Exploring the movement dynamics of manual and oral articulation: Evidence from coarticulation

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Abstract

This project explores three classes of human action through an investigation of long-distance coarticulation, defined here as the articulatory influence of one phonetic element (e.g., consonant or vowel) on another across more than one intervening element. Our first experiment investigated anticipatory vowel-to-vowel (VV) coarticulation in English. The second experiment was patterned after the first but deals instead with anticipatory location-to-location (LL) effects in American Sign Language (ASL). The sign experiment also incorporated a non-linguistic manual action, permitting a comparison of effects not only between spoken and signed language, but also between linguistic and non-linguistic manual actions.

For the spoken-language study, sentences were created in which multiple consecutive schwas (target vowels) were followed by various context vowels. Eighteen English speakers were recorded as they repeated each sentence six times, and statistical tests were performed to determine the extent to which target vowel formant frequencies were influenced differently by different context vowels. For some speakers, significant effects of one vowel on another were found across as many as five intervening segments. In the sign study, motion-capture technology was used to investigate LL coarticulation in the signing of five ASL users. Some evidence was found of significant LL coarticulatory influence of one sign on another across as many as three intervening signs. However, LL effects overall were weaker and less pervasive than the VV effects found in the spoken-language study. The outcomes in the sign study's linguistic and non-linguistic conditions did not substantially differ. Collectively, these results support and complement previous research which has found that in comparisons of linguistic and non-linguistic manual and oral actions, movement patterns associated with oral and manual actions differ appreciably, while the linguistic vs. non-linguistic distinction appears to show little or no influence.[1]

Keywords: *long-distance, coarticulation, sign language, ASL, vowel-to-vowel, non-linguistic, movement dynamics.*

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1. Introduction

In this paper, we explore movement patterns in three types of human action: speech, sign language, and a particular set of non-linguistic manual actions. In the case of speech, we make use of acoustic analysis to make deductions about the movements that were made in producing the acoustic signal; the other two action types are investigated through the use of motion-capture technology. In all three cases, we investigate the extent and magnitude of anticipatory coarticulation, which among other things can offer useful information about articulatory planning. A major goal of this project is to investigate whether coarticulatory effects in speech or sign language can be considered specifically language-based, rather than reflecting processes of motor planning and execution common to human actions in general.

1.1. *Signed and spoken language*

Manual-visual languages like American Sign Language (ASL) are naturally occurring and show syntactic, morphological and phonological complexity which is comparable to that of spoken languages. Since the groundbreaking work of Stokoe (1960), much progress has been made in understanding the underlying components of sign language structure. Just as phonological segments in spoken language may be characterized in terms of parameters like place and manner of articulation or tongue height, signs may be described in terms of the four parameters Handshape, Location, Movement and palm Orientation. However, the extent to which analogous structural descriptions are possible between languages of the two modalities (e.g., whether there is a sign analogue of the syllable) is not yet settled (e.g., see Perlmutter 1992; Brentari and Goldsmith 1993; Corina and Sandler 1993; Corina 1996; Sandler and Lillo-Martin 2006; van der Kooij and Crasborn 2008).

The "neutral signing space" in front of the signer's body, which serves as the Location parameter value for some American Sign Language (ASL) signs, admits a number of representational possibilities (e.g., see Brentari 1998; Sandler and Lillo-Martin 2006). The current project begins with the premise that with respect to its position and articulatory behavior in the greater signing space, neutral space might be somewhat analogous to English schwa. Consequently, it may be particularly susceptible to the coarticulatory influence of the location of neighboring signs in the flow of signed language just as schwa, relative to other vowels, tends to show greater coarticulatory influence from neighboring vocalic segments (e.g., Fowler 1981; Alfonso and Baer 1982). Figure 1 illustrates this comparison. A related suggestion by Mauk (2003) is that neutral space signs might be more variable than other signs because they lack contact or a close association with a body location.

To explore these possibilities, we created a number of ASL sentences containing multiple consecutive neutral-space signs followed by "context signs" varying in their Location parameter. Signers were outfitted with motion-capture sensors which enabled us to record the three-dimensional positioning of the signer's hands

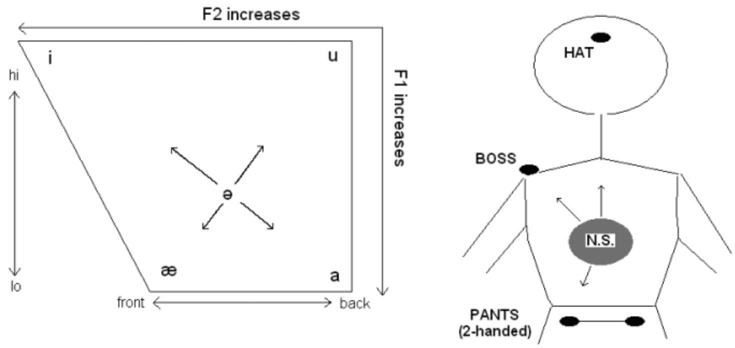

Figure 1. *Expected direction of influence of various vowels on schwa and of various sign locations on neutral signing space (N.S.).*

as they signed these sentences. Similar methods have proven fruitful in previous work on sign language phonetics (e.g., Vogler and Metaxas 1997; Cheek 2001; Mauk 2003; Tyrone and Mauk 2010). The coarticulatory effects of the context signs on preceding signs with respect to Location were then investigated. We hypothesized, for example, that neutral-space signs preceding a context sign articulated at the forehead (e.g., HAT; see Figure 1) would tend to have a higher z-coordinate (altitude) than the same neutral-space signs preceding a context sign articulated at a lower part of the signer's body (e.g., PANTS; see Figure 1). This sign study was carried out in parallel with a spoken-language study examining the coarticulatory effects of various context vowels on schwa, so that a cross-modality comparison might be possible in (arguably) analogous circumstances.

The signing task also included a non-linguistic condition involving the performance of a brief manual action requiring a range of motion similar to that needed for the corresponding sign contexts. To the extent that the coarticulatory effects found in speech can be considered specifically "linguistic" in nature, the English and ASL tasks might be expected to show similar outcomes, perhaps in contrast with the non-linguistic manual task. On the other hand, if coarticulation is more importantly related to the nature of the articulators involved, and not to the linguistic status of the items articulated during the task, we may expect to find that the outcomes for signing and non-linguistic manual actions are more similar.

This second possibility is foreshadowed by a study of Ostry et al. (1987), who examined movement patterns related to speech, non-linguistic oral (tongue and jaw) motions, and non-linguistic arm motions, and found that the linguistic and non-linguistic oral tasks patterned together. In contrast, the orally-based and arm-based tasks differed qualitatively. Specifically, the velocity curves of arm movements were found to be similar for movements of various amplitudes and durations, while the same was true for tongue and jaw movements over amplitude only, not duration.

	Linguistic		Non-linguistic
Tongue/jaw	speech	≈	other actions
	?		≠
Arm/manual	sign	?	other actions

Figure 2. *The top row and right column within the box indicate relationships among actions that are suggested by findings of Ostry et al. (1987). The left column and bottom row show relationships that are to be examined in the present study.*

As illustrated schematically in Figure 2, our study provides a complement to this work of Ostry et al. (1987). Their study examined tongue and jaw motions in linguistic and non-linguistic contexts, in addition to investigating non-linguistic manual actions. Ours examines manual actions in linguistic and non-linguistic contexts, in addition to investigating oral motions in a linguistic context (i.e., speech). As the top row in the figure indicates, speech and non-linguistic tongue/jaw actions have been found to be similar in movement-dynamic terms. The right column in the figure indicates that movement patterns for non-linguistic actions have been found to differ for oral vs. manual articulators. Both of these are central results of Ostry et al.'s (1987) study. The question marks in the figure indicate the comparisons of interest in the present study, which seeks to determine whether coarticulatory patterning is more similar (a) between signing and speech, or (b) between signing and the non-linguistic manual actions we investigate.

We now continue with an overview of our spoken-language study in Section 2, followed by the results of the parallel sign study, presented in Section 3. Our investigation of non-linguistic manual actions is incorporated into the sign study, so those results are also presented in Section 3. Implications of our findings are explored in the Discussion, which constitutes Section 4 of the paper.

2. Spoken-language study: English

2.1. *Introduction*

Transconsonantal VV coarticulation has been studied widely since Öhman's (1966) groundbreaking work on Swedish, English and Russian. Coarticulatory patterns are known to be influenced by many factors, such as prosodic context (Cho 1999, 2004; Fletcher 2004) and the particular segments that are involved (see Öhman 1966; Butcher and Weiher 1976; Purcell 1979; Recasens 1984, 2002; Recasens et al. 1997; Fowler and Brancazio 2000; Modaressi et al. 2004; Öhman 1966; Purcell 1979; Recasens 1984, 2002; Recasens et al. 1997, on consonants;

Gay 1974; Butcher and Weiher 1976; Bell-Berti et al. 1979; Butcher and Weiher 1976; Gay 1974, on vowels); such patterns also appear to vary across languages (Öhman 1966; Manuel and Krakow 1984; Manuel 1990). VV coarticulation is also known to occur across considerable distances (Recasens 1989; Magen 1997; Grosvald 2009; see also West 1999; Heid and Hawkins 2000; for related work). For example, Magen (1997) analyzed [bVbəbVb] sequences produced by four English speakers and found coarticulatory effects between the first and last vowel for some but not all of the four speakers. The present speech study was designed in part to address the question of how far such effects can extend.

2.2. *Methodology*

Eighteen participants (6 female, 12 male; ages ranging from 18 to 22, with mean 19.6 and SD 1.9) were recruited for the speech production experiment. All were undergraduate students at the University of California at Davis who received course credit for participating, were native speakers of American English and were uninformed as to the purpose of the study. The sentences used are given in (1):

(1) *It's fun to look up at a {keep, coop, cap, cop}.*

The final vowel in each sentence, respectively [i], [u], [æ], or [a], served as context vowel, while the preceding vowels in the words "*a*," "*at*," and "*up*," were the target vowels. These will be referred to as distance-1, -2 and -3 vowels, respectively. It was expected that in informal, connected speech, the distance-1 and -2 vowels would be reduced to schwa; the vowel [ʌ] was chosen to serve as distance-3 vowel because of its acoustic similarity to schwa. Coarticulatory influences of the context vowels on the target vowels were predicted to act as illustrated in Figure 1; for example, coarticulatory influence of the context vowel [i] should result in target vowels with lower F1 and higher F2 than for target vowels in the [a] context.

The sentences to be spoken were presented in random order on a computer screen located 24 inches in front of the subject. Subjects advanced through the task by pressing the space bar on a keyboard. Over the course of the task, each speaker said each sentence a total of six times. In order to encourage consistent prosodic patterning among these utterances, speakers were asked to say the sentences as if they were being spoken in a normal conversation in response to the question, "What's it fun to look up at?" Before beginning the experiment, speakers took part in a brief practice session.

Formant frequency measurements were performed onscreen using the Sound Edit function in Praat (Boersma and Weenink 2005), with the following settings: (for spectrogram) analysis window length 5 ms, dynamic range 30 dB; (for formant) maximum formant 5000 (5500) Hz for male (female) speakers, number of formants 5, analysis window length 25 ms, dynamic range 30 dB, and pre-emphasis from 50 Hz, using the Burg algorithm to calculate LPC coefficients. Formant frequency measurements for each target vowel were taken at the endpoint of the vowel rather than the middle. As a result, influences related to VV coarticulation from the context vowel were expected to be greater, though C-to-V effects from the immediately following consonant might also be expected to be stronger.

2.3. *Results*

2.3.1. *Group results.* For group analyses, a normalization procedure based on Gerstman (1968) was applied to each speaker's *n*th raw formant values for n = 1 and 2. Starting with a given speaker's average first and second formant values for full vowels [a] and [i] and with the raw formant value $F_{n\ raw}$ (for n = 1 or 2), the corresponding normalized value is given by the formula in (2)

(2) $F_{n\,norm} = 999 * (F_{n\,raw} - F_{n\,min}) / (F_{n\,max} - F_{n\,min})$

where $F_{n\,max}$ and $F_{n\,min}$ are the largest and smallest *n*th formant values among that speaker's vowels [a] and [i]. In other words, $F_{1\,max}$ and $F_{1\,min}$ are given by the speaker's average F1 for [a] and [i] respectively, with the reverse order for F2 values. The procedure has the effect of scaling each speaker's formant values relative to the width and height of the space defined by his or her [i] and [a]. Both F1 and F2 are scaled to a range 0–999 with the context [a] at (999, 0) and the context [i] at (0, 999), making comparisons between speakers more reasonable.

Figure 3 is a vowel-space plot showing mean normalized first and second formant frequencies for each distance condition and in each context. As might be expected, increased distance from the context vowel is associated with progressively reduced formant differences among the vowel contexts. Also, C-to-V effects seem to be superimposed over the VV effects at each distance: as place of articulation changes from labial to alveolar to velar at distance 3 ("*up*"), 2 ("*at*") and 1 ("*a keep|cop|coop|cap*"), F2 of the target vowel sets increases accordingly. Although these C-to-V effects are due to different consonants at different distances, for each distance condition the influencing consonant was the same for all vowel contexts, and the crucial distinctions for our purposes are the variations in F1 and F2 associated with those contexts.

To determine the extent to which the context-related differences seen in Figure 3 are significant, a number of analyses were performed on the group dataset. Here, for simplicity of presentation, statistical results will be presented only for the [a]–[i] contrast. For F1, a two-way ANOVA with factors of Distance (1, 2 or 3) and Context vowel ([a] or [i]), performed on the group dataset, found highly significant main effects of Distance ($F(2,34) = 52.1$, $p < 0.001$) and Context vowel ($F(1,17) = 75.8$, $p < 0.001$), as well as a Distance–Context interaction ($F(2,34) = 15.7$, $p < 0.001$). Planned comparisons showed that the [a]–[i] contrast was highly significant at both distances 1 and 2 ($p < 0.001$), and marginally significant at distance 3 ($p = 0.058$). For F2, a similar ANOVA found highly significant main effects of Distance ($F(2,34) = 207.8$, $p < 0.001$) and Context vowel ($F(1,17) = 141.4$, $p <$

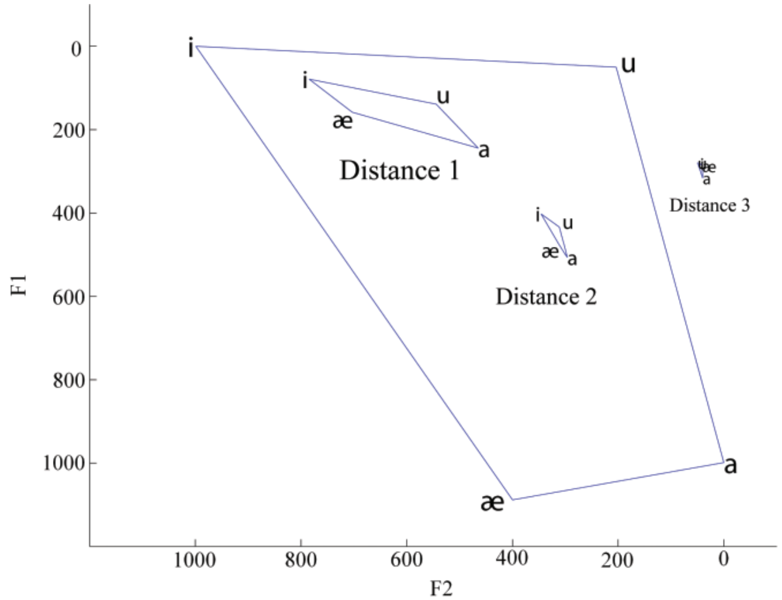

Figure 3. *Context-vowel and distance-1, -2 and -3 target-vowel positions in normalized vowel space, averaged over the 18 speakers. The averaged formant values are marked by the line segment endpoints, not the labels. Distance-1, -2 and -3 vowel sets are labeled with progressively smaller text size and are seen toward the left, center and right of the figure, respectively. Significance testing results are given in the text.*

0.001), and a Distance–Context interaction ($F(2,34) = 104.5$ $p < 0.001$). Planned comparisons showed that the [a]–[i] contrast was highly significant at both distances 1 and 2 ($p < 0.001$), but not at distance 3 ($p = 0.53$).

These results are indicative of strong coarticulatory tendencies for at least some speakers, at least as far ahead as two vowels before the context vowel, and perhaps three in some cases. To explore this finding, the coarticulatory tendencies of individual speakers were examined in more detail.

2.3.2. *Individual results.* For each speaker, one-tailed heteroscedastic t-tests were run for F1 and F2 for each distance condition (1, 2 or 3) to determine if formant values differed significantly between the [a] and [i] contexts. One-tailed tests were appropriate since it was predicted that [i]-colored vowels would have lower F1 and higher F2 than [a]-colored vowels. Results are summarized in Table 1; numerical results are given in Table 5 in the Appendix. Most speakers showed significant effects only as far as distance 1 or 2, but four showed significant distance-3 effects. Overall, these results confirm and extend Magen's (1997) finding of high variability between speakers in the production of long-distance VV coarticulation.

Table 1. *Anticipatory coarticulation in spoken-language study. For each speaker, the significance testing outcomes of three t-tests are shown, comparing F1 and F2 values of that speaker's target vowels for the [i] vs. [a] contexts for each distance condition. Significant results are shaded and labeled, where * = p < 0.05, ** = p < 0.01 and *** = p < 0.001 (not Bonferroni corrected).*[2] *Also noted are marginal results, where + = p < 0.10; a √ indicates a non-significant outcome in which averages were nevertheless in the expected direction (i.e., F1 greater for the [a] context than for the [i] context).*

Speaker	Distance 3 ("***up***")		Distance 2 ("***at***")		Distance 1 ("***a***")	
	F1	F2	F1	F2	F1	F2
1	√		*	+	***	***
2	√		*	√	**	***
3		√	*	***	***	***
4		√	√	+	**	***
5	√		√	+	**	√
6		√	√	√	**	**
7	*	+	√	**	+	***
8	√		*	**	***	***
9		√	√	**	**	***
10	**	+	+	+	***	***
11	√		+	**	+	***
12	√	√		*	**	***
13		√	*	***	***	***
14		√	√	***	**	***
15	+		√		**	**
16	√	+	***	√	√	***
17	*		*	***	*	***
18	*	√	**	+	**	*

3. Sign-language study: American Sign Language

3.1. *Introduction*

The long-distance effects seen in the spoken-language study just described inspired us to ask whether such long-distance effects might also be found in sign language, a question that appears to be unaddressed in the literature to date, though some researchers have examined other aspects of coarticulation in ASL. These include Cheek (2001), who found different handshape-based coarticulatory effects on target signs in the context of signs articulated with "1" versus "5" handshape; and Mauk (2003), who found Location-to-Location effects of signs on neighboring signs in the context of a study of undershoot.

In addition, earlier studies have shown "h2 spread" to be an example of a relevant sign-language phenomenon which can extend across non-adjacent signs. The term "h2 spread" refers to the fact that in some situations, the non-dominant hand (h2) may assume the handshape and location for which it is specified in a two-handed sign, during the articulation of neighboring one-handed signs. Nespor and Sandler (1999) give examples of h2 spread in Israeli Sign Language, noting that it can extend further than one sign away from the triggering sign, in either the anticipatory or carryover directions, though it is blocked by phonological phrase boundaries. These conclusions are supported by Brentari and Crossley (2002) in a study of prosody in ASL (for other relevant work see Lucas, Bayley, Rose and Wulf 2002; Ojala, Salakoski and Aaltonen 2009; Wilcox 1992).

The present study was motivated by the idea that schwa and neutral space might be somewhat analogous, both in terms of their central position within their respective articulatory spaces and of their coarticulatory behavior. It is important to point out that there is *no* claim being made here that (1) neutral space is in some sense underspecified in the way some researchers have suggested schwa may be (e.g., see Browman and Goldstein 1992; van Oostendorp 2003), or (2) that the sign parameter Location is analogous in sign phonology to vowels in spoken-language phonology.

In Grosvald and Corina (2008), we reported the results of a pilot study in which a single signer took part. When signing ASL sentences with consecutive neutral-space signs followed by signs articulated on the body at different heights (e.g., the forehead for FATHER vs. the chin for MOTHER), the signer often signed the neutral-space signs at a greater height in "higher" contexts than in "lower" ones. When present, these differences were on the order of 1.5 to 2 cm for adjacent signs and 1 cm in non-adjacent conditions in which target signs and context signs were separated by up to two intervening signs. In a variety of contexts, some evidence of coarticulatory effects in all three spatial dimensions was found. However, the effects seen, while certainly suggestive, were less pervasive than those found in the parallel speech study just discussed. Even the coarticulatory effects of adjacent signs (i.e., in the "distance 1" condition) often failed to reach significance, and most of the predicted effects reached marginal significance at best. Occasionally, apparent cases of dissimilatory effects were also seen, though their occurrence did not seem to follow any obvious pattern.

Here, we present findings from a full-scale study for which we recruited a total of five signing participants. In this study, we examined a total of eleven context items and two target signs in four distance conditions, and investigated coarticulatory influences of context items on target signs in all three dimensions. However, as with the speech study, for simplicity of presentation we present here a subset of the overall results, limited to our key findings involving the z-dimension (up vs. down) only.

3.2. *Methodology*

3.2.1. *Participants.* The first participant in the sign study, Signer 1, was a female native signer of ASL who was an employee in the laboratory where the study was conducted. The other four deaf participants were residents of Northern California who were recruited through advertisements or word-of-mouth and were paid for their participation. All of the signers were uninformed as to the purpose of the study. Although these signers' backgrounds varied in terms of their age of acquisition of ASL, all were fluent signers who considered ASL their primary means of communication. Table 2 gives some basic demographic information concerning the five signers.

3.2.2. *Task.* As in the speech study, the idea here was to investigate anticipatory coarticulation by having language users articulate sentences which contained target items (schwa in the speech study, neutral-space signs here) followed by context items articulated at the far edges of the articulatory space (corner vowels in the speech study, items with "high" and "low" locations here). Coarticulatory effects for ASL were expected to be manifested as consistent shifts in the 3-dimensional location of target signs, relative to the signer, in the environment of different context signs.

The results for the target sign WANT will be presented here. This was a convenient target item because it is articulated with a characteristic dip in the vertical (z)

Table 2. *Demographic information on the five signers who participated in the sign production studies.*

Signer	Gender	Age	Handedness	Age of Acquisition of ASL
1	F	35	R	Native
2	F	38	L	Native
3	M	37	L	Late (~high school)
4	M	40	R	Early (~age 3)
5	F	33	R	Early (~early childhood)

Figure 4. *Still frames showing Location of (from left to right) the target sign WANT and the context signs HAT and PANTS.*

Table 3. *Sentences and context items used in the sign production study.*

Distance	Sentence
1	I WANT (X) I.
2	I WANT FIND (X) I.
3	I WANT GO FIND (X) I.
4	I WANT GO FIND OTHER (X) I.

Context	Handshape, Palm Orientation	Location	Movement
HAT	B, palm down	Forehead	Tap head twice
PANTS	B/Bent B, palm down	Waist / lap	Flick fingertips twice
⟨red⟩	(not specified)	"high"	Flip a switch; see text
⟨green⟩	(not specified)	"low"	Flip a switch; see text

dimension that is clearly visible in the motion-capture data (see Figure 5). It is a two-handed sign that is articulated in neutral space with both palms up, and involves a lowering and pulling-back motion toward the signer. The leftmost panel in Figure 4 illustrates the neutral-space location of this item.

The sentences and context items that were used in this study are shown in Table 3, with (X) representing the location of the context item within each sentence. The two context signs, HAT and PANTS, are articulated at the head and waist, respectively. These signs were illustrated schematically in Figure 1, and actual articulations of the two signs are shown in Figure 4. The two other context items, which we called ⟨red⟩ and ⟨green⟩, were non-linguistic manual actions and are discussed in detail in Section 3.2.3. The intervening signs GO, FIND, and OTHER are also articulated in neutral space; these were used to provide additional distance between the context and target signs in order to create distance-2, -3 and -4 conditions. This was necessary because unlike the case of schwa (and other vowels and consonants) in spectrogram analyses, signs do not generally have a characteristic motion-capture profile like that of WANT that would permit the straightforward analysis of different target items in a single sentence. The first and last sign of each sentence, I, is articulated with the dominant hand's index finger pointed against the chest. According to our consultant, Signer 1, the sentences would not seem natural in ASL without the second occurrence of this pronoun "I".

Each sentence was articulated a total of six times by each signer. The subject signed them while seated, with ultrasound "markers" (emitters) attached to the back of the wrist of his/her dominant hand and to the front of his/her neck. The ultrasound signals were detected with a set of microphones located approximately 750 cm away (Zebris system CMS-HS-L with MA-HS measuring unit; data collection performed with WinData software). This system uses triangulation to determine the position in 3D space of each marker at a given moment; this spatial information is recorded every 10 ms with 0.1 mm precision. The coordinates of the neck marker were subtracted from those of the wrist marker since absolute coordinates would tend to change if the signer shifted his/her body position, while relativized coordinates should be more stable. The sessions were videotaped to permit cross-checking with the motion-capture data.

The sentences that the signer needed to sign were presented on a computer screen 36 inches in front of the signer, using the customary representation of signs with English words in capital letters. The signer began the articulation of each sentence with his/her hands in his/her lap, pressed a button on a keyboard (located at the nearest edge of the same table that the computer screen rested on) in order to see the next sentence that he/she was to sign, signed that sentence, returned his/her hands to his/her lap, and again pressed the button to proceed to the next sentence. Sentences for each distance condition were presented in blocks, with random presentation of the context items within each block. In order to encourage consistent prosodic patterning among these utterances, signers were asked to sign the sentences as if they were being given in a normal conversation in response to one of the questions "YOU {WANT, WANT FIND, WANT GO FIND, WANT GO FIND OTHER} WHAT?", as appropriate to the sentence frame. Before beginning the experiment, speakers took part in a brief practice session.

Figure 5 is based on data from the pilot study discussed earlier, and illustrates how coarticulatory effects related to two context signs used in that study, MOTHER (with a relatively lower location, on the chin) and FATHER (with a relatively higher location, on the forehead), would be expected to appear in the motion-capture signal. The figure shows the z-coordinate (altitude) of the signer's wrist during the articulation of two "distance-3" ASL sentences. Time is shown along the horizontal axis; successive labels are 1 s apart. The sentences shown at left and right have context signs MOTHER and FATHER respectively. The overall up-then-down pattern of each sentence reflects the movement of the signer's hand, first from the lap to the chest (for the sign I) and neutral space region (WANT GO FIND), then to its highest point on the chin or forehead (for MOTHER or FATHER), back down to the chest area for I, and finally down to the subject's lap. The two

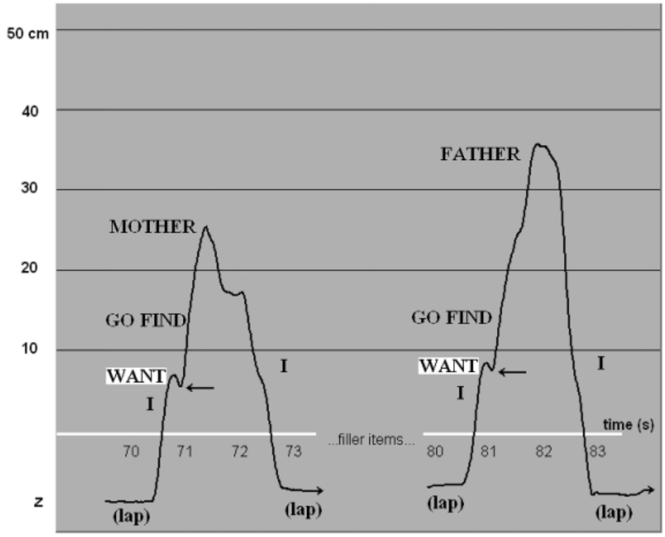

Figure 5. *The z-position (height in cm) of the signer's wrist during the articulation of two ASL sentences during the pilot study. For signs other than WANT and the context signs MOTHER and FATHER, the labels in the figure can only be considered approximate indications of sign position.*

arrows pointing toward the small zigzags near the start of each of those two sentences indicate the local minimum defining the target sign WANT; it is the z-coordinate at such local minima that will be compared between contexts. To the extent that LL coarticulatory forces are at work, one can expect that such z-values will tend to be greater for target signs preceding context signs located higher on the subject's body. Although this happens to be the case in the instantiations of the MOTHER and FATHER sentences shown in Figure 5, the crucial question is whether this pattern occurs consistently.

3.2.3. *Non-linguistic context items.* In addition to the signs HAT and PANTS, two non-linguistic actions were also included in the set of context items, so that a comparison of "linguistic" and "non-linguistic" coarticulation might be made. The goal here was to create sign-like actions articulated at locations spanning the vertical range of signing space just as the locations of the context signs HAT and PANTS do. The question then was whether coarticulatory effects in this "non-linguistic" condition would be similar to those in the linguistic condition for context signs spanning a similar distance in the articulatory space.

These non-linguistic actions, referred to as ⟨red⟩ and ⟨green⟩, were performed by flipping one of two switches attached to a vertically oriented bar-like device, shown in Figure 6, that was braced to the same table on which the computer screen and keyboard were resting. This device was positioned in front of the signer's

Figure 6. *The apparatus used for the non-linguistic contexts ⟨red⟩ and ⟨green⟩, performed by flipping the top and bottom switches on the device, respectively. The distance between the two switches as shown here is approximately 24 inches.*

dominant hand, with one switch at the device's high end and the second switch located at its low end directly below the first, a height difference of approximately two feet; this distance was adjusted slightly for each subject, as explained below. Flipping the top switch turned on a red light (and hence this non-signing action was termed the ⟨red⟩ context), and flipping the bottom switch turned on a green light (the ⟨green⟩ context). During the course of the signing task, the instruction to flip the top switch was given by a red upward-pointing arrow, and to flip the bottom switch by a green downward-pointing arrow. This red and green pattern was chosen in order to create a task that was non-linguistic but nevertheless intuitive and would not require much in the way of special training or a linguistic "go" signal on each trial, as it was assumed subjects would be familiar with the orientation of red and green lights on traffic signals.

The vertical position of top and bottom switches was adjustable, so that the distance between them could be modified for each signer. This was done in order to make their separation proportional to each signer's own signing space, this proportion being defined in terms of signers' height: the distance from the ⟨red⟩ location to the ⟨green⟩ one for each signer was set at one-third of that individual's height, with the ⟨green⟩ switch positioned just under the table, at lap level, and the ⟨red⟩ switch at head level with the subject seated, thus approximating the span of the locations of the linguistic context items PANTS and HAT.

During the course of signing the sentence-frame plus context-item combinations, ⟨red⟩ or ⟨green⟩ were treated like all of the other (i.e., sign) items. In other words, signers were instructed to embed them in the appropriate sentence frame, so that for example in the distance-3 condition with WANT as target sign and ⟨red⟩ as context item, the subject signed "I WANT GO FIND," immediately flipped the top switch, finished the sentence with the resumptive "I," and put his/her hands in his/her lap in preparation for signing the next sentence.

3.3. *Results*

3.3.1. *Group results.* For group analyses of the sign data, a normalization procedure was used, similar to the one based on Gerstman (1968) that was applied to speakers' raw formant values in carrying out group analysis for the speech study. Here, starting with a given signer's raw motion capture value z_{raw}, the corresponding normalized value is given by the formula $z_{norm} = 999 * (z_{raw} - z_{min}) / (z_{max} - z_{min})$, where z_{max} and z_{min} are the assumed highest and lowest values of z-locations in that signer's signing space. Each signer's z_{min} was an averaged z-value of the signer's hand in the lap position between signed sentences during the recording session (essentially the same height as that of the switch used in the ⟨green⟩ condition), while z_{max} was that value plus one-third the signer's height, the same value as that which had been used to determine the span between the switches the signers flipped in the ⟨red⟩ and ⟨green⟩ contexts. With the scaling factor used here, one normalized unit is equivalent to a spatial distance of about half a millimeter, varying somewhat for each signer.

First, an ANOVA with factors of Distance (1, 2, 3, or 4) and Context ("high" or "low") was performed on the group dataset, only for the "linguistic" component of the data. Therefore, the conditions "high" and "low" correspond to the contexts HAT and PANTS respectively. Because of the small number of subjects, a factor Subject was also included as a fixed factor, so it must be noted that any results found cannot be claimed to generalize to the signing population in general.

This analysis found no significant effects or interactions at all, with the exception of Subject ($p < 0.001$), which merely indicates that these signers differed in their relative articulatory positioning within their own signing space. Results were similar for an analogous ANOVA performed only on the "non-linguistic" component of the data.

Finally, an ANOVA was performed on the entire dataset, including an additional factor of Linguistic ("yes" for HAT and PANTS vs. "no" for ⟨red⟩ and ⟨green⟩); this produced only a main effect of Subject and a Subject-Distance interaction (p's < 0.01), reflecting articulatory variation for different subjects both in general

Table 4. *Anticipatory coarticulation in sign experiment. For each signer, the significance testing outcomes of eight t-tests are shown, comparing z-values of that speaker's articulation of WANT for the "high" vs. "low" contexts for each distance condition, for both the linguistic ("L"; i.e., HAT vs. PANTS) and non-linguistic ("NL"; i.e., ⟨red⟩ vs. ⟨green⟩) contexts. Significant outcomes are shaded and labeled, where * = $p < 0.05$ and ** = $p < 0.01$ (not Bonferroni corrected). Also noted are marginal results, where + = $p < 0.10$; a √ indicates a non-significant outcome in which averages were nevertheless in the expected direction. One result in the contrary-to-expected direction is indicated in parentheses.*

Distance	4 L	4 NL	3 L	3 NL	2 L	2 NL	1 L	1 NL
Signer								
1		√	√			(+)		√
2	√		*	√	√			
3	**		√	+				
4		√	√	√		√	√	√
5	+	√		√	√	+	na	√

and related to the different sentence frames, but giving no indication of consistent coarticulatory patterns of any kind. This stands in marked contrast to the results of the speech study.[3]

3.3.2. *Individual results.* Although the group results seem to indicate a general absence of coarticulatory behavior on the part of the signing subjects, it might be suspected that coarticulatory effects occurred but were inconsistent among signers in such a way as to mask them in the group analysis. Therefore, individual subjects' data were examined despite the absence of significant group results.

For individual signers, significance tests for the contrasts HAT vs. PANTS and ⟨red⟩ vs. ⟨green⟩ were performed using paired t-tests. The results are summarized in Table 4; numerical results are given in Table 6 in the Appendix. Paired t-testing was done to guard against the possibility that target locations in neutral signing space might drift slightly over the course of each subject's performance of the task, being more similar for adjacent or near-adjacent utterances. Thus, the pairings were made between z-values for WANT in the first articulation of the HAT and PANTS sentences, in the second such pair, and so on through the sixth (and similarly for ⟨red⟩ and ⟨green⟩). In the case of a rejected trial, non-paired t-tests were performed instead for that signer in that context and distance condition.

As can be seen in the table, very few comparisons turn out to be significant. Moreover, when taking into account all of the contexts that were examined (including some not presented here), the results which reached significance in these tests do *not* remain significant when Bonferroni corrected, unlike many of the contrasts seen in the individuals' results in the speech study. These weak outcomes are the norm in both the linguistic and non-linguistic contexts. The relative strength or weakness of individual signers' coarticulatory effects do not appear to be related to their ages of acquisition of ASL.

4. Discussion

A major goal of this project was to investigate to what extent coarticulatory effects in speech or sign might be considered specifically language-based, rather than reflecting processes of motor planning and execution common to human actions in general. The effects related to the non-linguistic context actions ⟨red⟩ and ⟨green⟩ were not substantially different in magnitude or distribution from those seen with linguistic (sign) context items, and as such, do not permit a straightforward distinction to be made here between "non-linguistic" and sign-based "linguistic" coarticulatory effects. Instead, the results obtained in our speech and sign studies indicate that if a distinction is to be made, a more logical division would be between orally-based coarticulation on the one side and coarticulation related to signing and other manual actions on the other.

This outcome complements findings of Ostry et al. (1987), who, as noted in Section 1.1, found that movement patterns associated with the oral articulators were consistent whether linguistic in nature or not, but differed from those associated with the arms. We illustrated those relationships earlier in Figure 2, noting in that figure the as yet uncertain relations between linguistic arm/manual actions (i.e., signing), linguistic oral actions (speech), and non-linguistic arm/manual actions. The results we have presented enable us now to draw some conclusions concerning those relationships. These are depicted in Figure 7, which is essentially a completed version of Figure 2, incorporating our results in addition to those of Ostry et al. (1987). The new figure indicates that we have found similar patterning between signing and non-linguistic manual actions (bottom row), but important differences between sign and speech (left column), at least in the contexts we have discussed. Taken together, these findings indicate that from a movement dynamics perspective, "linguistic vs. non-linguistic" is not nearly as important a distinction as "manual vs. oral."

A goal specific to the sign study was to determine whether evidence of location-based coarticulatory effects on neutral-space signs might be found in a manner analogous to the influence exerted by various vowels on schwa. Since the sign experiment was patterned after the speech study, where strong effects were quite

	Linguistic		**Non-linguistic**
Tongue/jaw	speech	≈	other actions
	≠		≠
Arm/manual	sign	≈	other actions

Figure 7. *Relationships suggested by findings of Ostry et al. (1987) and the present study.*

common, it is something of a surprise that the effects seen here for signs were relatively weak. Many of the speech-production effects were strong enough to remain significant after application of the Bonferroni correction, which was not the case in the sign study.

In connection with these results, it is worth mentioning again that the analyses reported here reflect just a subset of the speech and sign data that were collected and analyzed. Taken in their entirety, the results for the complete speech and sign datasets – including all four corner vowels in the speech study, and several additional contexts in the sign study in which all three spatial dimensions were investigated – were broadly consistent with those discussed here. However, there were more (uncorrected) significant testing outcomes seen in the sign data than would be expected by chance. With a total of 240 significance tests performed for the entire sign study, 12 spurious results significant at the $p < 0.05$ level and 24 marginally significant spurious outcomes (at the $p < 0.10$ level) would be expected merely by chance. For the entire sign dataset, the total numbers of such results were 20 and 36, respectively, either of which would be less than 5% likely in a random-chance scenario. Although a rigorous statistical approach does not permit one to consider this result "significant" in the usual sense, it does indicate that (1) some kind of coarticulatory influences were indeed occurring, but that (2) they were in almost all cases rather weak, were not pervasive and were not robust with respect to either context, distance or signer. In any case, this is markedly different from what was seen in the speech production study, where closer-distance effects were very strong and nearly ubiquitous among speakers, with a steady decrease in effects as distance increased, and with longer-distance effects seen only in speakers who had coarticulated strongly at closer distances. In addition, some cases of significant outcomes in the opposite-than-expected direction, which were never seen in the speech study, were found in the sign study.

The weak coarticulatory effects seen in our sign study seem to contradict the results obtained in the Cheek (2001) and Mauk (2003) sign studies discussed earlier, in which comparatively robust anticipatory and carryover effects were seen. However, the sign sequences used in Mauk (2003) had target signs placed *between* context signs, not only before or after, so the LL (location-to-location) effects that were found in that study involved carryover influences as well. In the case of Cheek (2001), significant anticipatory HH (handshape-to-handshape) effects were found in various sequences consisting of two signs each. Since the articulators involved in creating different handshapes are smaller than those used for shifts in location, perhaps anticipatory HH effects can be expected to be more prevalent than anticipatory LL effects. In light of these observations, a logical follow-up to the present sign study would be one in which carryover LL effects are targeted, using sign sequences whose first item has a location high, low or to the side in signing space, followed by multiple neutral-space signs.

Long-distance production results like those seen in the spoken-language study are problematic for any model of coarticulation not allowing for considerable range of influence of different elements on one another (e.g., see Öhman 1967; Fowler 1980, 1983; Bell-Berti and Harris 1981; Perkell and Chiang 1986; Keating 1988, 1990a, 1990b; Saltzman and Munhall 1989; Boyce et al. 1990; Smith 1992, 1995; Fowler and Saltzman 1993; Abry and Lallouache 1995; for an extensive overview of coarticulation models see Farnetani and Recasens 1999). Similarly, if long-distance signing effects like those hinted at here can be replicated in further research, they would have to be recognized in any viable model of sign production, even if such effects are relatively weak.

Long-distance effects also have obvious relevance from a perception standpoint (e.g., see Lehiste and Shockey 1972; Fowler 1981; Ohala 1981, 1994; Martin and Bunnell 1982; Przezdziecki 2000; Beddor et al. 2002; Scarborough 2003; Beddor 2009). In the particular contexts we examined, we saw weaker effects in signing than in speech. If this were to hold more generally – i.e., if there is less coarticulatory information available in the visual modality than in the auditory modality – we might expect that signed- and spoken-language users will exhibit different sensitivity to such effects in cases where they are present. We have recently completed a cross-modality perception study (Grosvald and Corina, forthcoming) that indicates that this is indeed the case.

Appendix: Numerical results

The tables give the average non-normalized values for the speech and sign studies underlying the significance testing results presented earlier.

Table 5. *Average target-vowel F1 and F2 values in Hz for each speaker at each distance; each cell shows the average for the [a] and [i] contexts, respectively. Significant and marginal results are labeled, where * = p < 0.05, ** = p < 0.01, *** = p < 0.001, + = p < 0.10.*

	Distance 3 ("**u**p")		Distance 2 ("**a**t")		Distance 1 ("**a**")	
Spkr	F1	F2	F1	F2	F1	F2
1	482, 430	1527, 1479	584, 560*	1751, 1809+	449, 352***	2126, 2564***
2	497, 472	1333, 1293	595, 547*	1770, 1803	402, 317**	1821, 2354***
3	441, 448	1291, 1334	607, 563*	1574, 1636***	513, 421***	1514, 2039***
4	429, 429	1150, 1173	452, 444	1426, 1447+	457, 369**	1517, 1785***
5	498, 490	1128, 1121	497, 444	1603, 1671+	503, 403**	1830,1835
6	415, 457	1215, 1236	538, 524	1513, 1530	415, 349**	1518, 2001**
7	469, 407*	1076, 1124+	575, 532	1586, 1647**	437, 389+	1666, 1957***
8	433, 394	1248, 1232	457, 369*	1512, 1638**	413, 268***	1659, 2246***
9	467, 525	1437, 1472	513, 503	1771, 1851**	402, 344**	1841, 2680***
10	375, 330**	1328, 1410+	586, 531+	1762, 1840+	363, 272***	1892, 2347***
11	470, 461	1259, 1244	563, 534+	1376, 1456**	428, 391+	1873, 2308***
12	550, 527	1134, 1138	484, 495	1350, 1442*	422, 379**	1647, 1968***
13	349, 367	1375, 1400	589, 500*	1723, 1836***	391, 303***	1950, 2469***
14	455, 458	1125, 1126	503, 481	1388, 1457***	415, 367**	1624, 1978***

Table 5 (*Continued*)

	Distance 3 ("**up**")		Distance 2 ("**at**")		Distance 1 ("**a**")	
Spkr	F1	F2	F1	F2	F1	F2
15	446, 413+	1324, 1270	519, 486	1519, 1500	384, 312**	1859, 2133**
16	521, 508	1369, 1430+	584, 473***	1673, 1706	409, 388	1883, 2191***
17	489, 453*	1178, 1149	532, 439*	1464, 1539***	410, 361*	1686, 1956***
18	367, 312*	1267, 1272	505, 421**	1679, 1758+	325, 282**	2204, 2541*

Table 6. *Average z-dimension (vertical) values for each signer's articulations of the target sign WANT at each distance. Each cell shows the average for the "high" and "low" contexts, respectively. L = linguistic (HAT, PANTS); NL = non-linguistic (⟨red⟩, ⟨green⟩). Significant and marginal results are labeled, where * = $p < 0.05$, ** = $p < 0.01$, + = $p < 0.10$. One result in the contrary-to-expected direction is indicated in parentheses.*

Distance	4 L	4 NL	3 L	3 NL	2 L	2 NL	1 L	1 NL
Signer								
1	8.47, 8.68	9.78, 9.58	8.67, 8.43	8.43, 8.75	8.66, 9.14	8.20, 10.8(+)	8.36, 8.65	7.60, 6.56
2	13.7, 12.9	12.5, 13.0	13.2, 11.0*	13.3, 12.8	13.3, 11.7	11.7, 12.1	10.2, 10.3	6.32, 6.39
3	20.0, 11.2**	13.1, 13.1	14.1, 13.5	16.2, 15.0+	11.1, 13.1	11.0, 13.2	13.8, 14.5	16.1, 16.8
4	9.57, 9.57	10.3, 9.80	10.4, 8.03	10.9, 10.4	11.6, 13.2	13.4, 12.1	14.0, 13.5	13.3, 12.8
5	12.8, 9.98+	14.6, 12.0	11.7, 12.5	15.9, 11.7	11.8, 10.3	13.8, 8.82+	8.63, n.a.	7.81, 7.72

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Notes

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2. Overall, at Bonferroni-corrected $p < 0.000463$, 13 of 18 speakers had significant effects at distance 1 for F1 or F2 or both, and 3 of 20 speakers had significant effects at distance 2. We note that two speakers (10 and 16) showed significant effects at longer distances without corresponding effects at all nearer distances. For discussion of such "interruption events," see Fowler and Saltzman (1993), Recasens (2002) and Grosvald (2009). A similar phenomenon is apparent in the sign data (see Table 4), but the possibility of spurious significance testing outcomes seems more relevant in that study, as described in some detail in the Discussion.

3. It should also be noted that data rejection rates in the sign and speech studies were also quite different. Very few trials had to be rejected in the speech study. In the sign study, a trial could be rejected for one of two reasons. First, if the video recording showed that the signer made an obvious error or false start during a sentence, that trial was rejected. For example, this would be the case if in signing the sentence "I WANT GO FIND PANTS I," the subject signed "I WANT GO FIND," then moved the dominant hand to the forehead and began to sign HAT before realizing his/her mistake and finishing the sentence with "PANTS I." A second possible reason for rejecting a trial was when a signer reduced the target sign enough that the sign's characteristic z-minimum was not visible. This occurred particularly often for Signer 5, especially for "low" signs at distance 1. The respective percentages of rejected trials for Subjects 1 through 5 were 7.7%, 12.7%, 2.8%, 4.5% and 30.6%. However, even subjects with low rejection rates did not consistently show significant coarticulatory effects, so the issue of data rejection is unlikely to explain the different results seen in the analyses for the speech and sign studies.

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