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Location in ASL:

Insights from phonetic variation

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Abstract

Recent work on location variation led us to investigate whether phonetic effects influence the lowering of certain forehead located signs in American Sign Language. We found that signing speed and the location of adjacent signs did affect these forehead signs in ways that conform to general principals of coarticulation. In this paper, we use those results as a basis to illustrate additional approaches to the evaluation of the phonetics of location. In particular, we suggest that finer grained analyses of location values may provide insights into directionality of coarticulatory effects, that changes in body posture assist in the achievement of location values, and that kinematic data can be used to describe the use of the signing space in a global sense. Previous work in sign phonetics has provided a solid foundation and new research is progressing well, but there is much work yet to be done.

Keywords

location variation; American Sign Language; signing speed; coarticulation; signing space; postural changes

1. Introduction

Several recent studies have carried out quantitative phonetic analyses of sign production in American Sign Language (ASL) (Grosvald & Corina 2011; Tyrone & Mauk 2010; Tyrone & Mauk in press; Eccarius & Scheidt 2010; Weast 2008). The exploratory analyses discussed in this paper developed out of that line of research but have a different emphasis. Instead of focusing on the original hypotheses and basic findings, this paper will discuss questions that emerged in the data which we had not considered beforehand. One goal of the paper is to shed light on issues that can be addressed by future research in sign phonetics and phonology.

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In fluent signing, sign language users' precise patterns of movement are influenced by a number of factors, including signing rate, phonetic environment, linguistic register, and the language's phonological rules (Mauk & Tyrone 2008; Quinto-Pozos et al. 2009; Crasborn 2001; Wilbur 1999). One of the goals of sign phonology is to better understand the underlying structural units of signed language, but in order to do so, it is necessary to tease apart the factors — phonetic, phonological, or otherwise — that can influence variation across productions.

In comparison to other branches of linguistics, phonetics has received limited attention in sign language research. As a result, there is much work to be done in identifying and describing basic phonetic processes in the sign modality. But in addition to this, a deeper understanding of sign phonetics will allow researchers to better explore other aspects of the structure of signed language. Because it focuses on precise measures of sign production, sign phonetics provides tools for describing a range of linguistic and non-linguistic phenomena. These tools can facilitate comparisons of groups or individuals which will illuminate aspects of sign language structure. For example, phonetic measurements can be used to compare groups of signers who differ in age, gender, or language background. Similarly, differences within groups or within individuals can be analyzed phonetically to identify patterns associated with formal vs. informal signing or to compare the production of signs to the production of gestures.

The specific area that we are considering in this paper is the interface between phonetics and phonology in the realization of sign location. Several studies have noted that the phonetic location of a sign can vary considerably from one production to another (Lucas et al. 2002; Schembri et al. 2009; Russell et al. 2011). While we know that signs are not always produced at their canonical locations, several questions remain. Where do signs shift away from their canonical locations? Which signs shift and which signs do not? What factors affect the realization of sign location?

In his work on the phonological parameters of ASL, Stokoe (1960) identified 12 contrastive locations on the body in ASL, including several locations on the face. The location parameter describes where a sign is produced, but the hand does not have to make contact with the body at its phonological location. In the ASL sign FATHER (Figure 1), the hand makes contact with the forehead, which is the sign's location. The forehead is also the phonological location for the sign WONDER (Figure 2), but the hand does not make contact with it at all. In addition, signs may have the same phonological location but use different parts of the hand to make contact. For example, it is the thumb that contacts the forehead for the sign FATHER (Figure 1); but the tips of the fingers touch the forehead for the sign KNOW (Figure 3). It is not clear how these factors — contact or lack of contact, and specific point of contact — influence sign location at a phonetic level.

1.1 Context effects in signed language

Several studies have examined coarticulation and phonetic variation in ASL and in other signed languages (Wilcox 1992; Cheek 2001; Mauk 2003; Grosvald 2009). Cheek (2001) used quantitative signing data to investigate whether there was systematic handshape variation in ASL. She examined ASL signs with 1-handshapes and 5-handshapes, that were preceded and followed by signs which also had either 1- or 5-handshapes. She found that ASL handshapes did show systematic variation as an effect of phonetic environment, which was rate-dependent. She interpreted the results as suggesting a process of coarticulation rather than assimilation.

Mauk (2003) investigated articulatory undershoot in fast signing (ASL) and fast speech (English). This was the first study to examine quantitative phonetic data both in sign and in speech. He found that undershoot occurred in ASL as an effect of phonetic environment and rate. During fast signing, signs that were low in the signing space tended to be raised when they were produced in a high phonetic environment. Conversely, signs that were high in the signing space were sometimes lowered in the low phonetic environment.

Similarly, Grosvald (2009) and Grosvald & Corina (this issue) examined coarticulation in the speech and sign modalities by analyzing productions of schwa-like vowels in English and signs with neutral space locations in ASL. Like the earlier study by Mauk, Grosvald's studies compared positional sign data to acoustic speech data (as opposed to comparing positional data in both modalities). Grosvald found that coarticulatory effects spanned as many as five segments in the speech data but only extended as far as three segments in the sign data. Moreover, perceptual testing revealed that coarticulatory effects were more perceptible in spoken English than in ASL.

1.2 Lowering

In their study of conversational signing, Lucas et al. (2002) observed that some ASL signs located at the forehead were produced at lower locations. They investigated a range of factors that might influence the lowering of these signs, including grammatical category and phonetic environment. They found that prepositions and other function words were lowered more often than forehead-located signs from other grammatical categories. In their analysis, grammatical category was a good predictor of phonetic location, but the phonetic environment of the preceding and following signs did not predict the phonetic location of the signs at the forehead. Schembri et al. (2009) carried out a similar sociolinguistic study of the lowering of high signs in Auslan and New Zealand Sign Language. They found that lowering occurred for different sociolinguistic groups but patterned differently from group to group. Moreover, grammatical category was a predictor of lowering, but there was an interaction between it and sociolinguistic group.

In order to examine the seeming contradictions between the findings of sociolinguistic and phonetic studies of sign lowering, Russell, Wilkinson & Janzen (2011) collected a set of ASL corpus data and examined signs with phonological locations on the face, head or neck. Their data were more naturalistic than prior phonetic data, but were also measured in more phonetic detail than prior sociolinguistic data. Russell et al. found that signs located on the head and neck were often lowered in conversational contexts. Based on their results, they suggested that sign lowering occurs in both a categorical and a gradient manner, but that gradient undershoot is nonetheless carefully planned.

1.3 Precursors to this study

In a previous study, we examined lowering in a sign that is high in the signing space but does not make contact with the forehead, the ASL sign wonder (Tyrone & Mauk 2010; Mauk & Tyrone 2008). Signing rate, phonetic environment, and phrase position were manipulated in order to determine their effects on the sign's phonetic location. Data were examined from six native Deaf signers who produced phrases which contained the sign wonder once at the beginning of the phrase and once at the end of the phrase. In total, 120 tokens of the sign were analyzed for each signer. The main result of that study was that signing rate had a significant effect on the sign's location for all participants either as a main effect or through interaction with another variable. For each signer, wonder was produced at a significantly higher phonetic location in slower signing than in faster signing.

More recently, we carried out a similar study in which we examined several signs with a phonological location at the forehead, and manipulated signing rate and phonetic environment in order to investigate phonetic reduction (Tyrone & Mauk in press). Data were collected from four native ASL signers, who produced forehead-located signs at one of three signing speeds (normal, fast, and very fast) and in a high or a low phonetic environment. The signs that were examined were KNOW, WHY, FATHER, and STUBBORN. The results indicated that forehead-located signs tended to be produced at a lower position when they were embedded in a low phonetic environment. Moreover, lowering was stronger and occurred more often at faster signing rates.

Lowering as an effect of signing speed and phonetic environment was not uniform for all signs or for all signers. We specifically selected two signs for this experiment, KNOW and WHY, because they are reported to be lowered in conversational contexts (Lucas et al. 2002). These two signs were lowered by signers in these experiments, too, though not as consistently as expected. The sign KNOW was not substantively lowered as an effect of phonetic environment alone, but it was lowered as an effect of both signing rate and phonetic environment. The signs WHY and STUBBORN were lowered as an effect of phonetic environment alone, but signing speed had inconsistent effects on lowering for those two signs. We had predicted that the sign FATHER would not undergo much lowering, given that the neighboring sign MOTHER shares the same handshape and movement but is located at the chin. The sign father was lowered only slightly by two signers as an effect of phonetic environment. It was lowered more at faster signing speeds, though not always as predicted based on the phonetic environment.

One of the unexpected results of this study was that some signs (such as FATHER) were produced at higher locations when certain signers were signing faster. What is less clear is whether fast signing was affecting the forehead signs in isolation or affecting the production of entire phrases. Another unexpected result was that signs were sometimes shifted along other positional axes (i.e., left-right or back-front). These shifts were more variable across subjects and not related to the factors we manipulated. (It should be noted that the experimental stimuli were not designed to elicit positional changes on the horizontal plane.)

These investigations of the lowering of forehead-located signs raised a variety of questions about the phonetic realization of signs and its implications for phonology. For instance, in our studies of coarticulation and undershoot, the positions of specific target signs were carefully measured, but the precise positions of the signs in the carrier phrases were not measured. Instead, phonetic environment was treated as a categorical variable (i.e., high or low). It may be that the exact position of the phonetic environment has a stronger coarticulatory effect than the broad category of the phonetic environment. In addition, we observed informally that changes in our independent variables (signing rate and phonetic environment) affected aspects of production other than the realization of the target signs. Signers adopted different coordination strategies and organized the signing space differently as a result of the articulatory demands of the different conditions.

1.4 The current study

Most of the data discussed here were collected from one participant, VF — a 46 year old woman who acquired ASL natively and is a member of the local Deaf community. Data from three other signers will be discussed briefly. All three are middle-aged Deaf adults who are members of the local Deaf community: a female native signer, a male non-native signer, and a female non-native signer.

The first signer's productions were captured with an Optotrak Certus system, which tracks the position of infrared light-emitting markers over time. Markers were taped to the signer's articulators, and marker positions were tracked at a 60 Hz sampling rate. Two markers were attached to the signer's right hand: one on the ulnar side, just below the metacarpophalangeal joint and the other on the dorsal side of the hand, at about the midpoint of the third metacarpal bone. In addition, six markers were attached to a head-mounted device, so that head movements could be tracked and compared to the hand's position. After the markers were attached but before signing trials were recorded, the signer was asked to practice producing the ASL target phrases, so that she could adjust to signing with the markers and the head-mounted device in place. She produced the target phrases at three rates: normal conversational signing rate, faster than normal, and as fast as possible. She was not coached more specifically on how fast to sign. For a more detailed description of data collection and analysis procedures, see Tyrone & Mauk (in press).

For the other three signers, similar procedures were carried out using a Vicon motion capture system. (The main difference between Optotrak and Vicon is that Optotrak uses wired markers that emit infrared light, and Vicon uses passive markers which reflect infrared light that is emitted by camera strobes.) In the Vicon procedure, 30 markers were placed on the body and data were sampled at a rate of 100 Hz. For more details about that procedure, see Tyrone et al. (2010).

2. Novel analyses

2.1 Coarticulatory effects of the exact position of preceding and following signs

The first question that we considered is the coarticulatory effect of the precise phonetic positions of preceding and following signs on the production of signs located at the forehead. Given that coarticulation can work in multiple directions, it is not necessarily true that a sign with a low phonological location will necessarily be produced at that location (cf. Mauk 2003). In an earlier work (Tyrone & Mauk in press), target signs' location data were analyzed with respect to a categorical independent variable for phonetic environment. Looking back on the data, we have taken a sample, know by signer VF, and carried out a more detailed analysis. In the sequence of signs elicited, the forehead sign know was embedded in one of two carrier phrases, one in which it was preceded by a point to a low location in the signing space and followed by the low neutral space sign RIGHT, and the other in which it was preceded by a point to a high location and followed by the cheek-located sign SEE. In the original analysis, phrase duration and phonetic environment category (low vs. high) were used as independent variables. We found that the sign KNOW frequently showed coarticulatory effects of its environment. This finding was true both for signer VF and for other participants in the study more generally.

We have now measured precise location values for the preceding point and the following sign in the carrier phrase. By looking at precise values, we are able to differentiate effects of the preceding and following elements. Through a linear regression, we find that the vertical location of know (regardless of signing rate) is more strongly correlated with the vertical location of the following sign than that of the preceding point. Figure 5 shows that as the location value of the following sign moves upward, the location of the sign KNOW moves upward as well ($r^2 = 0.78$). By contrast, in Figure 4, the vertical location of the end of the preceding point does not strongly correlate with that of the sign KNOW ($r^2 = 0.14$). This result suggests that the following sign has a greater influence on the sign know than the preceding point.

One possible explanation for why the following location is more strongly correlated with the target location than the preceding may be simply that the following signs were less variable in their production than the preceding points, especially in fast signing. Factors other than signing rate and coarticulation may be at play in the difference in variability. First, it may be the phonological specification of the elements that are in play. The following sign RIGHT or SEE both involve body locations, the former being the non-dominant hand and the latter the cheek. The preceding point, however, is not associated with a body location at either its beginning or end. It may be that body location specifications serve as a limiting factor in the variability of signs as suggested by Mauk et al. 2008. A second explanation may lie in the linguistic status of these neighboring elements. It has been suggested often that points have a less linguistic, and more gestural, status than signs (see for example, Liddell 2000).

With the right experimental design, this general method could be used to assess the directionality of coarticulation in signed languages. Creating carrier phrases that are asymmetrical (i.e., with one location preceding the target sign and another following it) would allow us to see whether coarticulation is more strongly anticipatory or perseverative. In this way, we could investigate whether preceding signs or following signs have more coarticulatory “power”.

2.2 Coordination of hand and head movement

The second question that we considered is the role of a “passive” sign articulator, i.e., the forehead. We observed informally that some signers not only moved their hands to reach the forehead location, but they also moved the head to facilitate contact between it and the hand. This compensatory head movement occurred more often at slower signing rates.

Figure 6 shows the position of the hand in three dimensions and the position of the head along the left-right (x-axis) dimension, as the signer VF is producing multiple repetitions of the ASL phrase “PICTURE (index) FATHER, RIGHT?” The dotted black line shows the left-right position of one marker on the head (leftward movement is lower and the rightward movement is higher in the figure). The solid black line shows the left-right position of a marker on the hand, and the dotted gray and solid gray lines show the up-down and back-front positions of the hand. The beginnings and ends of phrases are apparent from the large change in the hand's position on the vertical axis, as it goes from the lap to the upper part of the signing space to produce the beginning of the sign PICTURE. Next, the hand rises and falls again to produce a point downward and to the left. Then the hand rises moves up and rises to its highest position for the sign FATHER.

It is clear that as the hand rises and moves to the right, the head is also moving to the left to meet the hand to produce the sign FATHER. Apparently, sign articulators that are typically treated as passive locations (such as the forehead) can play an active role in sign production, adapting to the articulatory demands for a given utterance. It is partly for this reason that some phonetic studies have corrected for the head's position during signing (Tyrone & Mauk 2010; Russell et al. 2011). This point should be taken into account in considering which types of signs might be more difficult to acquire or to produce in a native-like manner. Presumably, signs with greater coordinative demands will be acquired later or with more difficulty.

2.3 Signing space

The third question that we considered is the overall size and position of the signing space under the different conditions. It may be that during fast signing, for example, it is not only the forehead-located sign that shifts, but the entire utterance. Here we present two preliminary analyses of the size of the signing space. The first examines the minimum and maximum range of movement over an extended period of signing for three signers. The second examines precise changes in the production of individual signs by one signer.

Vicon motion capture data were collected from a group of native and nonnative signers as they produced utterances with phrase boundaries placed at different positions (Tyrone et al. 2010). In these trials, signers produced a sequence of 18 scripted utterances, with multiple signs located at the forehead, chin, chest, and in neutral space. The same utterances occurred in all trials but the order of the utterances was randomized across trials. Signers were asked to produce the utterances at a normal signing speed. In a calibration trial at the beginning of each session, signers were asked to sit with their arms fully extended to the sides. From this calibration, the maximum distance between the right hand and the sternum was measured. For three signers, we selected twenty trials (each of about 20 seconds duration) and measured the maximum and minimum distances between the right hand and the sternum during signing, relative to the maximum anatomical distance between them. The maximum distances between the hand and sternum are likely to reflect the outer bounds of the signing space, while the minimum distances probably reflect how closely the hand approximates the body during signing.

In these data, the maximum distances between the right hand and sternum across signing trials for the native signer scarcely overlap with the maximum distances between the same two markers for the two non-native signers. There is only one case in which she moves the hand even half the distance that it can extend from the sternum. For the minimum distances between the hand and sternum during signing, the native signer and one of the non-native signers patterned similarly to each other, but differently from the second non-native signer, whose typical minimum distance was much larger. It appears that for the second non-native signer, the entire signing space is farther away from the body. These preliminary data suggest that native signers may use a more compact signing space, which could require them to make more subtle phonological contrasts in the location parameter.

Using data on the sign KNOW from one signer (Tyrone & Mauk in press), we examined the distribution of signs in the signing space. A marker on the ulnar side of the signer's dominant hand indicated the location of the hand in space in this data. Figure 8 shows a sample of this marker's trajectory for a single utterance in the lateral and vertical axes. The signer's hands began and ended the phrase at rest in her lap and transitions out of and back to rest were excluded from this sample. The furthest right marker value shown represents the start of the sequence wiinto the leftward and upward point.th the hand near the signer's cheek at the beginning of the sign PICTURE. The hand then moves down and to the left to contact the non-dominant hand at the end of PICTURE. From there, the hand arcs upward and to the left for a point toward a prop high in the signer's field of view. Next the hand returns to the right to the signer's forehead for the sign KNOW. Finally this sequence ends after the signer moves her dominant hand downward to the right cheek for the start of the sign SEE. This sign includes a movement away from the cheek, but because there was not a clear separation of this movement from a transition to rest, the movement of SEE has been excluded from the sample.

By looking at this kind of data we can have a sense of how the signer used the signing space, including the extent of the space, the amount of time the signer spent at various locations and the shape of movements within the space. Our data were scripted utterances and as such cannot reveal the full extent of the signing space. However, we can to a limited degree test how changes in signing rate affect spatial configurations. Figures 9 and 10 show ten tokens each of the utterance described above and compare the signer's normal conversational signing rate to her fastest production rate. The overall lateral range is slightly expanded in this fast signing sample (275 mm in the normal condition, 285 mm in the fast condition) and slightly shifted to the left. In the vertical dimension, the range used is expanded at the top by around 30 mm. While the range of the space used is not radically altered, the arrangement of the signer's movements has clearly changed. The excursion from cheek to dominant hand was similar, though shortened slightly in the fast condition. The movement from KNOW at the forehead to SEE at the cheek also similar. However, the transition into the point is clearly altered with the fast condition showing a large rebound to the right as the signer prepares to moves into the leftward and upward point.

Figures 11 and 12 show the low environment utterance picture downward point KNOW RIGHT. When comparing normal and fast, we find a larger alteration of the use of the space. The lowering of the forehead sign KNOW, shown by the upper right reversal in the trajectories reflects the primary finding of Tyrone & Mauk (in press), where forehead signs were shown to lower in low phonetic environments (to a greater degree than in high environments). An additional finding only now reported is that the end point of the downward and leftward point was also much lower in fast signing, depressing the lower limit of the space used for the utterance by around 150 mm. It should also be noted that fast signing did not lead to an overall shrinkage of the signing space, as might be predicted from models of articulatory undershoot in fast speech.

In these data, the greatest change seems to be in the realization of the point regardless of the phonetic environment. Points as potentially more gestural elements in signing may generally be more varied in their production. However, it seems in these data that the variability of the point within a given rate condition was smaller than across conditions. That is, it seems this signer has reorganized her productions in response to the rate condition, but then consistently used the new strategy.

Kinematic data of the kind reported here could be useful in investigations of signing space on a range of topics. For example, Uyechi (1996) suggested that a signer modifies their signing for public and private registers by using a scalar expansion and contraction of the space respectively, while stretching or shrinking lexically specified proportions for individual signs. However, it seems from these data that it may be the case that not all signing elements are treated equally in these situations.

3. Discussion

The findings from this study and several others suggest that signs produced in context differ from the citation forms of signs in predictable ways (Lucas et al. 2002; Russell et al. 2011; Mauk 2003; Schembri et al. 2009). In addition to our earlier, more systematic analyses of phonetic environment and rate, these preliminary analyses of precise phonetic environment, inter-articulator coordination, and the size of the signing space could have implications for the phonetics-phonology interface in the sign modality and for the structure of signed language more generally.

3.1 Quantitative vs. categorical measures

The comparison of detailed phonetic measurements, rather than strictly relying on general categories, can help illustrate a more complex picture of phonetic and phonological phenomena. For our data, we can see that the locations of some elements are more closely coarticulated with each other than with others. Similar applications can also be imagined in other areas of coarticulation research, but also perhaps with issues such as phonological assimilation or the use of space for grammatical purposes (cf. Cormier's (2002) instrumented analysis of indexicality).

Our research also suggests that the comparisons of gestural elements with signs can also be more carefully analyzed using these methods. We find that the articulation of gestural elements may be less constrained than that of signs. The issue of determining the best way to talk about the precise articulation of a variety of signing properties remains, however. Location values of markers can give a sense of where the hands and other articulators have been, but the field has yet to address best practices in analyzing movement shapes such as those seen in our signer's transition into her pointing gestures.

3.2 Inter-articulator coordination

Phonological locations should not be thought of solely as static targets that are situated on (or in front of) the body. While the hands are the primary articulators in the sign modality, articulatory targets on the head and body can (and do) move around as signs are being produced. As a result, different signs are likely to have different motoric demands, depending on which articulators' movements must be coordinated. Furthermore, signs with greater coordinative complexity will probably be more difficult to acquire, either during L1 or L2 acquisition, in much the same way that consonant clusters are more difficult to acquire than consonantvowel sequences in spoken language.

Past research suggests that some groups of signers, such as those with Parkinson's disease, have particular difficulty with coordination during sign and fingerspelling (Brentari et al. 1995; Tyrone et al. 1999). It may be worthwhile to consider inter-articulator coordination more broadly in looking at these types of group differences.

3.3 Signing space

Uyechi (1996) suggests that phonological location and signing space should not be viewed as entirely independent of each other. In her model, phonological locations are local spaces that are embedded in the larger signing space. Moreover, the larger signing space is modified as necessary to meet different communicative needs. That being the case, phonological locations are likely to be affected by the size, shape, and position of the signing space. Consequently, the nature of the signing space deserves more attention, because even though it is not inherently phonological, it can still influence sign phonology.

While it has scarcely been investigated at all, the signing space is probably not uniform across signers. In other words, not all signers use the same amount of space in relation to their own anatomical limits. In addition to using different amounts of space, signers may also use some areas of space more than others. For example, one signer's signing space may be farther to the left or right than another's. So when we look at phonological location, it might make sense to do so in the context of the size of the entire signing space. Further, some signers may favor certain portions of the signing space or certain locations on the body and use them more often. Moreover, signs in certain locations may be more likely to retain their association with those locations, whereas other locations might allow more flexibility in production.

The field of sign phonetics, and the larger field of sign linguistics, would benefit greatly from a valid, reliable procedure for normalizing sign production data. It will be possible to carry out much more robust linguistic analyses once such a procedure is in place. Grosvald (2009) and Russell et al. (2011) have made considerable progress in normalizing phonetic sign data so that productions can be compared across signers. Ultimately, a better understanding of the size and use of the signing space will be required for the development of a valid, comprehensive normalization procedure.

4. Concluding thoughts

Early research by Stokoe (1960) identified handshape, movement, and location as the phonological parameters in ASL that could be used to create contrasts between signs. His pioneering analysis has served as the primary framework for subsequent research in sign phonology. Many studies have explored various aspects of the phonological parameters of signed language (cf. Brentari 1998; Crasborn 2001; Best, Mathur, Miranda & Lillo-Martin 2010). However, until recently, there has been limited empirical investigation of individual variation in the realization of the parameters and its implications for the phonetics-phonology interface. This research, like some studies before it, suggests that the realization of phonological location in ASL is highly varied across signers, across signs, and across individual tokens. Moreover, some aspects of that variation are linguistically motivated while other aspects are not. It is incumbent upon sign phonologists and sign phoneticians to explore and identify sources of variation in sign production in order to better understand the structure of signed language.

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Figure 1. ASL FATHER

Figure 2. ASL WONDER

Figure 3. ASL KNOW

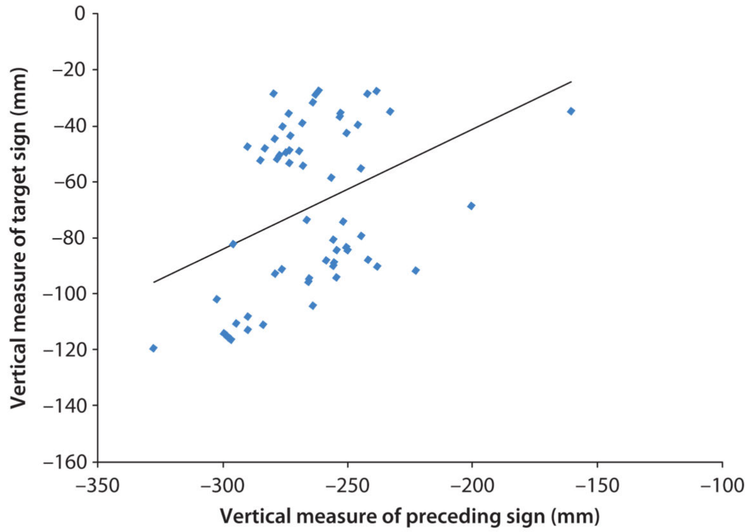

Figure 4.

A comparison of the location of know with the end point location of the preceding point

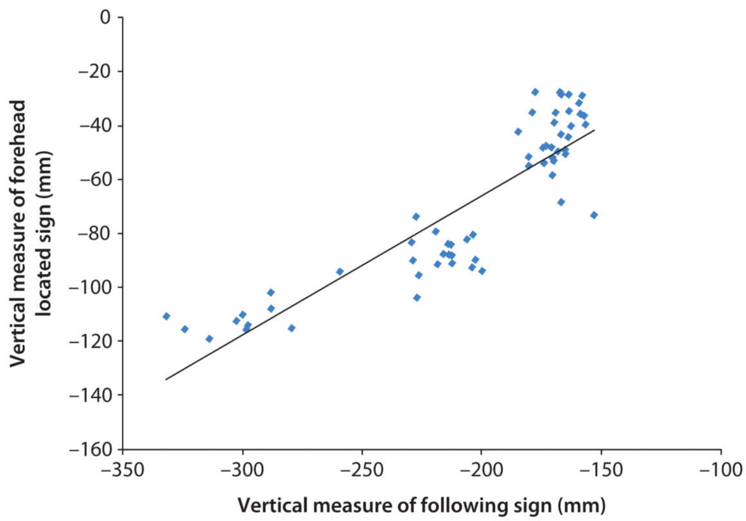

Figure 5.

A comparison of the location of know with the end point location of the following sign

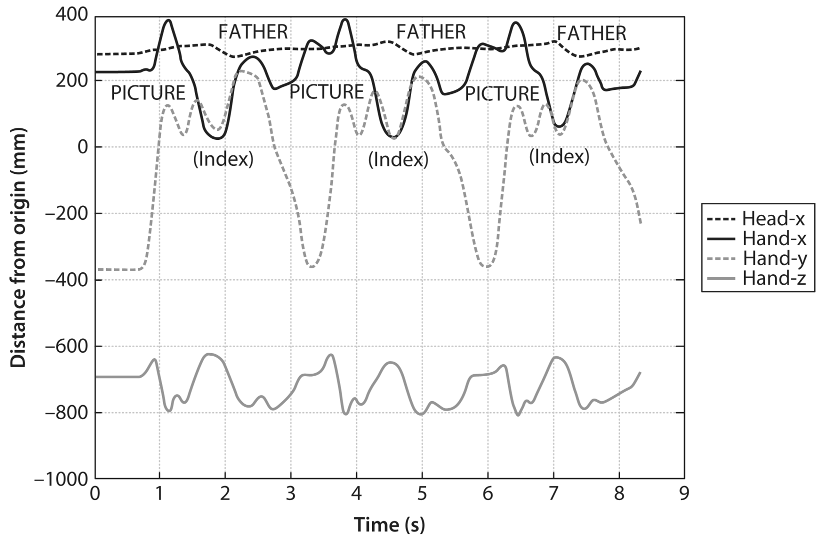

Figure 6.

Trajectory for the hand marker in three dimensions, lateral (x-axis), vertical (y-axis) and horizontal (z-axis) and trajectory for the head frame device in the lateral dimension (x-axis).

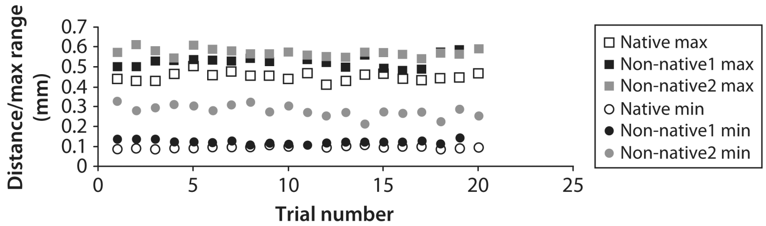

Figure 7.

The maximum and minimum distances between markers on the sternum and on the right hand during signing, as a ratio of the maximum anatomical distance between those markers.

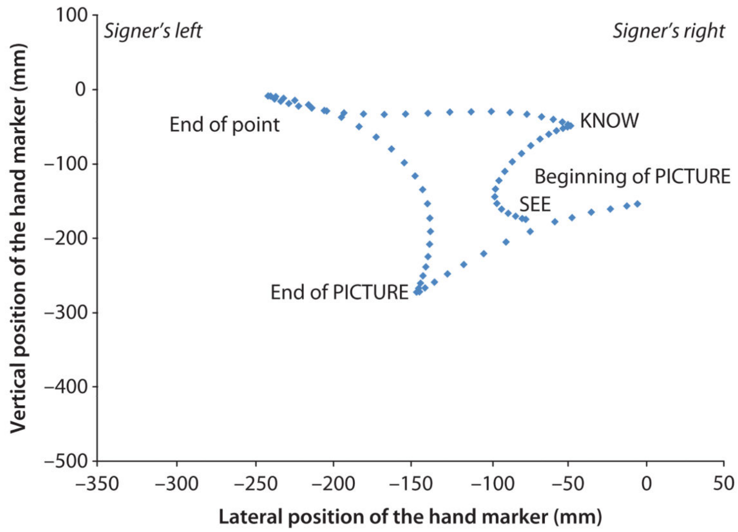

Figure 8.
Trajectory of the hand marker in two dimensions, lateral (x-axis) and vertical (y-axis), for a single utterance.

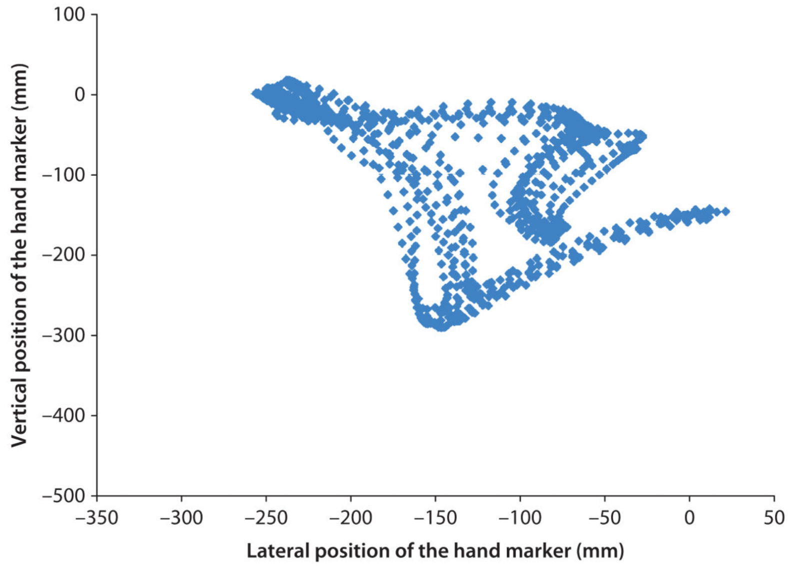

Figure 9.
Ten utterances with a high environment at a normal signing rate.

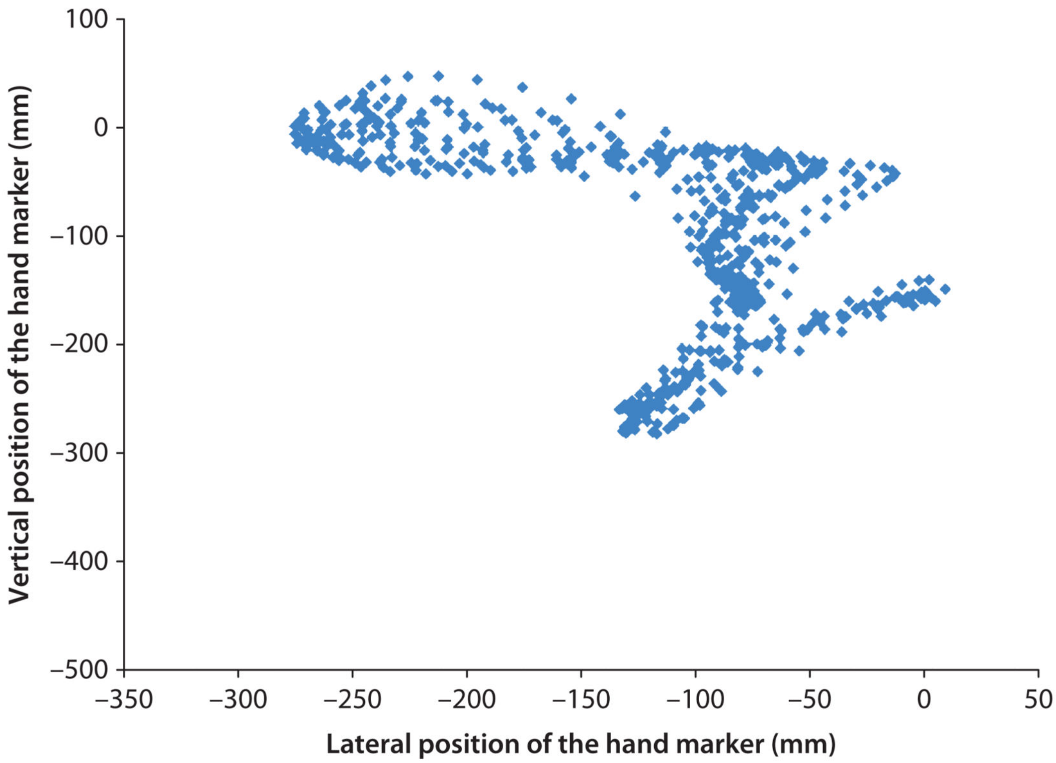

Figure 10.
Ten utterances with a high environment at a fast signing rate.

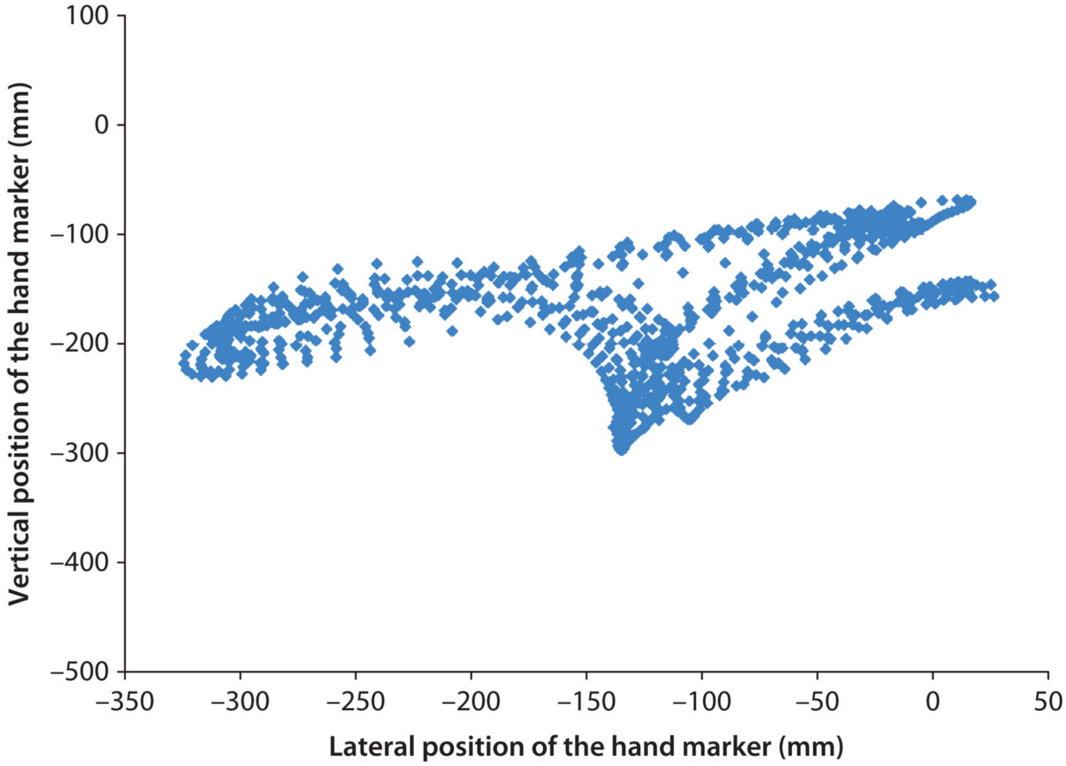

Figure 11.
Ten utterances with a low environment at a normal signing rate.

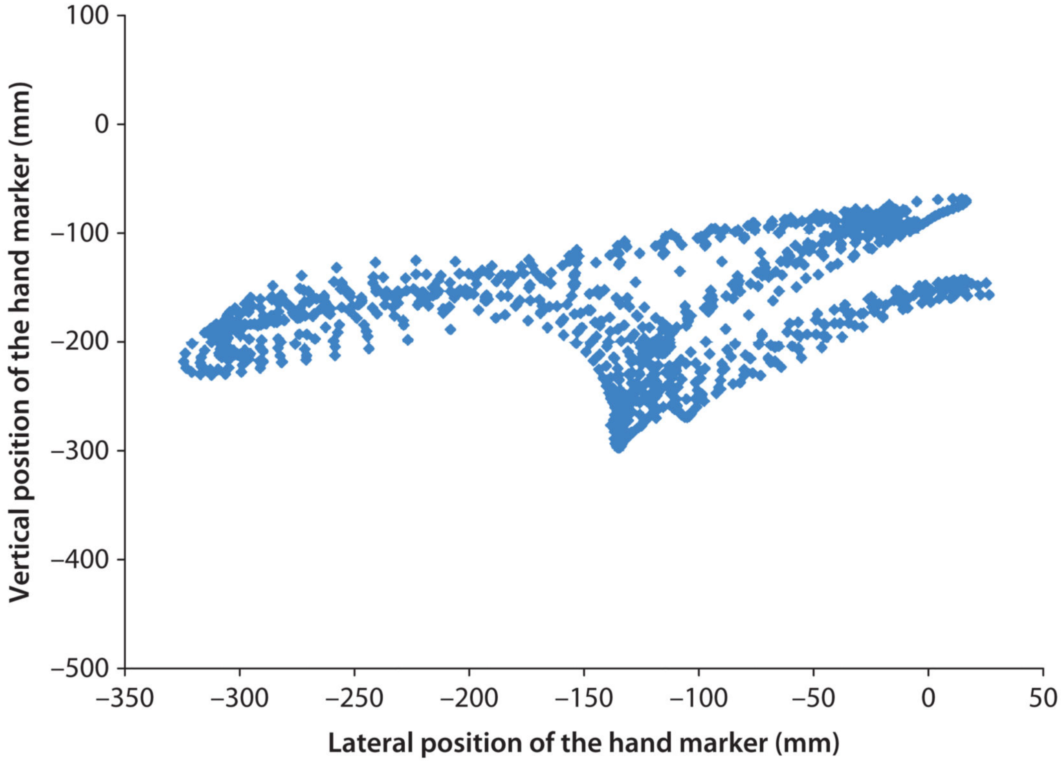

Figure 12.
Ten utterances with a low environment at a fast signing rate.