HHS Public Access
Author manuscript
Lab Phonol. Author manuscript; available in PMC 2015 July 02.

Published in final edited form as:
Lab Phonol. 2012 October 1; 3(2): 425–453. doi:10.1515/lp-2012-0019.

Phonetic reduction and variation in American Sign Language: A quantitative study of sign lowering

MARTHA E. TYRONE[*] and **CLAUDE E. MAUK**[**]

[*]Haskins Laboratories, Long Island University

[**]University of Pittsburgh

Abstract

During normal sign language use, a signer's productions will often be reduced from the citation forms of signs. This study examines a form of phonetic reduction in American Sign Language, in which signs that are located at the forehead are lowered in space. In particular, we explore the effects of signing rate and phonetic environment on the lowering of specific ASL signs and on their phonetic variation along the other two movement axes. Movement data were captured as native signers produced utterances that were controlled for phonetic environment and signing rate. We found that all signers produced lowered forms as an effect of the phonetic factors that we manipulated. In addition, several rate-induced effects occurred, which we had not predicted. Results are discussed in relation to past research on variation in sign production and in speech.

1. Introduction

American Sign Language (ASL) is the language used by Deaf communities in the United States and Canada. Research has shown that ASL is organized similarly to spoken languages, in that it has semantic, syntactic, morphological, and phonological structure (Klima and Bellugi 1979; Sandler and Lillo-Martin 2006). This study examines the phonetic structure of ASL, in light of past findings from spoken and signed language research.

The terms phonology and phonetics emerged in the context of research on spoken language; however, neither term is currently used to refer exclusively to acoustic information. Thus, the terms can be applied to sign language research to describe the sign modality's analogs of the phonological and phonetic aspects of spoken languages. Phonetics is the study of the physical transmission of language through a set of articulators. Therefore, sign language phonetics is the study of the physical transmission of language through the manual-visual channel by the movement of the arms, hands, fingers, and body.

The phonological system expresses the parameters by which one sign, or word, can (minimally) differ from another. Certain differences in the phonetic instantiation of a sign can result in changes in meaning, i.e., produce a new sign, similar to how some changes in pronunciation in spoken languages can produce a new word. The basic phonological parameters of signs are handshape, movement, and location (Stokoe 1960). Handshape

Correspondence tyrone@haskins.yale.edu.

describes the configuration of the hand(s) as a sign is produced. The signs FATHER (Figure 1) and KNOW (Figure 2) are differentiated by handshape. Movement describes how the sign articulators are moved as a sign is produced: the signs FAVORITE (Figure 3) and LUCKY (Figure 4) are differentiated by movement. Finally, location describes where a sign is located on the body or in space. The signs FATHER (Figure 1) and FINE (Figure 5) are differentiated by location.

Stokoe (1960) identified 12 contrastive locations in ASL, including multiple distinct locations on the face. While the location parameter describes where a sign is produced, the hand does not necessarily have to contact the body in order to be associated with a specific body location. In the example of FATHER above, the hand makes contact with the forehead, which is the sign's location. However, the sign WONDER (Figure 6) is also located at the forehead, even though the hand does not make contact with the forehead during production of the sign. Moreover, two signs with the same phonological location may use different parts of the hand to make contact with the body at that location. For example, for the sign FATHER (Figure 1), it is the tip of the thumb that makes contact with the forehead; while for the sign KNOW (Figure 2), the four fingers are bent and some of the fingertips make contact with the forehead.

Even for the same sign, the phonetic realization of location is varied (Lucas, Bayley, Rose, and Wulf 2002), but this phenomenon has not been measured precisely or in controlled conditions. One of the long-term goals of the current study is to better illuminate what information is consistent across productions of the same sign, which enables linguistic communication in the sign modality.

1.1. Phonetic reduction

Phonetic reduction has been described in the speech modality, but not explored in depth in the sign modality. For speech, a production can be classified as reduced if movements of the articulators are substantially smaller, or if the acoustic correlates of these movements fall short of their target values (Moon and Lindblom 1994; Mooshammer and Geng 2008). Reduction can occur as an effect of production rate: speaking quickly can cause articulatory movements to decrease in amplitude (Kuehn and Moll 1976; Kelso, Vatikiotis-Bateson, Saltzman, and Kay 1985). Reduction can occur as an effect of phonetic environment; for example, several consonants in English and Spanish undergo reduction when they are produced between two vowels (e.g., / b/ as [β]) (Goldstein 1992; Lavoie 2001; Romero Gallego 2001). In a similar way, reduction can occur as an effect of a lexical item's frequency: words that are very high frequency (such as 'can' or 'of' or 'don't' in English) tend to be pronounced less clearly than words that are lower in frequency (Bybee and Scheibman 1999; Bybee 2002).

As with speech, a reduction in movement amplitude or duration could constitute phonetic reduction in sign production. More specifically, a sign could be considered reduced if the hand falls short of making contact with a location on the body, if repetitions of a cyclic sign movement are deleted, or if movement displacements are smaller along any of the axes of movement.

Cheek (2001) studied coarticulation of ASL handshapes, finding that the form of a handshape can be influenced by the preceding or following handshape. Mauk (2003) examined the underachievement of articulatory targets (undershoot) in ASL as an effect of phonetic environment and signing rate. In the speech modality, a large proportion of the research on undershoot has focused on vowels (e.g., Lindblom 1963; Mooshammer and Geng 2008). Mauk (2003) applied methodologies used to study vowel undershoot to the sign modality and found that as ASL signers sign more quickly, both handshapes and locations may be undershot and that the degree of undershoot increased as signing speed increased. That study suggested that signs requiring contact with the head may be less likely to be lowered. Recently, Grosvald (2009) investigated the production of English schwa vowels and ASL signs located in neutral space at a range of distances from another segment that might cause the vowel’s formant frequencies or the hand’s position to shift. He found clear long-distance effects in the acoustic speech data but weaker effects in the positional sign data.

1.2. Lowering of forehead signs

While a sign may be reduced in different ways (e.g., loss of contact with the body, smaller number of cycles in a cyclic sign movement, or smaller movement displacements), the primary motivation for this study was the observation that some ASL signs that are located at the forehead can also be produced at lower locations, such as the cheek or the jaw. Studies on both ASL and Australian sign language (Auslan) suggest that signs located at the forehead are often lowered in conversational contexts (Lucas et al. 2002; Schembri, McKee, McKee, Pivac, Johnston, and Goswell 2009), perhaps as an effect of phonetic environment (Liddell and Johnson 1989; Johnston 1989). Several studies have documented the lowering of forehead-located signs, but no study has identified or discussed any other type of reduction of those signs (e.g., shifting signs toward the midline of the body).

Lucas et al. (2002) report that there is a class of ASL signs articulated with contact at the forehead that can move down to make contact with the cheek. For example, the sign KNOW (Figure 2) makes contact at the forehead in citation form, but it is often lowered to make contact at the cheek in fluent signing. Lucas and her colleagues found that a high location for the preceding sign tended to inhibit lowering, and that the single strongest predictor of sign lowering was the sign’s grammatical category. However, in that study, the sign’s phonetic environment was not explicitly controlled, and phonetic location was not measured quantitatively. Recent research suggests that ASL signs that are articulated in front of the forehead but do not make contact can also shift downward in the signing space. For example, the sign WONDER (Figure 6) is located at the forehead in citation form, but it is sometimes lowered as an effect of signing rate or phonetic environment (Tyrone and Mauk 2010).

Schembri et al. (2009) conducted a study of the lowering of forehead-located signs in Auslan and in New Zealand Sign Language. In analyzing the pattern of lowering in their data, they examined linguistic factors such as grammatical category, lexical frequency, phonetic environment, and proximity to a pause or utterance boundary. In addition, they examined factors such as age, gender, region, and social class. The researchers found a higher occurrence of lowering for the high-frequency verbs than for the other categories of high-frequency signs. Similarly, a recent corpus-based study by Russell et al. (2011) examined the lowering of ASL signs which have phonological locations on the head and chin. They assessed the phonetic realization of signs at these locations (corrected for head position and normalized across signers) and found that verbs were lowered to a greater extent than nouns.

While these studies have reported on specific forehead-located signs that are lowered, there are no comprehensive data indicating which ASL signs are lowered and which are not lowered. Moreover, there is a limited amount of information available on the frequency with which different signs occur in ASL. Morford and MacFarlane (2003) carried out an analysis of the frequency characteristics of a corpus of 4,111 spontaneously-produced ASL signs. Their resulting database is useful, but it provides substantially more information about high-frequency signs than about low-frequency signs. Given the preliminary nature of research on sign lowering in ASL, it is difficult to make predictions about which signs are likely to be lowered. Our prediction in the current study is that signs that have previously been reported to lower or that have widespread anecdotal evidence of lowering will be the signs that will tend to be lowered.

2. Methods

2.1. Participants

The data presented here are from four adult signers: one male and three female. All are from signing Deaf families in Connecticut, and all are active members of the Deaf community. All the participants are right-handed, and none has any known neurological or communication disorder. ASL is the primary language for all participants, and it is also the language that was used by the investigators and participants during data collection. All the research procedures are in compliance with the standards for human participant research outlined by the U.S. Public Health Service and were approved by the Human Investigation Committee at the Yale Medical School.

2.2. Target signs

The target signs for this quantitative study consist of a small sample of four ASL signs located at the forehead. Two are likely to lower, and two, which are structurally similar, are not. The target signs that have been reported to lower in casual signing are KNOW (Figure 2) and WHY (Figure 7) (Lucas et al. 2002). The target signs that have not been reported to lower are FATHER (Figure 1) and STUBBORN (Figure 8). For three of these signs (KNOW, FATHER, and STUBBORN), the hand typically makes contact with the forehead, and for the remaining sign, WHY, it typically does not. At the outset of the study, two native Deaf signers were consulted, and their intuition was that the ASL signs KNOW and WHY were likely to be lowered, and the signs FATHER and STUBBORN were less likely to be lowered in conversation.

The target signs were embedded in naturalistic phrases, which were developed in consultation with two Deaf ASL signers. The two phrases were designed to be as similar as possible, except that one would yield a phonetic environment with a high location and the other would yield a phonetic environment with a low location. In order to create this minimal contrast, we set up linguistic referents in the experimental space and asked participants to point to these referents in the context of the carrier phrases. Specifically, we placed two posters on the wall facing the participants, slightly to the participants' left. One poster was high on the wall and the other was low on the wall. Both posters depicted a person producing a sign, in the style of a sign language dictionary entry. The resulting carrier phrases were: PICTURE (point high) _____SEE?, and PICTURE (point low) _____RIGHT? These can be roughly translated into English as "That's a picture of the sign _____. Do you see?", and "That's a picture of the sign _____. Is that right?" For the ASL sign SEE, the index and middle fingers are extended, and the hand moves forward, beginning from a position at the level of the eyes. For the ASL sign RIGHT, both hands have extended index fingers with the remaining fingers closed in a fist. The non-dominant hand is held in front of the mid-torso, and the dominant hand moves down to make contact with it. As a result, in the two carrier phrases, participants produced target signs that were embedded between two high spatial locations or between two low ones. (While the referential "point" in the phrase might be more accurately described as a gesture than as a lexical sign, we chose the two phrases because of their naturalness and structural comparability. Further, we can make no straightforward prediction about how the kinematics of sign and gesture might differ.)

2.3. Procedure

Sign movements were recorded with an Optotrak Certus motion capture system. Infrared light-emitting markers were attached to participants' sign articulators and tracked by a three-camera unit at a sampling rate of 60 Hz. Six markers were attached to a device that was placed on the head (Figure 9), which made it possible to track the head's movements in three dimensions and to compare its location to the location of the hand. Two markers were attached to the dominant hand: on the ulnar side of the hand, just below the metacarpophalangeal joint, and on the dorsal side of the hand, at the midpoint of the third metacarpal bone. After the Optotrak markers were put in place but before data collection began, signers were asked to practice the target phrases. This gave signers time to get used to signing while wearing the markers and the head-mounted device.

Signers were asked to produce the target phrases at three signing speeds: normal conversational speed, faster than normal, and as fast as possible. They set their own pace based on these instructions and were not coached more specifically on how fast they should sign. Signers produced 15 tokens of each phrase for each of the signing speeds, and these 15 productions were collected as a single data trial. Recording sessions were videotaped as well as being recorded with Optotrak, so that coders could identify any anomalies in sign production. (For example, during one trial a signer coughed and said "Excuse me" in ASL.) For each trial, the first phrase was excluded from analysis, because it tended to be produced substantially more clearly than later phrases. Similarly, the final phrase or final two phrases in a trial were often substantially reduced. We excluded productions in which markers were occluded. For these reasons, only the first 10 unoccluded phrases that immediately followed the first phrase were analyzed for each signing speed category. (In a small number of cases, there were fewer than 10 unoccluded and error-free productions.) Thus, roughly 60 productions of each sign were analyzed for each signer.

2.4. Location measure

The ulnar side of the hand was selected as the point of measurement for the hand, because pilot data suggested that it was more reliably captured across signs than other sites on the hand or fingers. Positional data from the Optotrak markers were filtered using a low-pass Butterworth filter with a cutoff frequency of 6 Hz.

A transformation of the markers' positions from a camera-oriented reference scheme to a head-oriented reference scheme was necessary because the hand's location relative to the camera is a poor index of how well the hand approximates the forehead location. For this reason, reference data were collected to allow for the creation of a rigid body transformation in Matlab, with the markers on the head device acting as the rigid body components. When the markers on the head are treated as a three-dimensional rigid body, it is possible to compare the hand's location to the position, rotation, and translation of the head-centered coordinate scheme across an entire trial, and the axes of reference themselves change as the head's pitch, roll, and yaw change. All movements were analyzed in this head-centered coordinate scheme, which is similar to the types of local coordinate schemes that are used for measuring tongue movement during speech production (cf. Westbury 1994).

One of the markers on the head device, specifically, the lowest marker on the signer's right side, was used as the origin point for the three axes in the new coordinate scheme. No special significance was assigned to the value zero (i.e., the origin point) in our analyses; in other words, the origin point is not meant to represent the target location for any of the forehead-located signs that were examined. In this new coordinate scheme, the x-axis was lateral, the y-axis was vertical, and the z-axis was horizontal relative to the head. Thus, the x-y plane was coronal, and the y-z plane was sagittal.

Because the axes of the head-centered coordinate scheme move in three dimensions as the head moves, we can control for small changes in a participant's head position during individual signs and for gradual changes in body location or posture throughout the testing session. Without this coordinate transformation, 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.

For each target sign, local positional maxima or minima were used as the phonetic location of the sign. These positional landmarks were matched to local 3D tangential velocity minima, to ensure that the sign's movement endpoint was what was represented (Figures 10 and 11). Moreover, matching positional maxima/minima to velocity minima improves the spatial accuracy of the location measures. (Data in Figures 10 and 11 are presented in mm and mm/ms because we felt these units were the easiest to conceptualize with respect to hand and arm movement.)

Signing rate was estimated indirectly, based on the duration of a fixed portion of the phrase. In particular, we measured the duration from a horizontal minimum preceding the target sign to another horizontal minimum following the sign (Figure 12). Each measurement was coded for phonetic environment (High, Low) and analyzed with respect to rate.

2.5. Statistical analyses

Location values during normal rate productions were compared across the two phonetic environments using one-way ANOVAs with x-, y- and z-axis values as dependent variables and environment as the independent variable. Separate ANOVAs were conducted for each signer, each sign, and each axis. In addition, location values were compared with corresponding duration values for productions from all signing rates to see if significant relationships exist between the two. Separate regressions were generated for each sign in each phonetic environment along each axis. Data were not pooled across signers. Regressions were compared across phonetic environments for each sign via paired *t*-tests to determine if the difference in environment (high vs. low) was significant.

3. Results

The first analysis performed on the data was to determine if the phonetic environment had an effect on the articulation of the test signs regardless of a possible signing rate effect. Subsequent analyses examined the effect of signing rate and phonetic environment combined on the production of forehead-located target signs. These two analyses are considered separately.

3.1. Effect of phonetic environment

Data from the normal signing condition (i.e., before signers were asked to increase their signing rate) were analyzed to see if the forehead signs had a higher position in one carrier phrase than in the other. One-way ANOVAs were conducted with location of the hand marker as the dependent variable and phonetic environment (high or low) as the independent variable. Separate ANOVAs were conducted for position along each of the three axes, for each sign and for each signer. The results of these ANOVAs are reported in Table 1 and discussed below. (Whenever multiple analyses are conducted, the possibility of type 2 errors increases. In this set of analyses, 42 separate ANOVAs were conducted, so we would estimate that around two false positives may be present in the data presented in Table 1.)

For two signs, KNOW and STUBBORN, data are presented for only three signers, because there were marker occlusions which prevented the collection of sufficient data for one signer in each case (RD and MF, respectively).

There were 14 comparisons of the effects of phonetic environment on the dominant hand's position along the vertical axis. In 7 cases, the hand was significantly lower in the low environment. However, in 2 cases the hand was significantly higher in the low environment; both these instances involved the target sign FATHER.

3.1.1. Phonetic environment effects by sign—Signer VF produced the sign KNOW at a 40 mm lower position in the low environment than in the high environment at the normal signing rate (Table 1). In this case, there may have been coarticulation of the forehead-located target sign and the low carrier phrase. For the other two signers, the difference in the vertical position of the sign as an effect of environment alone was not significant. At the normal signing rate, KNOW was articulated more to the right in the low environment than in the high environment for two signers: MF (by 15 mm) and VF (by 42 mm). The same two signers also produced KNOW with the hand in a slightly more forward position in the same condition (by 5 mm and 8 mm, respectively). There was no significant variation on the lateral or horizontal axis for the third signer, LL.

The sign FATHER was sometimes produced at a lower position when it occurred in the low environment, but contrary to our expectations, there were cases in which it had a higher position when produced in the low environment. FATHER is the only sign that displayed an unexpected result on the vertical axis, but the differences were fairly small in those cases (10 mm). No consistent pattern was observed in this sign's position on the other axes.

There were only relatively small differences in the vertical position of the sign WHY as an effect of phonetic environment alone, and these were significant for two signers (LL and MF). In addition, two signers (LL and VF) shifted the sign WHY back on the horizontal axis when it occurred in the low environment and at the normal signing rate. It is unclear what might have led to this farther back position in the low environment but not the high environment.

For two signers (RD and VF), the sign STUBBORN was produced at a lower position when it occurred in the low phonetic environment. For both of these signers, this was the second largest vertical difference between the two environments. There were no consistent patterns in the differences along other axes at the normal signing rate.

To summarize, none of the signs examined here were lowered by all signers as an effect of phonetic environment alone. However, environment-related shifts along the vertical axis were mostly downward. WHY was the sign that was most consistently lowered as an effect of phonetic environment alone, though it was not lowered by a long distance. It was predicted that this sign would be lowered, based on the fact that a highly reduced form of this sign often occurs in informal signing. The sign KNOW was not lowered as an effect of phonetic environment as consistently as we had predicted, given that the sign has been reported to lower in conversational contexts (Lucas et al. 2002). The sign STUBBORN was lowered to a greater extent than the other signs, though not more consistently than the other signs. Finally, the sign FATHER showed minimal variation along any of the positional axes as an effect of phonetic environment alone. It should be noted that FATHER is the only one of these signs which is minimally contrastive with another sign that has a nearby location, i.e., MOTHER, which is at the chin.

3.1.2. Phonetic environment effects across positional axes—The current study is unique in that it examined not only the hand's vertical position but also its position along the horizontal and lateral axes (relative to the head) in forehead-located signs. For this reason, it is worth discussing the findings according to the different spatial dimensions, even though human movement is obviously not mapped in single dimensions separately. Shifts in the signs' positions along the lateral and horizontal axes were highly variable across signers and across signs, when phonetic environment alone was manipulated. This is not surprising, given that the two phonetic environments were controlled for their vertical position but not for their position along the other axes. Phonetic environment alone does not affect the hand's position along the horizontal axis to a great extent for any signer. This could result from the head acting as a lower bound for the hand's movement along that axis – as the hand moves toward the forehead, it cannot go past the surface of the forehead.

Where significant environment-related differences occur on the lateral axis, they are unidirectional for each signer. In other words, no signer moves some signs more to the left in the low environment while also moving other signs more to the right in the same environment. However, signers do not all shift signs in the same direction as an effect of environment. In addition, where left- or right-ward shifts occur, they tend to be quite large in magnitude. Each signer makes their most substantial environment-related shifts along the lateral axis, even though these differences are not very consistent by signer or by sign. This may be related to the absence of phonologically-contrastive locations along the lateral surface of the forehead.

3.2. Effects of signing rate and phonetic environment

Below we report the results of a series of linear regression analyses comparing the position of the hand marker to the rate of signing in the high and the low phonetic environments for each sign. Because sign phrases were designed to particularly contrast a high and low phonetic environment, significant effects were expected along the vertical axis, but rate-dependent variation was also found along the lateral and horizontal axes. Separate analyses were conducted for position along each of the three axes, for each sign and for each signer. (Across the analyses in Tables 2–5, a total of 90 separate regressions were considered. Type 2 errors may exist leading to roughly 4 or 5 false positives altogether.) Regression data were compared using paired *t*-tests to determine whether the relationship between the target sign and the signing rate was different across the two phonetic environments.

3.2.1. Rate and environment effects by sign—All four signers showed some significant rate-dependent variation in the hand's vertical position for the sign KNOW (Table 2). For two signers, LL and VF, the sign KNOW was raised as signing rate increased in the high environment, and the sign was lowered as rate increased in the low environment (Figure 13). A third signer, MF, raised the sign KNOW as an effect of increased rate in the high environment, but did not lower the sign as an effect of rate in the low environment. Both of these patterns are understandable in light of expectations about coarticulation. As these individuals signed more quickly, they shifted the sign KNOW in the direction of the preceding and following signs on the vertical axis. Signer RD showed a pattern that was not anticipated, however. For her, the sign KNOW was lowered as signing rate increased, but only in the high environment (Figure 14). (As stated previously, the origin point in the movement coordinate scheme was higher than the position of the forehead location for most signs, so measured values on the y-axis are negative.)

The sign FATHER was lowered more often and to a greater extent as an effect of rate plus phonetic environment than it was as an effect of phonetic environment alone (Table 3). However, not all signers lowered the sign as an effect of those factors, and the sign did not always shift in the direction we predicted. For example, the signer LL lowered the sign FATHER as an effect of rate in the high phonetic environment but not in the low phonetic environment.

For this sign, there were no large shifts on the horizontal axis that were not accompanied by a simultaneous shift along another axis (Table 3). When the sign was moved back by more than 14 mm, it was simultaneously moved along one of the other axes, which suggests that the signer may have been modifying the orientation of the hand rather than moving the entire hand backwards. One signer, RD, had an exceptionally large leftward shift in the hand's position as an effect of signing rate, irrespective of phonetic environment. There are a few possible explanations for this. It could be that the target sign was shifted to be more central in the signing space. Alternatively, it could be that the preceding deictic gesture to the left influenced the target sign's position. What is less clear is why the leftward shift was so large for this sign but not for the other signs.

Three signers shifted the sign WHY substantially leftward as an effect of rate, and in one case (MF), this shift occurred irrespective of the phonetic environment (Table 4). (This leftward shift is unlike the conversational form of the sign, though it is consistent with the sign being reduced medially and/or moving in the direction of the pointing sign.) The same three signers all shifted the sign so that the marker on the hand was closer to the head on the horizontal axis, irrespective of the phonetic environment. The signer RD showed a different effect of rate + environment, which is partially consistent with the conversational form of WHY, in which the hand's position is farther forward from the body (and also farther down and to the side).

As discussed above, the sign STUBBORN was lowered to a greater extent than other signs as an effect of phonetic environment. However, STUBBORN was not lowered to a greater extent than other signs as an effect of both phonetic environment and signing rate (Table 5). Moreover, for this sign, the phonetic environment did not seem to have a consistent effect in the direction we would have predicted on the vertical axis. For one signer, the sign was raised as an effect of rate in the low environment but not in the high environment.

STUBBORN also showed less of a tendency to be shifted to the left as an effect of both signing rate and phonetic environment, compared to other signs. This could be because the sign is fairly low on the temple relative to the other signs, and moving it medially would cause it to cover the eyes. On the horizontal axis, there was no clear pattern across signers, in terms of the magnitude or direction of the shift related to rate and phonetic environment.

3.2.2. Summary of rate and environment effects—In summary, forehead-located signs tended to be produced at a lower position when they were placed in a low phonetic environment. In addition, lowering occurred more often and to a greater extent when the low phonetic environment was combined with faster signing rates. However, these effects were not uniform across signs or across signers. Some signs were more likely to be lowered than others. Two signs that are often lowered in conversational contexts, KNOW and WHY, were also lowered in these experiments, though not as consistently as we had predicted. The sign KNOW, in particular, was not substantially lowered as an effect of phonetic environment, but it was lowered more often as a combined effect of signing rate and phonetic environment. The sign WHY was lowered as an effect of phonetic environment alone, but that effect was diminished when the sign was produced at faster rates in the low environment. Likewise, the sign STUBBORN was lowered as an effect of phonetic environment, but rate did not seem to have an effect in addition to the effect of phonetic environment. We had predicted that the sign FATHER would not be lowered substantially, given that there is another ASL sign that is minimally contrastive with it which is located at the chin (i.e., MOTHER). In fact, FATHER was lowered by a very small amount by a couple of signers as an effect of phonetic environment. When it was produced at faster rates, it was lowered more, though not always according to the direction of the phonetic environment.

The current study is unusual in that it examined modifications to sign location along all three spatial axes. As a result of this analysis, one environment-independent pattern in the data became noticeable. In particular, signs were often shifted leftward on the x-axis as an effect of rate. No significant rightward shifts occurred as an effect of rate for any signer or sign. We had not predicted a rate-dependent leftward shift in the target signs, but it is not especially surprising or counterintuitive. This is what would occur if signers were either shifting the target sign toward a more central position in the articulatory space or shifting the sign toward the deictic gesture to the left that precedes it in the utterance.

Finally, there was variability by sign and by signer on the horizontal axis, as an effect of signing rate plus phonetic environment. When signing rate was not modified by participants, shifts along the horizontal axis were small. However, the rate-induced shifts in the hand's horizontal position were fairly large.

4. Discussion and conclusion

While research on the phonology of signed language relies heavily on citation forms of signs, it is apparent from this research and previous research that signers' productions vary from the citation forms in systematic ways (Johnston 1989; Lucas et al. 2002; Mauk 2003; Russell et al. 2011; Schembri et al. 2009). For this study in particular, the realization of a sign's location was influenced by the phonetic factors that were manipulated in the experiment, namely, signing rate and phonetic environment. In general, phonetic sign locations moved closer to the vertical positions of the signs they were adjacent to, particularly when signing rates were increased. Sign locations were also shifted along the horizontal and lateral axes, but these variations were largely independent of the high and low carrier phrases that we used, and occurred as an effect of rate, target sign, and signer.

4.1. Predicted and unpredicted findings

As with speech, production rate alone can affect the phonetic realization of signs. One of the more striking results from this study was that the effect of signing rate on a sign's lateral position was highly uniform. When signing rate had an effect along that axis, it consistently caused the sign to move leftward, which for these right-handed signers was toward the midline of the body. This may have resulted from perseverative coarticulation of the leftward deictic movement that preceded the target sign, but since the preceding leftward movement was present for all productions, it is not possible to make this determination. Future research could examine the effects of signing rate on phonetic location in more detail. Variation on the horizontal axis became substantial only at faster signing rates.

Previous studies have suggested that signs that make contact with the head in citation form may be less likely to lower than signs that do not make contact (Mauk 2003). We took this point under consideration but found no clear effect of contact (in the citation form of the sign) on lowering. It should be noted that the method of data capture used in this study allowed no objective measurement of the hand making contact with the head, so it was not possible to determine the effects of the realization of contact with the head. Indeed, contact itself may be modified as an effect of the factors we manipulated. For example, casual observation of signers' productions suggested that the hand achieved contact with the head less often at faster signing rates.

As predicted, one sign that had been reported to lower in conversation, KNOW, underwent lowering as an effect of phonetic environment and signing rate in this experiment. However, the extent and incidence of lowering were not observably greater for this sign than for other signs. It may be that lowering as an effect of linguistic register or lexical frequency and lowering as an effect of phonetic factors operate largely independently of each other. Another sign that had been reported to lower, WHY, was not lowered, but perhaps was reduced, as a combined effect of rate and environment. The sign WHY was shifted medially as an effect of rate, particularly in the high environment, which may be a different form of reduction (possibly related to the preceding sign). It is worth noting that the phonetically reduced form of WHY that was observed in this study does not resemble the conversational form of the sign, in that the form observed here was shifted toward the midline of the body, while the conversational variant of WHY is shifted downward, forward and lateral to the body.

A few limitations of these findings deserve brief mention. First, with respect to how the measures were taken, it should be noted that marker position is not an exact index of sign location. The marker's position could reflect the hand's configuration or orientation in addition to its location. Moreover, no systematic measures were taken for the positions of the carrier phrase signs, so it is difficult to know precisely how strongly the target signs were influenced by phonetic environment. In addition, because this was a controlled phonetic study, data collection took place in a laboratory setting, and only a few signers and phonetic environments were studied. It would be informative to investigate similar patterns across a broader range of language users, utterances, and communicative contexts.

4.2. Developing measures of sign production

Sign language research is a new field, compared to linguistics or speech science. Early sign language research was oriented towards answering broad questions, related to the nature and existence of grammatical rules, lexical forms, and sublexical structure (cf. Stokoe 1960; Battison 1978; Klima and Bellugi 1979). Without this seminal work, there would have been no motivation for examining the phonetic structure of signed language, because it would have been assumed that signed language had no structure other than its physical form. Moreover, early researchers had to emphasize that signed languages were full-fledged languages, and in doing so, they often downplayed the differences between signed and spoken languages, such as those related to the size and structure of the articulators. Because of the early emphasis on abstract properties of language, the phonetics of signed language did not receive much attention.

Experimental research on the phonetics of signed language emerged later, in part due to the development and increased availability of research techniques for analyzing sign language data (Poizner, Klima, and Bellugi 1987; Wilbur 1999; Mauk 2003). Unlike the broader field of phonetics, sign phonetics does not have measures of production that are well-established or easily quantified. One of the long term goals of this study has been to contribute to the development of articulatory measures of sign production that are based on the physiology of sign production rather than relying on abstract principles or features or on phonological contrasts that are language-specific.

4.3. Sign lowering and phonetic reduction

Phonetic reduction in a signed language can occur in multiple spatial dimensions, just as in speech articulation. While previous studies have reported high signs moving downward in some contexts (Lucas et al. 2002; Schembri et al. 2009; Russell et al. 2011), our data suggest that signs can shift in other directions as well. Crucially, for forehead-located signs, shifting the sign along the lateral or horizontal axis does not cause it to cross any phonological boundaries: producing a forehead sign farther forward, or farther to the left or right cannot create a different lexical item. This could be the reason that past studies have examined lowering but not other forms of reduction for signs located at the forehead – non-contrastive reduction may have been less noticeable to sign language users and researchers, or its implications for phonology may have been seen as unimportant.

In our study, the effects of phonetic environment in particular were more consistent on the vertical axis than on the lateral or horizontal axis. However, it is unclear whether this difference emerged because the vertical axis was explicitly varied, or whether it emerged because there is more vertical variation in sign production to begin with. Only one study has examined phonetically-controlled contrasts along all three positional axes (Grosvald 2009), and it found that coarticulatory effects along all three axes were minimal, due to a high level of variability across signers. Grosvald's study was highly innovative in that it implemented a normalization procedure so that data could be pooled across participants. However, it is possible that this preliminary attempt at normalization masked true differences in the data, because the normalization procedure relied on a combination of anatomical and physiological factors whose role in shaping the signing space is unknown. The field of sign phonetics would be greatly advanced by a normalization procedure based on the magnitude, shape, and variability of the signing space as used by different signers. In this way, individual variation could be better disambiguated from variation that is linguistically motivated.

4.4. Non-phonetic factors in reduction

There are multiple reasons why some signs might be reduced and others not, or why signs might be reduced in different ways. Grammatical category may also be a good predictor of a sign's tendency to be reduced. In conversational speech, for example, function words such as 'and,' 'of,' or 'the' are often reduced. Indeed, Lucas et al. (2002) report that function words located at the forehead or temple in ASL (such as the sign FOR) are more likely to be lowered than signs of some other grammatical categories, such as nouns or adjectives. In addition, they report that verbs are more likely to be lowered. The current study did not attempt to control for the distribution of signs from different grammatical categories, and it is unclear how many of the signs examined here were also examined by Lucas and colleagues. In the small number of signs that we examined, it was not clear that grammatical category alone was related to lowering or to phonetic reduction.

It is likely that the frequency of particular signs in ASL influences the phonetic reduction of those signs. In their study of sign lowering in Auslan, Schembri et al. (2009) examined both sign frequency and grammatical category as factors and found that high-frequency verbs were more likely to take a non-citation form than any other sign type. While we made a reasonable attempt to exclude extremely low-frequency signs from this study, we could not do a systematic comparison by sign frequency, because there are limited frequency data available for ASL. According to Morford and MacFarlane's analysis of the frequency characteristics of ASL signs, two of the signs analyzed in this study (FATHER and WHY) were among the higher frequency signs in ASL. For the other two signs that were examined (KNOW and STUBBORN), we do not have any information about frequency. Our data do not suggest that frequency alone has an effect on lowering. The lack of consistent lowering of the two high-frequency signs is perhaps consistent with the findings from Schembri et al. related to the combined effect of grammatical category and frequency (i.e., high-frequency verbs were lowered but other high-frequency signs were not).

The proximity of other ASL signs to the target signs that we examined could have influenced phonetic reduction in particular and variation more generally. Only one of the signs included in this analysis had a minimal pair with a nearby location. That sign is FATHER, which is similar to the sign MOTHER, located at the chin. The sign FATHER changed very little as an effect of phonetic environment alone, but was shifted quite substantially when signing rate increased. More generally, there are no phonological contrasts for any forehead-located signs along the lateral or horizontal axis: producing a sign farther to the left or right on the forehead, or producing it farther forward does not render it a different lexical item. This could explain why variation along these two axes was both large and inconsistent.

4.5. Phonetic reduction in sign and in speech

One potential difference between sign and speech, based on the findings from this study and from others (Grosvald 2009), is that there seems to be little effect of phonetic environment alone on reduction or coarticulation in the sign modality. This difference should be interpreted with caution, however, because the measure that we have used for phonetic reduction (i.e., the hand's position relative to the body) may not be analogous to the measures used for reduction in speech. Positional data and acoustical data are inherently different, simply by virtue of differences in their physical properties. Indeed, raw positional data from articulatory studies of speech show a great deal of variability across speakers

(Kent and Moll 1972; Ostry and Munhall 1985), which is partially related to articulator size (Kuehn and Moll 1976). Grosvald (2009) compared speech acoustics to sign kinematics, and found a limited effect of phonetic environment on sign production compared to speech production. However, the physical properties of the two signals may have been different enough to mask any modality effects. Moreover, the acoustical measures of coarticulation and reduction that are typically used for speech are highly refined, based on decades of research on speech production and perception. It may be that when better measures of sign production are in place, we would find more consistent patterns of phonetic reduction in signed as well as spoken language.

Like hearing speakers, signers use different strategies for accomplishing faster production rates. Several studies have observed the variability of speech movements across speakers when speech rate and phonetic segments are manipulated (Kent and Moll 1972; Kuehn and Moll 1976; Gay 1981; Ostry and Munhall 1985). Ostry and Munhall (1985) measured tongue dorsum excursions for velar consonants via an ultrasound system and found that the three speakers they tested exhibited different changes in movement amplitude and velocity as an effect of increased speech rate. However, all speakers showed a stable relationship between movement amplitude and peak velocity, which is consistent with findings from previous studies (Kent and Moll 1972). Based on this finding, the authors suggest that a single set of principles could account for rate-induced changes in articulatory movement as well as rate-induced changes in targeted limb movement. Comparisons between sign and speech are less straightforward, because unlike most experimental movement tasks, sign movements are three-dimensional, unconstrained, and often include reversals in movement direction. In addition to the highly variable movement displacements shown across signers in this study, there may also be invariant movement patterns across multiple productions of the same sign that have not yet been identified, given the limited body of phonetic sign research.

A larger issue that is raised by the current study is whether the articulatory phenomena that we have observed in sign production and that others have observed in speech production are features of motor control or whether they are inherently linguistic in nature. We would conjecture that the phenomena of reduction and coarticulation are essentially the result of similar motor synergies across sign and speech. There have been a few studies of coarticulation in non-linguistic movement tasks (Klein Breteler, Hondzinski, and Flanders 2003; Torres and Zipser 2004). But given that, relative to sign and speech, those tasks are simpler (such as pointing), less sequential (such as reach and grasp), or less practiced (such as drawing), it is unclear how comparable such tasks might be to sign or speech production. It seems likely that sign and speech would exhibit more reduction and coarticulation than other movement tasks, because they require highly complex yet routinized movement sequences and are not structured around external objects. Thus, it may not be the linguistic nature of the two systems, per se, that causes them to pattern similarly, but rather their need to allow rapid, complex, and flexible information transfer via the unconstrained movement of human articulators.

The earliest research on ASL phonology delineated the sublexical elements that could differentiate one sign from another: handshape, movement, and location (Stokoe 1960). This analysis formed the framework for almost everything that has followed in sign phonology. Since Stokoe's time, many theoretical and empirical studies have explored the phonological parameters of signed language (Sandler 1989; Brentari 1998; Emmorey, McCullough, and Brentari 2003; Best, Mathur, Miranda, and Lillo-Martin 2010). Yet there has been little consideration given to the phonetics-phonology interface or to the relationship between sign production and sign perception. This study, like past descriptive studies, suggests that there is considerable variation in the realization of the location parameter for some ASL signs. Along other lines, some studies have shown that the location parameter in particular facilitates sign perception (Emmorey and Corina 1990; Corina and Knapp 2006). So while signers use information about sign location when they perceive signs, the physical manifestation of location is not very consistent from one production to another. This suggests that our traditional conceptualization of location (i.e., a static position fixed relative to the body) is different from phonological location as signers perceive and produce it, in that articulatory targets and their realizations in signed language are more flexible than typically modeled.

Acknowledgments

The authors would like to thank Susan Pedersen, Debra L. Hast, Erin "Airza" Bosley, Maryjean Shahen, and Shayna Benjamin for their advice and assistance with experimental design and data analysis. We would also like to thank the two anonymous reviewers who helped us greatly improve the manuscript. This research was supported by National Institutes of Health grant DC008881.

References

Battison, Robbin. Lexical Borrowing in ASL. Silver Spring, MD: Linstok; 1978.

Best, Catherine T.; Mathur, Gaurav; Miranda, Karen A.; Lillo-Martin, Diane. Effects of sign language experience on categorical perception of dynamic ASL pseudosigns. Attention, Perception, & Psychophysics. 2010; 72:747–762.

Brentari, Diane. A Prosodic Model of Sign Language Phonology. Cambridge, MA: MIT Press; 1998.

Bybee, Joan. Word frequency and context of use in the lexical diffusion of phonetically conditioned sound change. Language Variation and Change. 2002; 14:261–290.

Bybee, Joan; Scheibman, Joanne. The effect of usage on degrees of constituency: The reduction of don't in English. Linguistics. 1999; 37:575–596.

Cheek, Davina Adrianne. PhD dissertation. University of Texas; Austin: 2001. The phonetics and phonology of handshape in American Sign Language.

Corina, David P.; Knapp, Heather P. Lexical retrieval in American Sign Language production. In: Goldstein, Louis; Whalen, DH.; Best, Catherine T., editors. Papers in Laboratory Phonology 8. Berlin: Mouton de Gruyter; 2006. p. 213-239.

Emmorey, Karen; Corina, David. Lexical recognition in sign language: Effects of phonetic structure and morphology. Perceptual and Motor Skills. 1990; 71:1227–1252. [PubMed: 2087376]

Emmorey, Karen; McCullough, Stephen; Brentari, Diane. Categorical perception in American Sign Language. Language & Cognitive Processes. 2003; 18:21–45.

Gay, Thomas. Mechanisms for the control of speech rate. Phonetica. 1981; 38:148–158. [PubMed: 7267717]

Goldstein, Louis. Comment on Pierrehumbert and Talkin. In: Docherty, Gerard J.; Robert Ladd, D., editors. Papers in Laboratory Phonology. Vol. 2. Berlin: Mouton de Gruyter; 1992. p. 120-123.

Grosvald, Michael A. Unpublished PhD dissertation. Department of Linguistics, University of California; Davis: 2009. Long-distance coarticulation: A production and perception study of English and American Sign Language.

Johnston, Trevor. Unpublished PhD dissertation. Department of Linguistics, University of Sydney; 1989. Auslan: The sign language of the Australian Deaf community.

Kelso, JA Scott; Vatikiotis-Bateson, Eric; Saltzman, Elliot L.; Kay, Bruce. A qualitative dynamic analysis of reiterant speech production: Phase portraits, kinematics, and dynamic modeling. Journal of the Acoustical Society of America. 1985; 77:266–280. [PubMed: 3973219]

Kent, Raymond D.; Moll, Kenneth L. Cinefluorographic analyses of selected lingual consonants. Journal of Speech and Hearing Research. 1972; 15:453–473. [PubMed: 5080037]

Breteler, Klein; Mary, D.; Hondzinski, Jan M.; Flanders, Martha. Drawing sequences of segments in 3D: Kinetic influences on arm configuration. Journal of Neurophysiology. 2003; 89:3253–3263. [PubMed: 12611990]

Klima, Edward S.; Bellugi, Ursula. The Signs of Language. Cambridge, MA: Harvard University Press; 1979.

Kuehn, David R.; Moll, Kenneth L. A cineradiographic study of VC and CV articulatory velocities. Journal of Phonetics. 1976; 4:303–320.

Lavoie, Lisa M. Consonant Strength: Phonological Patterns and Phonetic Manifestations. New York: Garland Publishing; 2001.

Liddell, Scott K.; Johnson, Robert E. American Sign Language: The phonological base. Sign Language Studies. 1989; 64:195–277.

Lindblom, Bjorn. Spectrographic study of vowel reduction. Journal of the Acoustical Society of America. 1963; 35:1773–1781.

Lucas, Ceil; Bayley, Robert; Rose, Mary; Wulf, Alyssa. Location variation in American Sign Language. Sign Language Studies. 2002; 2:407–440.

Mauk, Claude E. PhD dissertation. Department of Linguistics, University of Texas; Austin: 2003. Undershoot in two modalities: Evidence from fast speech and fast signing.

Moon, Seung-Jae; Lindblom, Bjorn. Interaction between duration, context, and speaking style in English stressed vowels. Journal of the Acoustical Society of America. 1994; 96:40–55.

Mooshammer, Christine; Geng, Christian. Acoustic and articulatory manifestations of vowel reduction in German. Journal of the International Phonetic Association. 2008; 38:117–136.

Morford, Jill P.; MacFarlane, James. Frequency characteristics of American Sign Language. Sign Language Studies. 2003; 3:213–225.

Ostry, David J.; Munhall, Kevin G. Control of rate and duration of speech movements. Journal of the Acoustical Society of America. 1985; 77:640–648. [PubMed: 3882804]

Poizner, Howard; Klima, Edward; Bellugi, Ursula. What the Hands Reveal about the Brain. Cambridge, MA: MIT Press; 1987.

Romero Gallego, Joaquin. PhD dissertation. Department of Linguistics, University of Connecticut; 2001. Gestural organization in Spanish: An experimental study of spirantization and aspiration.

Russell, Kevin; Wilkinson, Erin; Janzen, Terry. ASL sign lowering as undershoot: A corpus study. Laboratory Phonology. 2011; 2:403–422.

Sandler, Wendy. Phonological Representation of the Sign: Linearity and Nonlinearity in American Sign Language. Dordrecht, The Netherlands: Foris; 1989.

Sandler, Wendy; Lillo-Martin, Diane. Sign Language and Linguistic Universals. New York: Cambridge University Press; 2006.

Schembri, Adam; McKee, David; McKee, Rachel; Pivac, Sara; Johnston, Trevor; Goswell, Della. Phonological variation and change in Australian and New Zealand Sign Languages: The location variable. Language Variation and Change. 2009; 21:193–231.

Stokoe, William C. Studies in Linguistics: Occasional Papers 8. Buffalo, NY: University of Buffalo Press; 1960. Sign language structure: An outline of the visual communication systems of the American Deaf.

Torres, Elizabeth B.; Zipser, David. Simultaneous control of hand displacements and rotations in orientation-matching experiments. Journal of Applied Physiology. 2004; 96:1978–1987. [PubMed: 14688032]

Tyrone, Martha E.; Mauk, Claude E. Sign lowering and phonetic reduction in American Sign Language. Journal of Phonetics. 2010; 38:317–328. [PubMed: 20607146]

Westbury, John R. X-ray Microbeam Speech Production Database User's Handbook. Madison: University of Wisconsin at Madison, Waisman Center; 1994.

Wilbur, Ronnie. Stress in ASL: Empirical evidence and linguistic issues. Language and Speech. 1999; 42:229–250. [PubMed: 10767990]

Appendix

Linear regression equations and R^2 values for each comparison of duration and hand position, and an indication of whether the hand's position differed across the two phonetic environments. When the regression was not significant for either environment, no comparison was made between the two environments.

Sign	Environment	Vertical axis	Lateral axis	Horizontal axis
KNOW LL	High	$y = 0.0221x + 81.5$ $R^2 = 0.409$***	$y = -0.0075x + 47.2$ $R^2 = 0.050$	$y = 0.0022x + 116.6$ $R^2 = 0.009$
	Low	$y = -0.0306x + 168.2$ $R^2 = 0.431$***	$y = 0.0236x - 6.2$ $R^2 = 0.363$***	$y = 0.0161x + 89.9$ $R^2 = 0.366$***
	Different?	Yes***	Yes***	Yes*
KNOW MF	High	$y = 0.0137x + 92.0$ $R^2 = 0.450$***	$y = 0.0045x + 36.55$ $R^2 = 0.017$	$y = -0.0394x + 161.7$ $R^2 = 0.762$***
	Low	$y = -0.0015x + 121.6$ $R^2 = 0.011$	$y = 0.0311x - 13.4$ $R^2 = 0.524$***	$y = -0.0248x + 141.7$ $R^2 = 0.607$***
	Different?	Yes***	Yes***	Yes*
KNOW RD	High	$y = -0.0511x + 145.3$ $R^2 = 0.541$***	$y = 0.0311x - 50.2$ $R^2 = 0.214$**	$y = -0.0307x + 116.4$ $R^2 = 0.249$**
	Low	$y = -0.041x + 170.2$ $R^2 = 0.087$	$y = -0.0279x - 26.0$ $R^2 = 0.037$	$y = -0.0244x + 92.8$ $R^2 = 0.205$*
	Different?	Yes***	Yes***	Yes*
KNOW VF	High	$y = 0.025x + 17.7$ $R^2 = 0.174$*	$y = 0.0073x - 56.3$ $R^2 = 0.006$	$y = -0.0182x + 94.9$ $R^2 = 0.163$*
	Low	$y = -0.0515x + 150.0$ $R^2 = 0.431$***	$y = 0.0685x - 100.4$ $R^2 = 0.537$***	$y = 0.0547x + 10.4$ $R^2 = 0.541$***
	Different?	Yes***	Yes***	Yes*
WHY LL	High	$y = 0.0025x + 109.8$ $R^2 = 0.002$	$y = 0.026x - 20.3$ $R^2 = 0.166$*	$y = 0.0201x + 110.5$ $R^2 = 0.250$**
	Low	$y = -0.0088x + 138.4$ $R^2 = 0.051$	$y = 0.0114x - 4.3$ $R^2 = 0.056$	$y = 0.023x + 96.2$ $R^2 = 0.503$***
	Different?	N/A	No	No
WHY MF	High	$y = 0.0095x + 84.9$ $R^2 = 0.276$**	$y = 0.0485x - 98.2$ $R^2 = 0.503$***	$y = 0.0037x + 113.6$ $R^2 = 0.039$
	Low	$y = 0.0155x + 80.3$ $R^2 = 0.580$***	$y = 0.0312x - 63.2$ $R^2 = 0.436$***	$y = 0.0071x + 106.3$ $R^2 = 0.169$*
	Different?	No	No	No
WHY RD	High	$y = -0.0255x + 159.1$ $R^2 = 0.044$	$y = 0.0136x - 85.5$ $R^2 = 0.015$	$y = -0.0264x + 107.8$ $R^2 = 0.061$
	Low	$y = 0.0052x + 99.3$ $R^2 = 0.007$	$y = 0.0029x - 88.8$ $R^2 = 0.002$	$y = -0.0914x + 215.1$ $R^2 = 0.585$***

Sign	Environment	Vertical axis	Lateral axis	Horizontal axis
	Different?	N/A	N/A	Yes*
WHY VF	High	$y = 0.036x + 34.1$ $R^2 = 0.153$*	$y = 0.072x - 74.7$ $R^2 = 0.354$***	$y = 0.0118x + 99.0$ $R^2 = 0.044$
	Low	$y = -0.028x + 123.0$ $R^2 = 0.283$**	$y = -0.0141x + 29.8$ $R^2 = 0.094$	$y = 0.0321x + 61.7$ $R^2 = 0.253$**
	Different?	Yes***	Yes***	Yes***
FATHER LL	High	$y = - 0.0695x + 178.0$ $R^2 = 0.397$***	$y = 0.0313x - 5.8$ $R^2 = 0.107$	$y = 0.0097x + 110.5$ $R^2 = 0.069$
	Low	$y = 0.0059x + 97.9$ $R^2 = 0.023$	$y = -0.0008x + 30.8$ $R^2 = 0.000$	$y = 0.015x + 105.1$ $R^2 = 0.338$***
	Different?	Yes***	N/A	No
FATHER MF	High	$y = 0.0017x + 70.3$ $R^2 = 0.006$	$y = -0.0057x - 35.2$ $R^2 = 0.048$	$y = -0.0081x + 115.2$ $R^2 = 0.166$*
	Low	$y = -0.0149x + 92.0$ $R^2 = 0.599$***	$y = 0.0059x - 52.8$ $R^2 = 0.116$	$y = 0.0186x + 74.6$ $R^2 = 0.475$***
	Different?	Yes***	N/A	Yes***
FATHER RD	High	$y = 0.0124x + 44.6$ $R^2 = 0.215$**	$y = 0.1397x - 215.0$ $R^2 = 0.804$***	$y = 0.0481x + 38.9$ $R^2 = 0.375$***
	Low	$y = 0.0047x + 48.6$ $R^2 = 0.008$	$y = 0.1518x - 251.2$ $R^2 = 0.659$	$y = 0.1023x - 25.2$ $R^2 = 0.616$***
	Different?	No	No	Yes**
FATHER VF	High	$y = -0.0161x + 31.8$ $R^2 = 0.141$*	$y = -0.0103x - 51.0$ $R^2 = 0.097$	$y = 0.0187x + 103.8$ $R^2 = 0.301$**
	Low	$y = -0.0389x + 74.4$ $R^2 = 0.483$***	$y = 0.0115x - 74.1$ $R^2 = 0.094$	$y = 0.0425x + 68.1$ $R^2 = 0.520$***
	Different?	Yes*	N/A	Yes*
STUBBORN LL	High	$y = 0.0265x + 38.4$ $R^2 = 0.454$***	$y = 0.028x + 22.4$ $R^2 = 0.373$***	$y = 0.007x + 115.7$ $R^2 = 0.425$***
	Low	$y = -0.044x + 149.1$ $R^2 = 0.597$***	$y = -0.0089x + 57.7$ $R^2 = 0.057$	$y = 0.0133x + 101.4$ $R^2 = 0.556$***
	Different?	Yes***	Yes***	Yes*
STUBBORN RD	High	$y = 0.0131x + 74.0$ $R^2 = 0.039$	$y = 0.0179x + 37.1$ $R^2 = 0.046$	$y = -0.0276x + 137.5$ $R^2 = 0.338$***
	Low	$y = 0.0225x + 65.5$ $R^2 = 0.220$**	$y = -0.0092x + 79.2$ $R^2 = 0.034$	$y = -0.0052x + 103.4$ $R^2 = 0.015$
	Different?	No	N/A	Yes*
STUBBORN VF	High	$y = -0.0205x + 57.4$ $R^2 = 0.039$	$y = -0.0401x + 28.7$ $R^2 = 0.045$	$y = -0.0214x + 160.6$ $R^2 = 0.191$*
	Low	$y = -0.0306x + 92.9$ $R^2 = 0.233$**	$y = 0.0415x - 24.8$ $R^2 = 0.060$	$y = -0.0075x + 141.2$ $R^2 = 0.129$
	Different?	No	N/A	No

Figure 1.
The ASL sign FATHER: the fingers are extended and the hand moves up so that the thumb contacts the forehead.

Figure 2.
KNOW: the four fingers are bent at the base knuckle and some of the fingertips contact the forehead.

Figure 3.
FAVORITE: the middle finger is bent at the knuckle and contacts the chin.

Figure 4.
LUCKY: the middle finger is bent at the knuckle and the hand twists and moves forward and down from the chin.

Figure 5.
FINE: the fingers are all extended and spread apart and the hand moves toward the body so that the thumb contacts the torso.

Figure 6.
WONDER: the index finger is fully extended and the clenched hand moves in small circles just in front of the forehead.

Figure 7.
WHY: the palm faces the side of the head and the middle three fingers repeatedly flex at the knuckle.

Figure 8.
STUBBORN: the thumb contacts the temple then the four fingers bend at the knuckle.

Figure 9.
The head device that holds the light-emitting Optotrak markers.

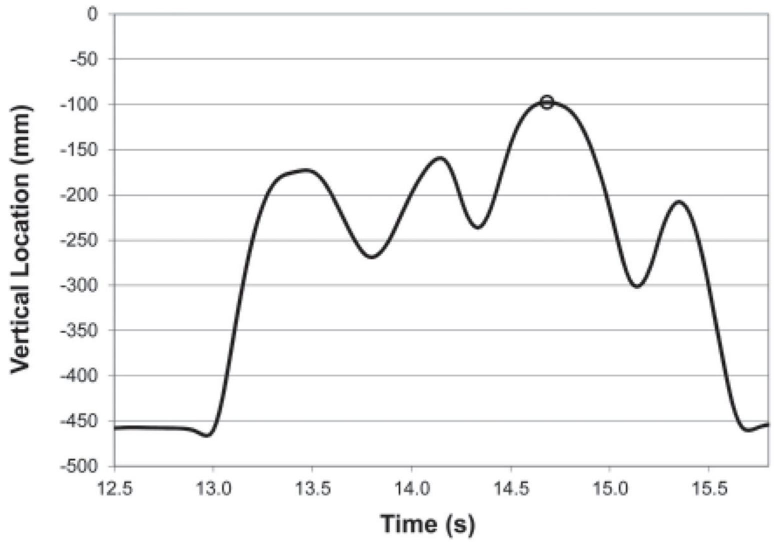

Figure 10.

Determining phonetic location: vertical maximum during the target sign.

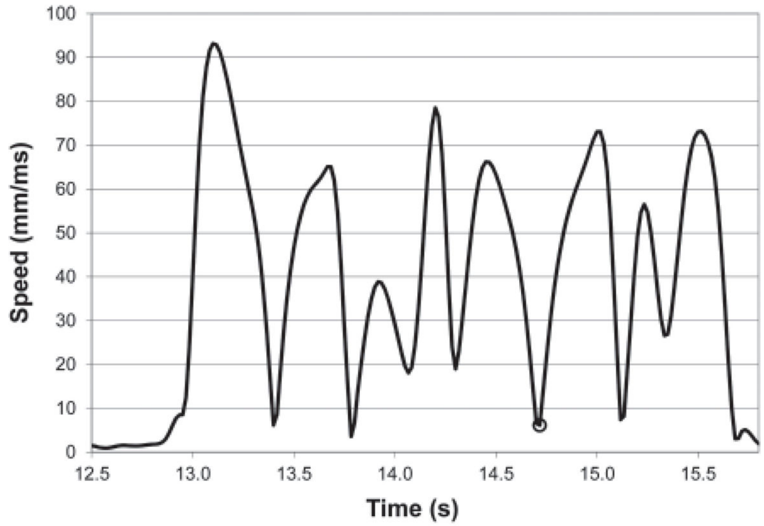

Figure 11.
Determining phonetic location: 3D tangential velocity minimum during the target sign.

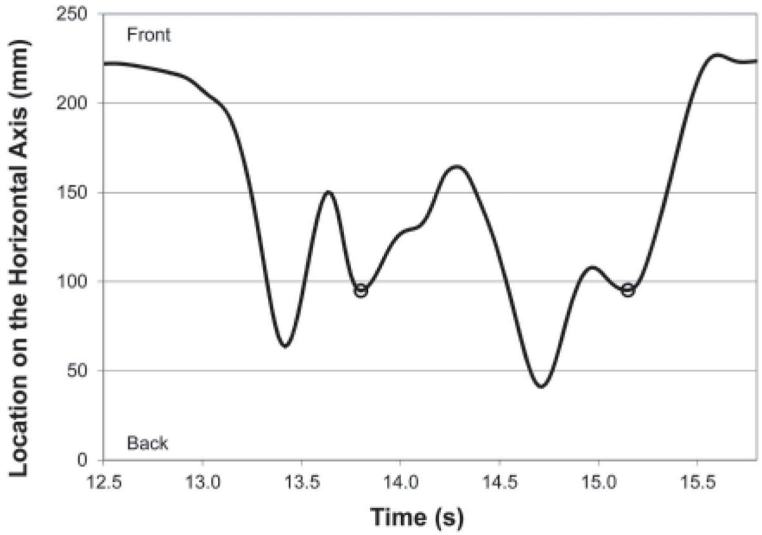

Figure 12.
Procedure for estimating rate: small circles indicate stable landmarks along the horizontal axis.

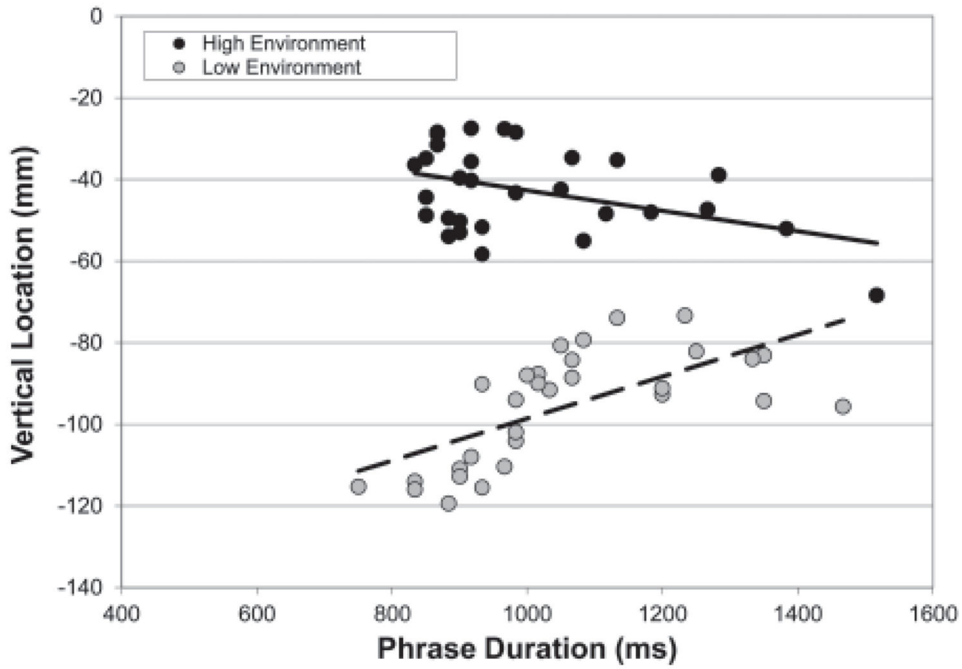

Figure 13.
Signer VF's production of KNOW as an effect of phonetic environment and signing rate.

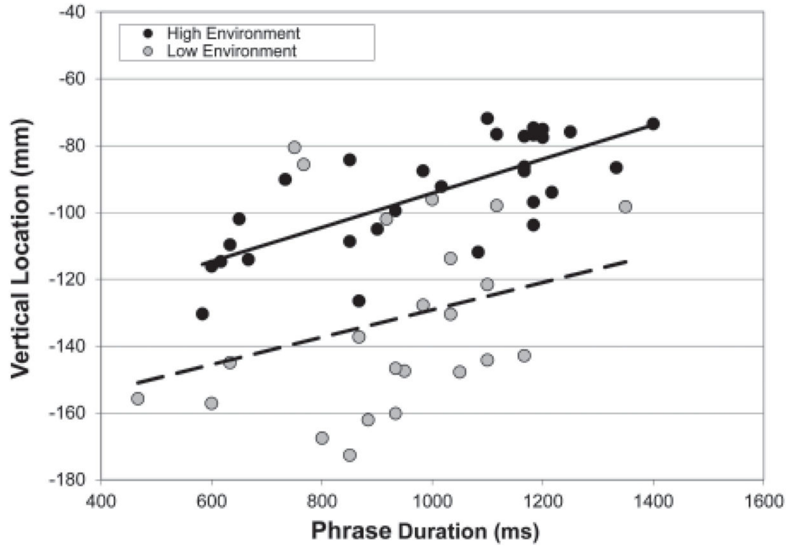

Figure 14.

Signer RD's production of KNOW as an effect of phonetic environment and signing rate.

Table 1

Effects of the low phonetic environment on the position of the hand on the vertical, lateral, and horizontal axes, organized by sign and by signer. Each cell shows the difference in the position of the target sign in millimeters in the low environment compared to the high environment.

Sign	Signer	Vertical axis	Lateral axis	Horizontal axis
KNOW	LL	ns	ns	ns
	MF	ns	15 mm to right***	5 mm forward**
	VF	40 mm lower***	42 mm to right***	8 mm forward*
FATHER	LL	23 mm lower***	ns	ns
	MF	10 mm higher*	ns	13 mm forward*
	RD	10 mm higher*	53 mm to left***	ns
	VF	10 mm lower**	ns	ns
WHY	LL	12 mm lower*	ns	10 mm back*
	MF	10 mm lower*	ns	ns
	RD	ns	23 mm to left*	ns
	VF	ns	ns	12 mm back**
STUBBORN	LL	ns	28 mm to left***	5 mm back***
	RD	20 mm lower**	ns	ns
	VF	34 mm lower***	88 mm to right***	ns

* $p \leq .05$

** $p \leq .01$

*** $p \leq .001$

Table 2

The difference in the hand’s position along each axis (in mm) as an effect of increased signing rate for the sign KNOW. Numbers in each cell represent the predicted positions of the hand at the maximum and minimum duration value for each produced utterance, as determined by a linear regression model. (See Appendix for regression equations.)

Signer	Environment	Vertical axis	Lateral axis	Horizontal axis
LL	High	−122.8 to −98.1 Δ = 24.7 up***	33.2 to 41.6 Δ = 8.4 right (ns)	120.7 to 118.2 Δ = 2.5 back (ns)
	Low	−117.2 to −143.7 Δ = 26.5 down***	33.1 to 12.7 Δ = 20.4 left***	116.7 to 102.8 Δ = 13.9 back***
MF	High	−127.6 to −108.2 Δ = 19.4 up***	48.2 to 41.9 Δ = 6.3 left (ns)	59.3 to 115.1 Δ = 55.8 forward***
	Low	−117.3 to −120.0 Δ = 2.3 down (ns)	75.2 to 20.3 Δ = 54.9 left***	71.0 to 114.8 Δ = 43.8 forward***
RD	High	−73.8 to −115.5 Δ = 41.7 down***	−6.7 to −32.1 Δ = 25.4 left**	73.4 to 98.5 Δ = 25.1 forward**
	Low	− 114.9 to −151.1 Δ = 36.2 down (ns)	−63.7 to −39.0 Δ = 24.7 right (ns)	59.9 to 81.4 Δ = 21.5 forward*
VF	High	−55.6 to −38.5 Δ = 17.1 up*	−45.2 to −50.2 Δ = 5.0 left (ns)	67.3 to 79.7 Δ = 12.4 forward*
	Low	−74.5 to −111.4 Δ = 36.9 down***	0.1 to −49.0 Δ = 49.1 left***	90.6 to 51.4 Δ = 39.2 back***

* $p \le .05$

** $p \le .01$

*** $p \le .001$

Table 3

The difference in the position of the hand along each axis (in mm) as an effect of increased signing rate for the sign FATHER.

Signer	Environment	Vertical axis	Lateral axis	Horizontal axis
LL	High	−88.8 to −131.1 Δ = 42.9 down***	34.4 to 15.1 Δ = 19.3 left	122.9 to 117.0 Δ = 6.0 back
	Low	−107.7 to −102.2 Δ = 5.5 up	29.5 to 30.2 Δ = 0.7 right	130.1 to 116.1 Δ = 14.0 back***
MF	High	−74.5 to −71.6 Δ = 2.8 up	−49.2 to −39.7 Δ = 9.5 right	95.4 to 108.9 Δ = 13.5 forward*
	Low	−53.8 to −79.3 Δ = 25.6 down***	−37.7 to −47.8 Δ = 10.1 left	122.3 to 90.4 Δ = 31.9 back***
RD	High	−64.6 to −52.2 Δ = 12.4 up**	10.8 to −128.9 Δ = 139.7 left***	116.7 to 68.6 Δ = 48.1 back***
	Low	−55.8 to −52.2 Δ = 3.6 up	−18.4 to −134.8 Δ = 116.4 right	131.7 to 53.2 Δ = 78.4 back***
VF	High	−7.9 to −22.1 Δ = 14.2 down*	−66.3 to −57.2 Δ = 9.1 right	131.5 to 115.0 Δ = 37.5 back**
	Low	−15.4 to −49.8 Δ = 34.4 down***	−56.7 to −66.8 Δ = 10.2 left	132.6 to 95.0 Δ = 37.5 back***

* $p \leq .05$

** $p \leq .01$

*** $p \leq .001$

Table 4

The difference in the position of the hand along each axis (in mm) as an effect of increased signing rate for the sign WHY.

Signer	Environment	Vertical axis	Lateral axis	Horizontal axis
LL	High	−113.7 to −111.6 Δ = 2.2 up	20.4 to −2.1 Δ = 22.5 left*	142.0 to 124.6 Δ = 17.4 back**
	Low	−123.9 to −133.0 Δ = 9.1 down	14.5 to 2.7 Δ = 11.8 left	134.2 to 110.4 Δ = 23.8 back***
MF	High	−111.3 to −96.6 Δ = 14.7 up**	36.8 to −38.4 Δ = 75.2 left***	123.9 to 118.2 Δ = 5.7 back
	Low	−126.8 to −97.9 Δ = 28.9 up***	30.4 to −27.8 Δ = 58.2 left***	127.6 to 114.3 Δ = 13.3 back*
RD	High	−114.9 to −138.3 Δ = 23.4 down	−61.9 to −74.4 Δ = 12.5 left	62.0 to 86.2 Δ = 24.2 forward
	Low	−109.1 to −102.3 Δ = 6.8 up	−83.3 to −87.1 Δ = 3.8 left	43.0 to 161.8 Δ = 118.8 forward***
VF	High	−87.5 to −64.1 Δ = 23.4 up*	32.1 to −14.7 Δ = 46.8 left***	116.5 to 108.8 Δ = 7.7 back
	Low	−80.5 to −99.2 Δ = 18.7 down**	8.4 to 17.8 Δ = 9.4 right	110.4 to 89.0 Δ = 21.4 back**

* $p \leq .05$

** $p \leq .01$

*** $p \leq .001$

Table 5

The difference in the position of the hand along each axis (in mm) as an effect of increased signing rate for the sign STUBBORN.

Signer	Environment	Vertical axis	Lateral axis	Horizontal axis
LL	High	−85.7 to −60.0 Δ = 25.7 up***	72.3 to 45.3 Δ = 27.0 left***	128.2 to 121.4 Δ = 6.8 back***
	Low	−69.2 to −111.7 Δ = 42.5 down***	41.5 to 50.1 Δ = 8.6 right	125.6 to 112.7 Δ = 12.9 back***
RD	High	−96.9 to −84.7 Δ = 12.2 up	68.4 to 51.7 Δ = 16.7 left	89.2 to 115.0 Δ = 25.8 forward***
	Low	−106.4 to − 87.3 Δ = 19.1 up**	62.5 to 70.3 Δ = 7.8 right	94.0 to 98.4 Δ = 4.4 forward
VF	High	−28.4 to −44.4 Δ = 16.0 down	−28.1 to 3.3 Δ = 31.4 right	130.3 to 147.0 Δ = 16.7 forward*
	Low	−51.1 to −67.9 Δ = 16.8 down**	31.9 to 9.1 Δ = 22.8 left	131.0 to 135.1 Δ = 4.1 forward

* $p \leq .05$

** $p \leq .01$

*** $p \leq .001$