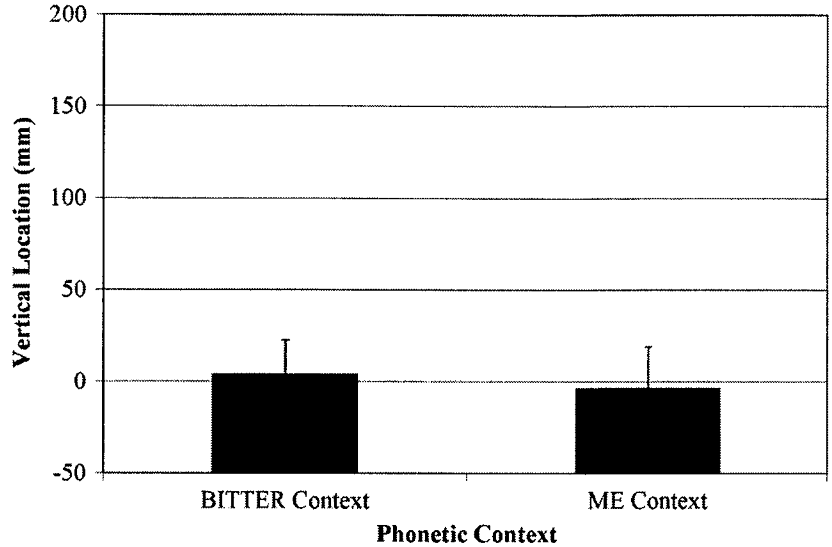

Fig. 10. Mean vertical locations for WONDER for signer KM for each phonetic context.

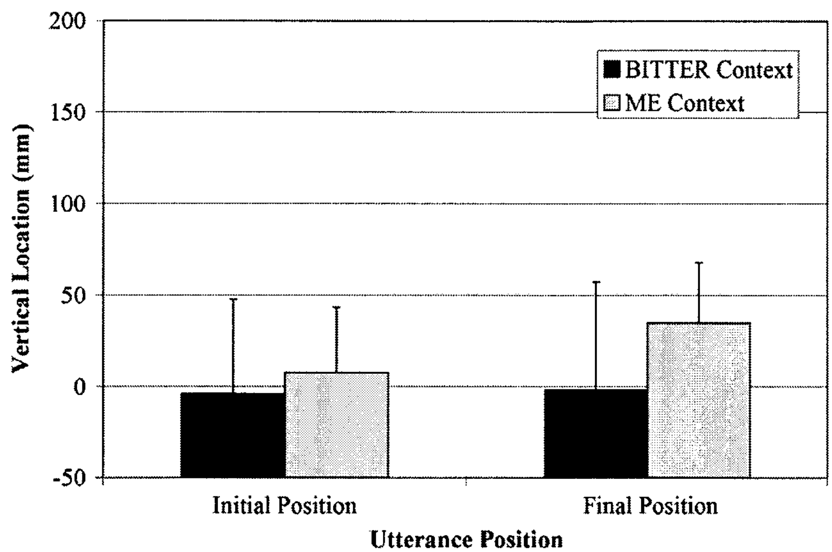

Fig. 11. Mean vertical locations for WONDER for signer DSM for each phonetic context and utterance position.

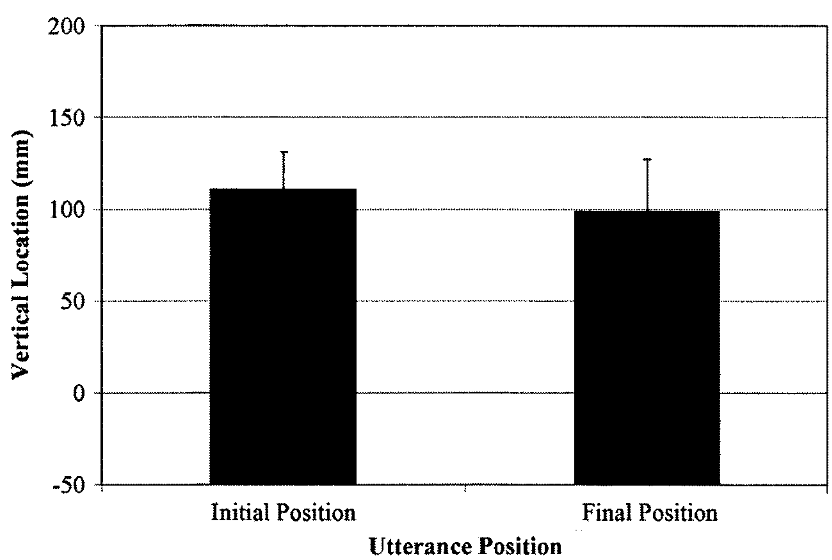

Fig. 12. Mean vertical locations for WONDER for signer RD for each utterance position.

4.1. Signing rate

The primary finding of this study is that signing rate had a significant effect on the vertical position of the hands during the sign WONDER for all participants, as we had predicted. Having to sign at a faster rate places demands on the production system, such that signers will either sacrifice accuracy in their movements or reduce the size of the movements in order to produce the sign in a shorter time period. All of the signers we tested reduced the size of their movements. While phonetic reduction occurs in speech and sign as an effect of increased production rate (Lindblom, 1963; Mauk, 2003; Shaiman, 2001), research on non-linguistic limb movement also suggests that increased movement speed can cause individuals to overshoot a movement target (Adamovich, Berkinblit, Fookson, & Poizner, 1999). It will be interesting to see whether the results from this study and future studies are more consistent with the research on speech or with the research on limb movement. In addition, it would be informative to explore signing rate further to determine its effects on signs at other locations.

4.2. Phonetic context

Our findings with respect to phonetic context were somewhat surprising. For three signers, phonetic context was relevant to their productions of WONDER, but only one signer, KM, had productions that were lowered as an effect of phonetic context, independent of signing rate. Two other signers showed an effect of phonetic context which interacted with other phonetic variables. For one of these two (DSM) the effect of phonetic context was the opposite of what we had predicted – i.e. her productions of WONDER were lower in the higher of the two phonetic contexts – when there was an effect at all, which was seldom.

Articulatory studies of speech production have also found interactions between phonetic context and other factors (Recasens, 2004). More research is called for to better understand the effects of phonetic context in relation to other phonetic factors for sign production. It is also worth examining possible dissimilatory effects in sign production. There may be phonetic or other reasons why two signs would become more distinct rather than similar when they are adjacent to each other.

Perhaps the limited effect of phonetic context in our data should not be too surprising, given the high inter-participant variability that has been documented in the movement kinematics of speech (Mooshammer & Geng, 2008; Shaiman, 2001). It could be that the variation seen here is an effect of low-level biomechanical factors that have no bearing on the invariant aspects of sign structure. More research is necessary to explore this possibility.

4.3. Utterance position

Little is known about the effects of utterance position on a sign's phonetic realization. For this reason, while it was anticipated that utterance position might have an effect on sign location, it was unclear what that effect would be. Indeed, the effects of utterance position were somewhat varied across signers and across phonetic contexts.

There are potentially two phonetic sources of an utterance position effect in the experimental design that we used. For each production, the signer returned her hands to her lap at the end of each utterance. It may be that movement to this position caused the hands to move downwards, and further, that the effect was stronger when the rest position at the lap preceded the sign than when it followed the sign. In other words, it may be that the magnitude of the coarticulatory effects of an adjacent hand position differs according to whether the coarticulatory pressure precedes or follows the target sign. If this is the case, it should be possible to test this effect empirically to determine whether the enhanced effect of a preceding low location holds true for other signs and for other sign contexts. The other possibility is that utterance position had an effect for the utterances that we tested because signers can use the phonetic location of a sign to mark linguistic boundaries in normal production. If this is the case, then it should be possible to identify similar cases of lowering for other signs and in more naturalistic data.

It is not clear that the utterance position effect for these sign data is analogous to f0 declination or declination of articulatory gestures in speech (Cooper & Sorensen, 1981; Vayra & Fowler, 1992), particularly in light of the fact that the direction of the effect was not consistent across the signers who showed it. In other words, while the sign WONDER was lowered in utterance-final position for two signers, it was raised in utterance-final position for another signer. Along similar lines, it is unclear how the different signers parsed the utterances and what effect this might have had. Moreover, three of the six signers discussed here did not show an effect for utterance position in either direction.

4.4. Sign production, speech acoustics, and motor control

While it is potentially informative to compare reduction in signed language to both acoustic reduction and articulatory reduction in speech, it is important to exercise caution in drawing direct parallels between speech acoustics and sign kinematics. It is not clear that the acoustic space for speech and the articulatory space for sign would scale similarly. There are crucial differences between the physical signals being analyzed in the two cases (i.e. sound waves vs. movement kinematics), as well as differences between the physiology of the articulators themselves. For example, there is no obvious reason to believe that sign structure is affected by respiration cycles or by a vibration source internal to the body. Moreover, for non-linguistic limb movements, many factors, such as movement speed, target size, and movement direction with respect to gravity can influence the occurrence and extent of target undershoot and overshoot (Adamovich et al., 1999; Lyons, Hansen, Hurding, & Elliott, 2006).

While comparing sign kinematics to speech acoustics is potentially problematic, comparing sign production to non-linguistic limb movement tasks can be problematic as well. In a variety of ways, sign production is unlike the movement tasks that are typically examined in motor control research. Crucially, the movement targets in sign production, like in speech, are somewhat flexible, while the targets in typical movement tasks such as pointing or reaching are more rigidly defined. If a participant in a motor control experiment undershoots a target, their movement is classified as a type of error (see, for example, Chieffi, Conson, & Carlomagno, 2004), but articulatory undershoot is a common occurrence in conversational or fast signing (Lucas et al., 2002; Mauk, 2003). Similarly, sign production is an everyday behavior for the participants in our experiment, while complex or kinesthetically-defined movements in a motor control experiment typically have to be practiced and learned by research participants. Thus non-linguistic movement tasks tend to be very simple (e.g. grasping an object), novel (e.g. pointing to a specific sequence of external targets), or both (e.g. reaching to a specific kinesthetically-defined target). Two exceptions to this tendency are the studies on typing and handwriting (Contreras-Vidal, Teulings, & Stelmach, 1998; Rabin & Gordon, 2004)—tasks which, unlike signing, require interaction with an external object that provides tactile feedback. So while this and other studies of sign phonetics are informed by research on both speech production and non-linguistic limb movement, it is important to recognize the limitations of the comparisons to either of those two fields.

5. Conclusions

This study makes an important contribution to the field of sign language research by focusing on the precise phonetic details of normal linguistic variation. Past research has attributed phonetic reduction in the form of sign lowering to multiple factors (Liddell & Johnson, 1989; Lucas et al., 2002; Schembri et al., 2009). However, patterns of phonetic modifications emerged in this study, which were not obvious from past research. The findings from this study are only obtainable because of the development of precise methods for data capture. The use of optoelectronic motion capture systems to collect sign data allows us to capture and analyze sign data in spatial and temporal detail, and as a three-dimensional signal. At the same time, standard video is undoubtedly more useful for exploring broad research questions or examining phenomena that are sociolinguistic in nature. While motion capture is somewhat limited in terms of breadth and versatility, we feel that its advantages provide a useful complement to the more established research methods used in fields such as sociolinguistics and pragmatics.

Our research and past research suggest new areas of sign phonetics to be explored. It would be interesting to examine sign lowering as an effect of the frequency of occurrence of a sign. We did not control for the frequency of the signs that were elicited for this study, but there is evidence suggesting that high frequency signs are more likely to be phonetically reduced (Schembri et al., 2009). As databases of ASL corpora become more numerous and accessible, it should become easier to analyze phonetic reduction and sign lowering as an effect of a sign's frequency of occurrence in the language.

While this study focused on the lowering of the hand's position for forehead-located signs as a type of phonetic reduction, other forms of reduction were observed but not examined quantitatively. One readily observable aspect of phonetic reduction was the adjustment that signers made to posture or trunk position to facilitate sign production. In addition to the hand being lowered, the body was also often moved forward as a body- or head-located sign was articulated. Up until now, sign production has been viewed primarily in terms of how the hands and arms move. It would be interesting to measure the extent to which sign production is accomplished by adjusting the body's position as opposed to manipulating the hand's position. Future studies could optimize their data collection procedures and set-up to investigate this question specifically.

The kind of information obtained from this study will help us to understand in more precise detail how signs are produced. One striking aspect of this research has been the amount of individual variation we have found in the articulation of signs. This is of interest because identifying forms of normal phonetic variation among signers allows us to begin to identify and describe phenomena such as suprasegmentals, cross-linguistic variation, and individual production differences analogous to accent or voice quality in speech.

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