word count: 8735

Segmentation and pinky extension in ASL fingerspelling

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1 Introduction

At first glance, fingerspelling as a system, seems easy to segment: there are a limited number of possible segments: 26, one for each letter used to write English. These segments are executed in a temporal sequence, just like written glyphs are used in a spatial sequence. However, when looking closer, fingerspelling is just like any other language stream, with many contextual dependencies and a blending of one segment into another in actual production. There are no clean boundaries between any two segments as the articulators, in this case the digits on the hand, move from one configuration to the next. Additionally, as will be described here, there are some examples of configurations from one segment spanning across many segments previous and following (*ie* coarticulation). This phenomenon complicates a model of segmentation: a model of segmentation that not only allows for, but predicts the types of coarticulation seen is preferable to one that cannot.

This chapter is structured as follows: section 2 shows one example of handshape variation found in fingerspelling: pinky extension coarticulation. A large corpus of fingerspelling is analyzed, and pinky extension coarticulation is found to be conditioned by surrounding segments with pinky extension. Not every letter is equally susceptible to this coarticulation, however. This will be further explored with three case studies in section 3. Finally, a model of segmentation that accounts for this coarticulation is proposed, where segments in fingerspelling are not the entire configuration of the hand, but rather, only a subpart of the hand, the active part, that has been proposed in many models of sign language phonology.

1.1 Fingerspelling

American Sign Language — ASL — is used by approximately 500,000 to 2 million people in the USA and Canada[1], the majority of which are deaf. As with other sign languages, ASL makes use of the hands, arms, face, and body for communication.

Fingerspelling, while not the main method of communication, is an important part of ASL — used anywhere from 12 to 35 percent of the time in ASL discourse (Padden and Gunsauls, 2003). Fingerspelling is used more frequently in ASL than in other sign languages (Padden, 1991). Fingerspelling is a loanword system that has a form derived from the representation of English words through a series of apogees[2], each of which maps to a letter in the word. Every letter used in English has a unique combination of handshape, orientation, and in a few cases movement path[3] (Cormier et al. (2008) among others). These are used sequentially to represent an English word. Figure 1 shows the handshapes for ASL. The orientation of each handshape is altered in this figure for ease of second language learning. In reality, all letters are articulated with the palm facing forward, away form the signer, except for -H-, -G- (in, towards the signer), -P-, -Q- (down) and the end of -J- (to the side).[4]

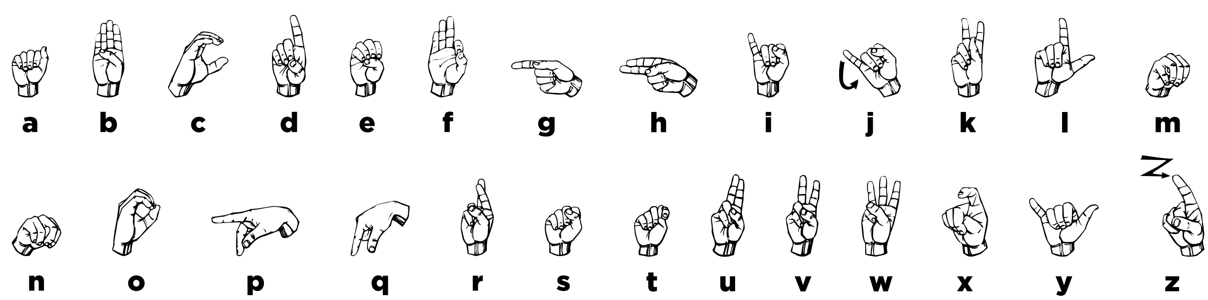


Figure 1: FS-letters for ASL fingerspelling.

Throughout this chapter only handshape is discussed. This is not to say that orientation is not important for fingerspelling (in fact the paris -H- and -U- as well as -K- and -P- differ only in orientation). Rather, we concentrate on handshape because the coarticulatory process is specific to handshape alone; additionally, because most letters are differentiated by handshape alone. This relationship is similar to the relationship that handshape has to core lexical items in other parts of the ASL lexicon, although here there are other additional paramaters: location, movement, and non-manual markers in addition to handshape and orientation. However, a sign segment will include a stable handshape (or two, if there is a handshape change in the sign), in the same way that is expected of segments in fingerspelling.

Fingerspelling is not used equally across all word categories. Fingerspelling is generally restricted to names, nouns, and to a smaller extent adjectives. These three categories make up about 77 percent of fingerspelled forms in data analyzed by Padden and Gunsauls (2003). In early research many situated fingerspelling as a mechanism to fill in vocabulary items that are missing in ASL. On further investigation, it has been discovered that this is not the whole story (Padden and Le Master, 1985). Fingerspelling can be used for emphasis as well as when the ASL sign for a concept is at odds with the closest English word, mainly in bilingual settings. One often cited example of the first is the use of Y-E-S-Y-E-S[5] and G-E-T-O-U-T. An example of the second is a teacher fingerspelling P-R-O-B-L-E-M as in a scientific problem in a science class, to clarify that what was intended here was not an interpersonal problem, but rather the setup for a scientific hypothesis. While fingerspelling is an integral part of ASL for all speakers of ASL, it is used more frequently by more educated signers, as well as more frequently by native signers when compared with non-native signers (Padden and Gunsauls, 2003).

Finally, there is already some literature on the nativization process from fingerspelled form to lexicalized sign (Brentari and Padden, 2001; Cormier et al., 2008). The phonetics and phonology of fingerspelling are in many ways related to ASL in general, because it uses many of the same articulators, but there are important differences. One major difference is that because fingerspelling is comprised of rapid sequences of handshapes, it provides an excellent area to look at the effects of coarticulation on handshape. Thus it is important that we study the phonetics and phonology of fingerspelling as well as of ASL generally. With the exception of (Wilcox, 1992), (Tyrone et al., 1999), Emmorey et al. (2010); Emmorey and Petrich (2011), and Quinto-Pozos (2010) there is little literature on the phonetics of fingerspelling. Wilcox (1992) looks at a very small subset of words (~7) and attempts to describe the dynamics of movement in fingerspelling. Tyrone et al. (1999) looks at fingerspelling in Parkinsonian signers, and what phonetic features are compromised in Parkinsonian fingerspelling. Emmorey et al. (2010); Emmorey and Petrich (2011) studied the effects of segmentation on the perception of fingerspelling and compared it to parsing printed text. Finally Quinto-Pozos (2010) looks at the rate of fingerspelling in fluent discourse in a variety of social settings.

2 Pinky extension Coarticulation

We have found that there is, indeed, coarticulation with respect to pinky extension (compare the two images of hands fingerspelling -R- in figure 2a and 2b). This coarticulation is conditioned by both preceding and following handshapes that include an extended pinky, although there is a clear distinction between handshapes where the pinky is extended and the other fingers are not (-I-, -J-, and -Y-) and those where the pinky is extended along with other fingers (-B-, -C-, and -F-).

There has been a small amount of work on coarticulation in fingerspelling specifically. Jerde et al. (2003) mentions that there is coarticulation with respect to the pinky. Tyrone et al. (1999) describes some Parkinsonian signers who blend letters together and gives an example of the first two FS-letters of P-I-L-L-S being blended together. Finally, Hoopes (1998) notes the existence of pinky extension coarticulation in fingerspelling but separates it from the pinky extension that he is interested in: the use of pinky extension in core lexical items as a sociolinguistic marker.

2.1 Methods

We generated a large corpus of fingerspelled words for multiple concurrent linguistic and computer-vision projects. This is the source of all of the data presented below. It was recorded with the intent to use the data in multiple ways, and thus be as flexible as possible.

2.1.1 Data collection

Three wordlists were created. The first list had 300 words: 100 names, 100 nouns, and 100 non-English words[6]. These words were chosen to get examples of as many letters in as many different contexts as possible, and are not necessarily representative of the frequency of letter, or letter combinations in English, or even commonly fingerspelled words. The second list consisted of 300 mostly non-English words in an effort to get examples of each possible letter bigram. The third list had the 300 most common nouns in the CELEX corpus in order to get a list of words that are reasonably familiar to the signers. The data analyzed here is only from the first word list.

So far, four deaf signers have been recorded, three are native ASL users, and one is an early learner. The ages of the signers are: 65, 58, 51, and 32. Approximately 6 hours of video has been recorded, which includes 5,700 words (11,400 tokens) and approximately 71,250 apogees.

The data was collected across different sessions that consisted of all of the words on one wordlist. During each session the signer was presented with a word on a computer screen. They were told to fingerspell the word, and then press a green button to advance if they felt that they fingerspelled it accurately, and a red button if they had made a mistake. If the green button was pressed the word would be repeated, the signer would fingerspell it again, and then they would move on to the next word. If the red button was pressed the sequence was not advanced, and the signer repeated the word. Most sessions were collected at a normal speed, which was supposed to be fluid and conversational, the signers were told to fingerspell naturally, as if they were talking to another native signer.[7] For a small number of sessions the signers were asked to fingerspell at a careful speed, which was supposed to be slow and deliberate.[8] Each session lasted between 25-40 minutes, there was a self timed break in the middle of each session for the signer to stretch and rest.

Video was recorded using at least two cameras, both at 45 degrees angles from straight on. Each of these cameras recorded video that was 1920×1080 pixels, 60 fields per second, interlaced, and using the AVCHD format. These files were then processed using FFMPEG to deinterlace, crop, resize, and reencode the video files so that they were compatible with the ELAN annotation software (Crasborn and Sloetjes, 2008).

In order to quantify timing properties of the fingerspelled words, we needed to identify the time where the articulators matched the target for each FS-letter in the word. In other words, we needed to segment the fingerspelling stream. We will use the term *handshape* to refer to the canonical configuration of the articulators for each FS-letter and the term *hand configuration*[9] to refer to the actual realization of handshape for a specific FS-letter in our data. We call the period of hand configuration and orientation stability for each FS-letter an *apogee* (*ie* where the instantaneous velocity of the articulators approached zero). This point was the period where the hand most closely resembled the canonical handshape, although in normal speed the hand configuration was often very different from the canonical handshape. For now, apogees can be thought of as synonymous with segments. We will refine our definition of what constitutes a segment in section 3.

2.1.2 Timing annotation

So far we have annotated a total of three hours of video across four sessions and two different signers. This set contains 15,125 apogees, of which 7,868 are at a normal conversational speed. This is the data that was used in the pinky extension and case studies that will be discussed below.

Once the video was processed, 3–4 naive human coders identified the approximate time of each apogee while watching the video at around half of the real time speed. In order to determine more precise apogee times, the apogees from each coder were averaged using an algorithm that minimized the mean absolute distance between the individual coders' apogees. This algorithm allowed for misidentified apogees by penalizing missing or extra apogees from individual coders. Using logs from the recording session, a best guess at the FS-letter of each apogee was added using left edge forced alignment. Finally, a researcher trained in fingerspelling went through each clip and verified that this combined apogee was at the correct time, and the FS-letter associated with it matched the FS-letter being fingerspelled. A single frame was selected as the time of each apogee, even if the apogee spread over multiple frames. Most apogees are only stable for a single frame, and of those that show stability for more than one frame, it is usually only for 2–3 frames. Where there were multiple frames, the first frame of hand configuration and orientation stability was chosen. Where there was no perceptible hold the frame where the hand configuration and orientation most closely matched the canonical handshape and orientation was chosen. This will introduce some noise into measurements of transition time, but for almost all apogees this noise is at most 48 msec. Finally the information from these verified files was imported into a MySQL database to allow for easy manipulation and querying.

2.1.3 Hand configuration annotation

Using the timing data annotated so far, we extract still images of every apogee. This image was associated with the corresponding apogee data in the database which now only allowed for exploratory data analysis, but was also the basis of our resulting hand configuration annotations: The still images were then used to annotate a number of different features of hand configuration. The major guiding principle in this feature annotation was to keep the task as simple and context free as possible. This has two major goals:

Simplicity — The first principle is simplicity, we wanted each annotation task to be as simple as possible. This allows the training to be simple, and the task to be incredibly quick. Rather than attempting to annotate features of hand configuration as a whole using recent annotation methods (Eccarius and Brentari, 2008; Liddell and Johnson, 2011b,a; Johnson and Liddell, 2011), we use binary decision tasks that involving looking at an image of an apogee and deciding if some feature of the hand configuration is one of two values. This makes the actual annotation very, very quick, so a number of annotators can be used for every apogee, in order to check agreement, rate annotator accuracy, and even derive some amount of certainty or gradience about the particular phenomenon (although this gradience will not be explored or used in the current study). We defined a pinky as extended if the tip of the pinky was above a plane perpendicular to the palmar plane, at the base of the pinky finger (the MCP joint) and the proximal interphalangeal joint (PIP) was more than half extended. Note that the canonical -E- shape would not have pinky extension (fig 2e), although some exhibited coarticulation (fig 2f). A more nuanced definition might be needed for further work but this is sufficient to identify apogees where the pinky is not in a closed, flexed configuration. With this metric the handshapes for -B-, -F-, -I-, -J-, -Y-, and sometimes -C- would have extended pinkies, and the rest of the FS-letters would not. Figure 2c shows a -C- without pinky extension, figure 2d shows one with pinky extension. Given this definition annotators were shown images of every apogee, and determined if the pinky was extended or not. Of course, as with all phonetic realizations, pinky extension is not actually binary. A variety of measures of the amount of extension (either for the finger overall, or individual joints) could be used, however these are all much more complicated to annotate than a simple binary decision, requiring much more annotator training and time per annotation.

Context free — Every image was presented with as little context as possible to ensure that the annotations were as objective as possible. Annotators are likely to have a variety of biases about how canonical they expect or do not expect given hand configurations to be. In order to try and reduce the influence of annotator bias, no information was given about the apogee in the image as it was annotated. The FS-letter of the apogee was

(a) -R- [−ext] (b) -R- [+ext] (c) -C- [−ext] (d) -C- [+ext] (e) -E- [−ext] (f) -E- [+ext]

Figure 2: Apogees from (a) D-I-N-O-S-A-U-**R**, (b) C-H-**R**-I-S, (c) Z-A-**C**-K, (d) E-X-P-E-**C**-T-A-T-I-O-N, (e) **E**-V-E-R-G-L-A-D-E-S, and (f) Z-D-R-O-Q-I-**E**

not included, nor was the word, or any features of the surrounding apogees. Although hand configurations (and orientations) that are near the handshape for a given FS-letter are easy to identify, and thus could still influence annotation decisions, hand configurations that are far from any canonical FS-letter handshape there will have little to distract the annotator from the task at hand (*eg* pinky extension annotation). Additionally even if the annotator knows the hypothesis to be tested (*eg* that certain handshapes in neighboring apogees condition coarticulation), their annotation cannot be biased because they have no way of knowing what the neighboring apogees are. One possible drawback to this method is that in the case of occlusions, it is sometimes impossible to determine some hand configuration features. It's possible that in some of these cases being able to play back the contextual video would provide enough information to determine the appropriate annotation. Although this might be true for a small number of cases, the benefit of reducing annotator bias far outweighs the additional (possible) accuracy in this edge case.

2.2 Results

Looking at table 1 we see that the apogees of handshapes that have pinky extension (-B-, -F-, -I-, -J-, -Y-, and sometimes -C-) by and large have it in the hand configuration as well (1438 apogees, versus 49 apogees with no extension). Of the 49 in this set that don't have pinky extension the majority of them (36) are -C- which leaves only 13 apogees in this group. For the rest of the apogees (*ie* the handshapes that don't have pinky extension) we see a surprising 295 apogees have pinky extension, which is a bit under 5% of all apogees in this set. One source of hand configuration variation is coarticulation. In order to test if the distribution of pinky extension observed is a result of coarticulation, contextual variables around each apogee (*eg* surrounding apogee handshapes, surrounding transition times) need to be investigated.

There are numerous factors that are known or suspected to condition phonetic variation like the variation we see with respect to pinky extension.[10] Two contextual factors are the handshape of the surrounding signs, or in this case FS-letters, as well as the transition times to and from the surrounding apogees. The hypothesis here is that surrounding FS-letters that have handshapes with pinky extension will increase the chance of an apogee's hand configuration exhibiting pinky extension even though its handshape does not specify pinky extension. Additionally we hypothesize that if the transition between a conditioning apogee and the apogee we are interested in is faster, this will also increase the chance of pinky extension. In addition to these contextual factors there are other noncontextual factors that might effect rates of pinky extension: the category of the word being fingerspelled (name, noun, non-English) as well as which signer is fingerspelling the word.

For a first look at the effect of the handshape of surrounding apogees we will check the two possible groups that could condition pinky extension in the hand configuration of apogees that don't have pinky extension in their handshape. The two groups of FS-letters that have pinky extension in their handshapes are -I-, -J-, and -Y- as well as -B-, -C-, and -F-. For apogees with handshapes that do not have pinky extension (all FS-letters but -B-, -C-, -F-, -I-, -J-, and -Y-) we see that apogees that have an -I-, -J-, or -Y- on either side of them have

		expected	
		+pinky extension	−pinky extension
observed	+pinky extension	1438	295
	−pinky extension	49	5870

Table 1: Counts for expected and observed pinky extension: where the columns are handshapes with and without piny extension, and the rows are hand configurations with and without pinky extension. The shaded cells are those where the pinky extension in the hand configuration matches the handshape specification. Here we are using the familiar terminology observed and expected. We use the terms *observed* and *expected*, even though our hypothesis is that there is coarticulation. In other words, we are using these labels in the naive way that we do not expect any apogee that does not (phonologically) have pinky extension in its handshape, to have it (phonetically) in its hand configuration. This set excludes 216 apogees for which there were an equal number of annotations for extended and flexed.

more instances with pinky extension than those that have any other letter on either side, including -B-, -C-, and -F- (see figure 3).

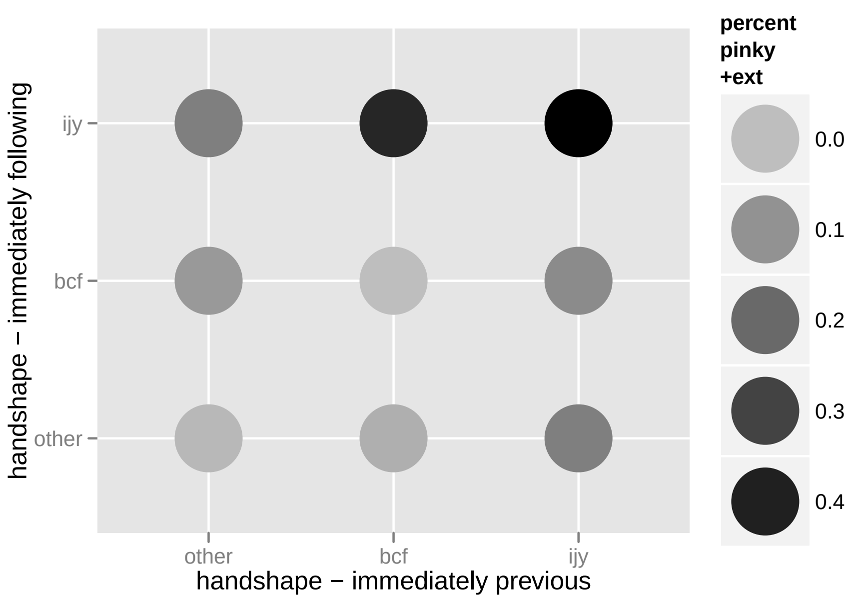


Figure 3: A plot showing the percent of apogees with hand configurations that have pinky extension, despite their handshapes not specifying pinky extension, based on surrounding handshapes. Darker colors represent a higher percentage of pinky extension.

Using a mixed effects logistic regression with varying intercepts for the FS-letter of the apogee, as well as the specific word, we determined that the following have a significant effect on pinky extension: handshape of the apogee (of interset), handshape of the previous apogee, handshape of the following apogee, word type, and the interaction of following handshape and following transition time. Specifically, the following were correlated with an increased probability of pinky extension in the hand configuration: if the apogee of interest was a -B-, -C-, -F-, -J-, or -Y- (and thus the handshape had pinky extension), if the previous or following apogee was an -I-, -J-, or -Y-, if the following apogee was a -B-, -C-, or -F- (marginally), if the word type was English (as opposed to non-English), and finally if both the following apogee's handshape was -I-, -J-, -Y-, -B-, -C-, or -F- and the following transition time was shorter (see appendix for full model details).

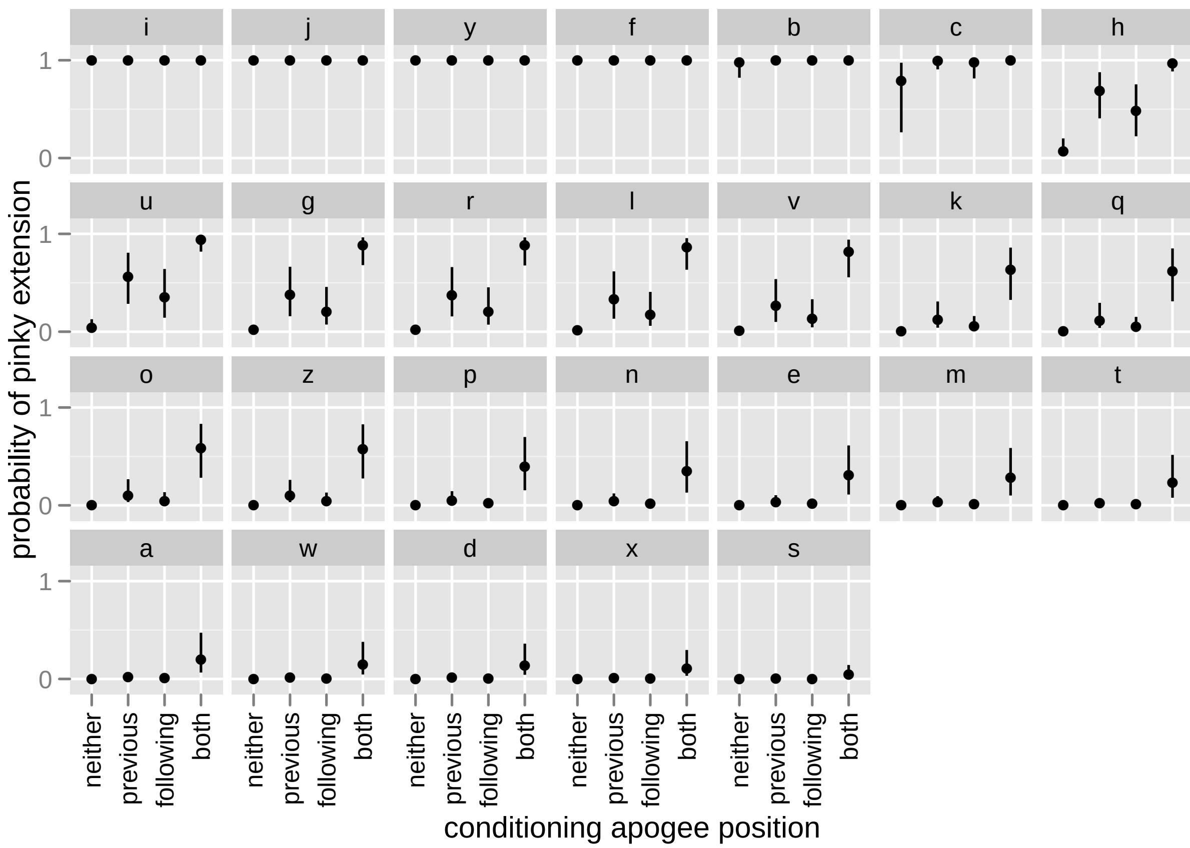


Figure 4: A plot showing the effect of conditioning apogees (-I-, -J-, and -Y-) on the probability of pinky extension at mean transition times for both previous and following. Dots are model predictions for an apogee with a conditioning apogee in the previous position, following position, both, or neither. The lines are 2 standard deviations on either side. The order of the FS-letters is based on the overall amount of pinky extension

Model predictions from the regression are visualized in figure 4. Here we can see that apogees with handshapes that specify pinky extension (-I-, -J-, -Y-, -F-, -B-, or -C-) almost all have pinky extension in their hand configuration as we expect (they are near ceiling). For apogees of all of the other FS-letters we can see the effect that a conditioning, surrounding apogee (FS-letter: -I-, -J-, or -Y-) have on the probability that an apogee's hand configuration will have an extended pinky. For apogees of FS-letters that do not have pinky extension in their handshapes, the probability that the hand configuration is realized with an extended pinky is nearly zero if there is no -I-, -J-, or -Y- before or after. For some of these FS-letters (in particular -H-, -U-, -G-, -R-, -L-, -V-, -K-, -Q-, -O-, and -Z-), that probability is higher if there is an -I-, -J-, or -Y- apogee before or after, and increases greatly if there is an -I-, -J-, or -Y- both before and after.

We have found that although an -I-, -J-, or -Y- on either side of an apogee conditions coarticulatory pinky extension, a -B-, -C-, or -F- only conditions pinky extension marginally, if at all (see figure 5). The generalization is that when a pinky is extended along with other fingers (especially the ring and middle fingers), there

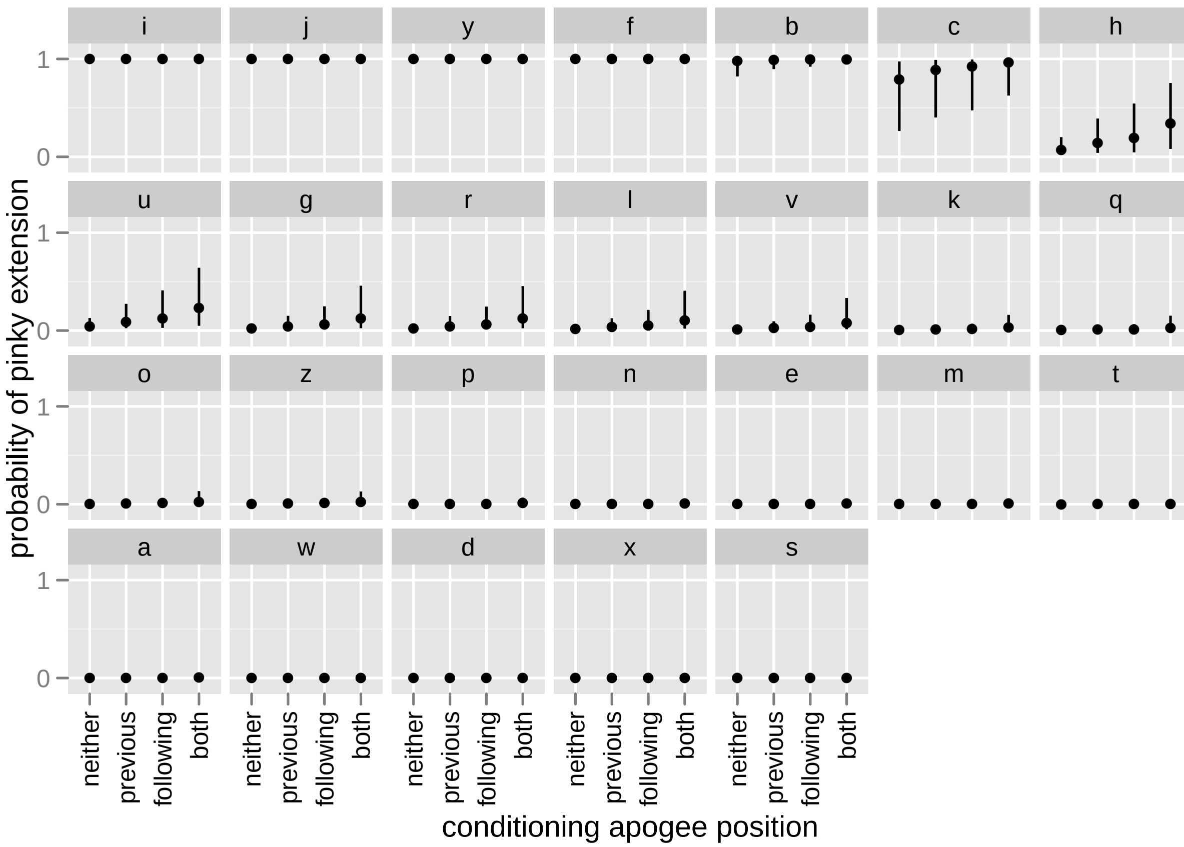


Figure 5: A plot showing the effect of conditioning apogees (-B-, -C-, and -F-) on the probability of pinky extension at mean transition times for both previous and following. Dots are model predictions for an apogee with a conditioning apogee in the previous position, following position, both, or neither. The lines are 2 standard deviations on either side. This is the same style of plot as figure 4, with the only difference being that the conditioning handshape here is a -B-, -C-, or -F-.

is less coarticulated pinky extension in surrounding apogees. Although this seems like an odd distinction, it is quite natural when we look at the physiology of the hand. There are three extensors involved in finger (excluding thumb) extension: extensor indicis proprius (for the index finger), extensor digiti minimi (for the pinky finger), and extensor digitorum communis (for all of the fingers) (Ann, 1993). When extended with the other fingers there are two extensors acting on the pinky, where as when it is extended alone there is only a single extensor. Additionally when the pinky is extended and the ring finger is flexed, it must act against the juncturae tendinum which connects the pinky to the ring finger. This asymmetry results in slower, less precise pinky extension when the pinky is extended alone, compared to when the other fingers are extended with it. We suggest that it is this muscular asymmetry that accounts for the fact that -I-, -J-, and -Y- condition coarticulation more than -B-, -C-, and -F-.

Although transition times do not have a large main effect, the interaction between the handshape of the following apogee and the following transition time is significant. This interaction is not surprising (quick signing or speech results in more coarticulation see Cheek (2001) for hand configuration coarticulation in ASL), but it is surprising that there is no interaction between previous handshape and previous transition time. One possible explanation for this is that there is an asymmetry between flexion and extension of the pinky. As stated above, the pinky and ring fingers are connected to each other by the juncturae tendinum while this ligamentous band cannot exert its own force, it connects the pinky and ring fingers, and will be stretched if the fingers are not in the same configuration (either flexed or extended) (Ann, 1993). For this reason we can expect that pinky extension alone will be slower than pinky flexion alone when the ring finger is also flexed. This is because only the extension is acting against the juncturae tendinum, where as flexion would be acting in concert with it. Whereas, pinky flexion is easier when the ring finger is flexed because it relieves the tension on the juncturae tendinum, so there is no physiological force that forces the pinky to remain extended. In other words, due to the physiology of the hand we expect to see slower pinky extension, but faster pinky flexion when the ring finger is flexed. Which is confirmed in our data: we see an interaction with time for only following apogees. That is, this coarticulation is time dependent only when it is regressive, not when it is progressive.

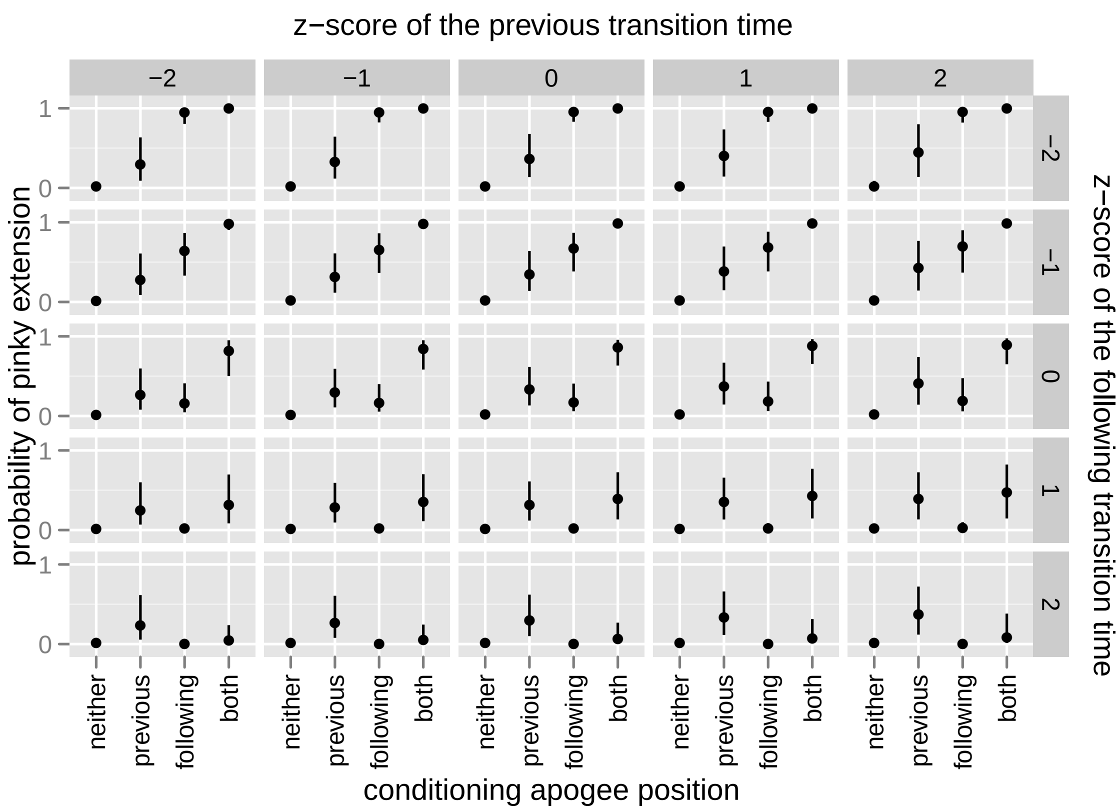


Figure 6: A plot showing the effect of conditioning apogees (-I-, -J-, and -Y-) on the probability of pinky extension for the FS-letter -L- only, faceted by previous and following transition time (z-scores of the log transform, where smaller values are shorter transitions).

Figure 6 visualizes the effect of transition time and the handshape of surrounding apogees for the FS-letter -L-. As before, the x-axis in this plot is the location of a conditioning handshape and the y-axis is the probability of pinky extension. The vertical and horizontal facets (boxes) are the z-scores of the log transformed transition times[11] for previous and following transition times respectively. We can see that for apogees that have a conditioning handshape in either the following or both apogees, the probability of pinky extension is high at short following transition times (negative z-scores), but is much lower when the following transition time is longer (positive z-scores). Apogees that have a previous conditioning handshape do not vary much based on transition time. Finally, apogees that do not have a conditioning handshape in either apogee are near 0 regardless of the transition time. The main point is that if there is a conditioning apogee as the following apogee, the following transition time magnifies the effect of a conditioning handshape when it is short, and attenuates it when it is long (the difference between the top row and bottom row of facets, with respect to apogees with condition handshapes in following and both positions).

Additionally, when the word type is non-English, there is less pinky extension. This could be explained by an effect of familiarity. Both of the signers have some familiarity with English, and thus the names and nouns chosen should not be completely unfamiliar, and some were even words that the signers fingerspell frequently in ASL discourse. The non-English words however, will not be words that the signers are familiar with, and it is expected that this will be the first time that they are fingerspelling that combination of letters. We already know that the transitions in non-English words are slightly longer (Keane, 2010). It is not surprising that signers exhibited less coarticulation with non-English words beyond what is predicted by the longer transitions because of a familiarity effect. There were no significant differences between names and nouns, which also fits with data on transition times that shows little difference between these two groups. Finally, there is not a significant difference between the two signers we have data for with respect to pinky extension.

2.3 Discussion

We have seen that there does appear to be coarticulation with respect to the pinky finger: an extended pinky in a neighboring apogee will increase the probability that an apogee with no specification for pinky extension will have pinky extension in its hand configuration. This is exacerbated by transitions times that are shorter, and attenuated by transition times that are longer, for conditioning apogees that follow the apogee of interest, but not for conditioning apogees that are previous to it.

The set of FS-letters that condition coarticulation is initially a bit surprising: it is not all of the FS-letters that have handshapes with pinky extension (-B-, -C-, -F-, -I-, -J-, and -Y-), but rather only those where the pinky is extended and other fingers are flexed (-I-, -J-, and -Y-). This asymmetry is explained by the physiology of the hand: because when the pinky extensor acts alone it acts slower than when it is used in combination with the common extensor. Thus signers allow pinky extension to overlap across other apogees in order to maintain an overall rhythmic timing.

The fact that there is an interaction between conditioning handshape and time only for apogees following the apogee of interest has a similar explanation. Because the pinky is connected to the ring finger, it will be harder, and thus slower, to extend the pinky when the ring finger is completely flexed. And like before, in order to maintain the overal timing of apogees in fingerspelling, the pinky must be extended earlier, intruding into the hand configuration of earlier apogees that don't have pinky extension in their handshape.

3 Segmentation

The previous section showed that the gestures associated with pinky extension for one apogee often spread onto the apogees that surround them. Although this is just one aspect of coarticulation, it shows that it is not possible to discreetly associate every slice of time with one, and only one apogee. Because of this, simplistic models of segmenting fingerspelling will not work: we cannot assume that every apogee's handshape is a unit that can be separated from the context that surrounds it. Rather, a model is needed that allows for, and ideally accounts for, the coarticulation observed above. Using a phonological model of handshape that breaks the hand down into smaller units that can be controlled separately allows for such a model of fingerspelling segmentation that accounts for variability seen in some parts of the hand, but not in others.

Rather than assuming that each handshape is entirely unique, where similarities or differences between them are accidental, modern sign language phonological theories decompose each handshape into a number of features allowing for relationships to be established between handshapes based on featural similarities (Mandel, 1981; Liddell and Johnson, 1989; Sandler, 1989; van der Hulst, 1995; Brentari, 1998; Eccarius, 2002; Sandler and Lillo-Martin, 2006). They all make use of a system of selected versus nonselected fingers to divide the articulators (digits) into groups based on what digits are active in a given handshape. The selected finger group can take on more numerous, and more complicated configurations, while the nonselected finger group will be either fully extended or fully flexed. Figure 7 shows how handshapes are broken into their component parts. What is important here is that the selected and nonselected fingers branch at the top, and that it is only the selected fingers that are then composed of additional features to make contrastive joint configurations. Additionally, work on active and inactive articulators in speech, inactive articulators are more susceptible to coarticulatory pressures than active articulators.

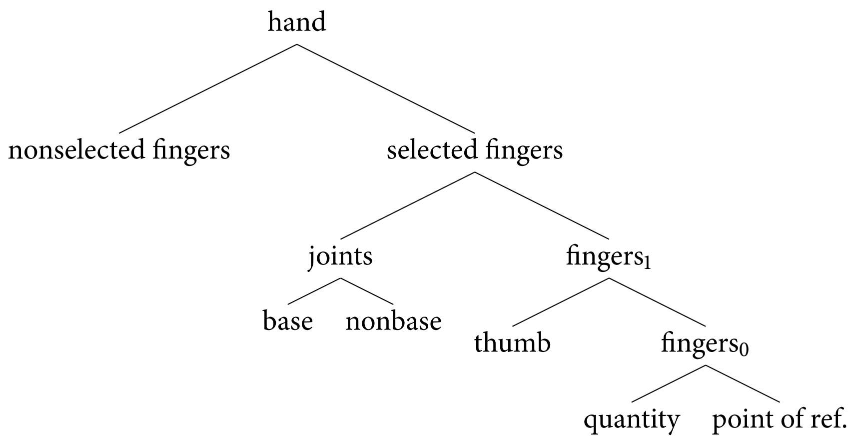


Figure 7: Handshape portion from the Prosodic Model (Brentari, 1998)

In addition to the overall finding that there is pinky extension coarticulation, there appears to be a tendency for some FS-letters to be resistant to pinky extension coarticulation (see figue 4 reprinted here as figure 8). Of the FS-letters that are not phonologically specified for pinky extension, that is, all FS-letters except for -B-, -C-, -F-, -I-, -J-, and -Y-, the FS-letters with the least amount of pinky extension coarticulation, are those that do not have the pinky selected (-H-, -U-, -G-, -R-, -L-, -V-, -K-, -Q-, -O-, and -Z-). The FS-letters that have the pinky selected (-A-, -E-, -I-, and -O-) are all towards the lower end of pinky extension coarticulation. The FS-letters -A- and -S- stand out: both have very low rates of pinky extension. -S- does not have a single instance of an apogee with pinky extension in 217 apogees, and -A- has 4 apogees with pinky extension out of 599 total. Both of these FS-letters have handshapes where all of the fingers (including the pinky) are selected and flexed. The FS-letters -E- and -O- show a bit more pinky extension than -A- and -S-, even though they ostensibly have all fingers selected as well. However, recent work (Keane et al., 2012) has shown that -E- and -O- are susceptible to a process which changes which fingers are selected. This typically results in the ulnar fingers (pinky and ring) becoming nonselected, while the radial fingers (index and middle) remain selected. This trend indicates that if the pinky is flexed and selected it resists the coarticulatory pressure from surrounding extended pinky fingers. However, if the pinky is flexed and nonselected, it is more susceptible to this same coarticulatory pressure.

Definition of segments in fingerspelling — In light of the asymmetry between selected and nonselected (pinky) fingers discussed above, we propose that a segmental unit of fingerspelling is not based on the whole

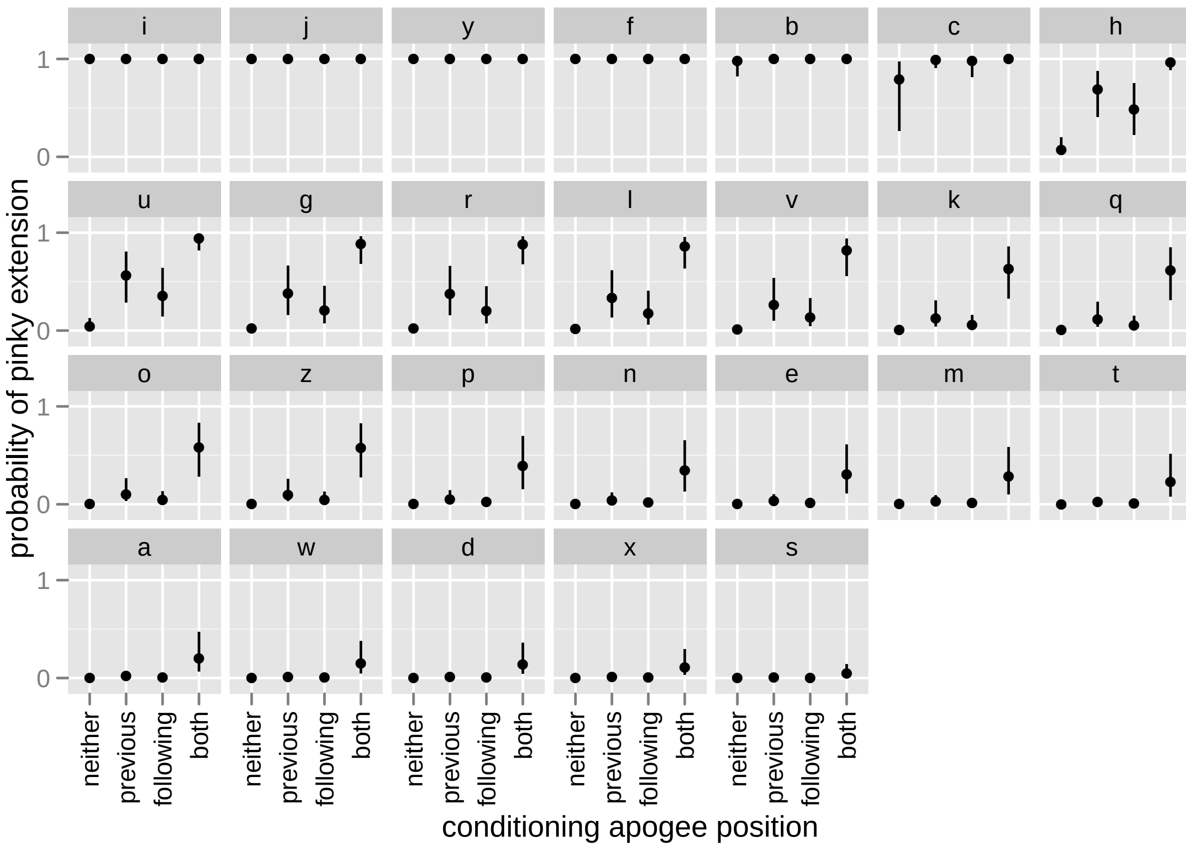


Figure 8: A plot showing the effect of conditioning apogees (-I-, -J-, and -Y-) on the probability of pinky extension at mean transition times for both previous and following. Dots are model predictions for an apogee with a conditioning apogee in the previous position, following position, both, or neither. The lines are 2 standard deviations on either side. Same as figure 4.

handshape (and orientation), but rather is the period of stability of the selected (or active) fingers. The selected fingers are less susceptible to contextual variation and are thus more invariant than the handshape taken as a whole. The next section will go through three case studies of fingerspelled words that exhibit different aspects of the pinky extension coarticulation, as well as a case where two segments seem to overlap completely by being fused together. This is accounted for (and allowed) because there is no configuration clash between the selected fingers in the handshape of either FS-letter.

3.1 Case studies

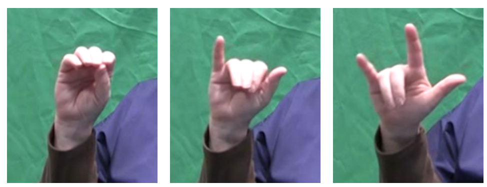
Three case studies have been conducted using visual estimation of extension to examine how the articulator positions change over time, and how well that aligns with any periods of stability. For each word below, the overall extension of every finger was estimated frame by frame for the entire period of time that the signer was fingerspelling the word. An extension value of was defined as when the finger was fully flexed; that is when all three of the joints of the finger (the metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joints) were completely flexed. An extension value of one was defined as when the finger was fully extended; that is when all three of the joints of the finger were extended completely. The thumb's measurement of extension is lateral across the palm, with zero being on the side of the hand, negative when the thumb is crossing over the palm, and positive when it is extended away from the thumb. Although these measurements of extension are coarser than other phonetic transcription systems (ie that of Johnson and Liddell (2011); Liddell and Johnson (2011a,b)), they should be sufficient for our purposes.

Figures 9 and 10 show the extension of each finger over time for one signer, and one example of the word O-I-L. For each frame and each finger, a visual approximation of extension was made. A value of zero is the most flexed that particular finger can be, and a value of one is the most extended. Lines are given for the observed values (thick, black) and the expected values (thin, red). Additionally gray boxes extend over periods of hand configuration stability, labeled with the associated FS-letter. For each period of handshape stability, the extension values for the selected fingers of a given FS-letter are overlaid (in darker, red boxes) as deviations form the dotted line at zero. We adopt the Articulatory Phonology framework, which has been used for extensively for spoken languages (Browman and Goldstein, 1986, 1992; Saltzman and Kelso, 1987) as well as for some sign language data (Tyrone et al., 2010). This visualization is meant to function in a way similar to the gestural scores used by Browman and Goldstein (1986, 1992) among others. The expected values line is generated by using the extension values of both the selected and nonselected fingers from the phonological specification of a canonical version of the handshape for a given FS-letter, with spline interpolation between apogees.

Starting with the first apogee, -O-, the observed and expected extension values match. For this FS-letter, all of the fingers are selected, for the fingers, the joints are phonologically specified so that they should have about 0.5 extension, and for the thumb there should be a little bit less than zero extension[12]. Moving on to the second apogee, the -I-, only the pinky finger is selected, which should be fully extended (ext = 1). All of the other fingers are nonselected, and should be fully flexed (ext = 0). For this apogee the observed extension for the fingers aligns with the phonological specification, the thumb, however, deviates slightly, being more extended than expected. This deviation makes the thumb more like the configuration for the FS-letter that follows it: -L-. Finally, for the last apogee, the -L-, only the index finger and the thumb are selected, both being fully extended. The rest of the fingers are nonselected, and should be completely flexed. The thumb, as well as the index, middle, and ring fingers match the expected extension values. The pinky, however, stands out: although it should be flexed, it is almost completely extended. The pinky has the same extension as the apogee before it (the -I-), an example of the coarticulation discussed in section 2. In this word, the only two deviations from expected values of extension occur with digits that are non-selected and should be extended, but are realized as more extended, being more like the configurations of surrounding apogees (the following -L- in the case of the -I- and the preceding -I- in the case of -L-) .

Figures 11 and 12 show the extension over time for the word B-U-I-L-D-I-N-G. The first apogee, -B- shows no deviation from the expected extension. The next apogee, -U-, shows no deviation for the thumb or the index or middle finger (the latter two, are selected), however the ring and pinky fingers, which are nonselected, are a little bit more extended than expected. The next apogee, the first -I-, shows a lot of deviation from expected extension values. The only digit that matches the expected extension value is the pinky, which is also the only selected finger. The ring, middle, and index fingers all are slightly more extended than expected, and the thumb is completely extended, matching the configuration of the following apogee. For the -L- apogee, the thumb and index finger are selected, and both match their expected extension values. The middle and the ring finger are slightly more extended than expected, and finally the pinky is nearly fully extended, which matches the -I- before it. In the next apogee, the -D-, the thumb as well as the index and ring finger are selected[13]; and they all match the expected extension values. The ring and pinky fingers are nonselected; the ring finger matches the expected extension, however the pinky is much more extended than expected. Across the last two apogees the pinky is more extended than expected given the phonological specification for each handshape, however there is a handshape with an extended pinky on either side of these two (both -I-s), which is conditioning coarticulation of pinky extension. Moving on to the second -I- apogee, the pinky is selected, and matches the expected extension value. The other digits approximate their expected values, with the exception of the thumb and ring finger. Following that, the -N- apogee, has the index and middle fingers selected, both of those, along with the other digits match the expected values. There are only slight deviations of the ring and pinky fingers, both of which are not selected. Finally the last apogee, -G-, has the index finger selected, which matches the expected extension value. Additionally all of the other digits similarly match their expected extension values. This case study shows again, that there is quite a bit of extension variation for fingers that are non-selected; especially on the pinky finger when it has apogees with pinky extension on either side. In contrast, the selected fingers of a given apogee always match the expected extension.

Moving on to a more complicated example, A-C-T-I-V-I-T-Y in figures 13 and 14, continue to show the relationship between selected and nonselected fingers. The first observed extension matches the expected extension for the first five apogees (-A-, -C-, -T-, and -I-) for both the selected and nonselected fingers. After



(a) -O- (b) -I- (c) -L-

Figure 9: Still images at apogees for O-I-L.

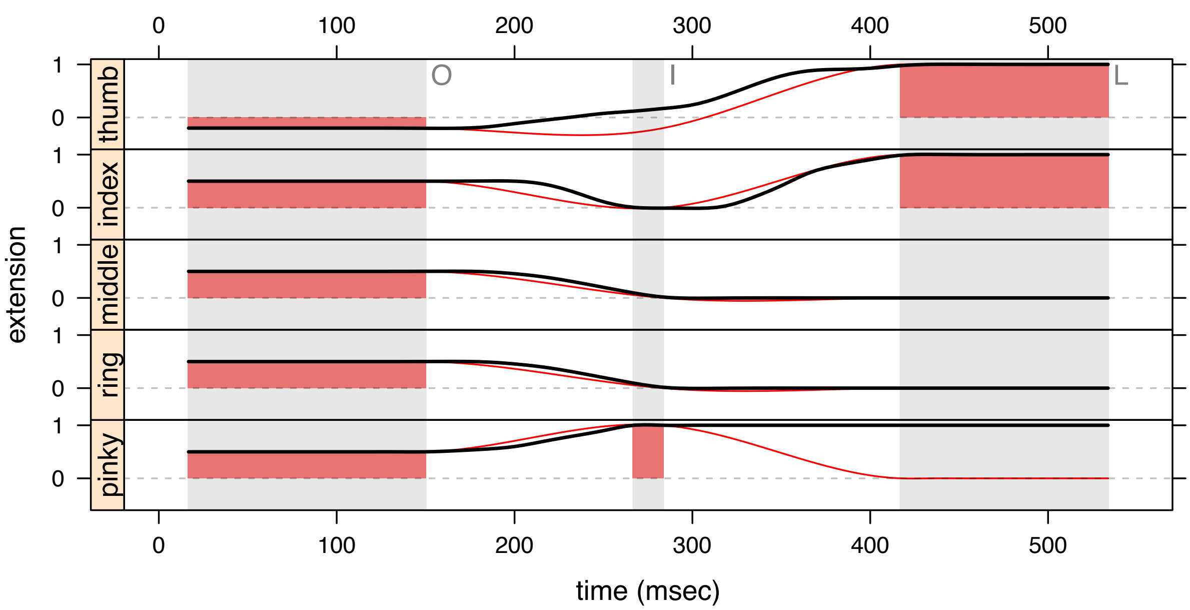
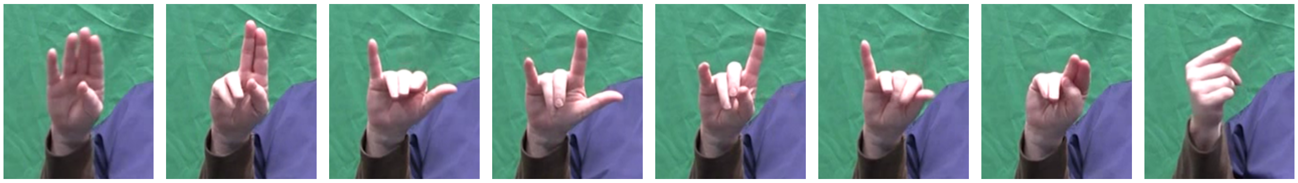


Figure 10: Articulator trajectories for O-I-L. Gray boxes represent periods of hand configuration stability, thick, black lines represent observed extension (visually estimated), and the thin, red lines represent articulator trajectories if each apogee's hand configuration were canonical, with smooth transitions.



(a) -B- (b) -U- (c) -I- (d) -L- (e) -D- (f) -I- (g) -N- (h) -G-

Figure 11: Still images at apogees for B-U-I-L-D-I-N-G.

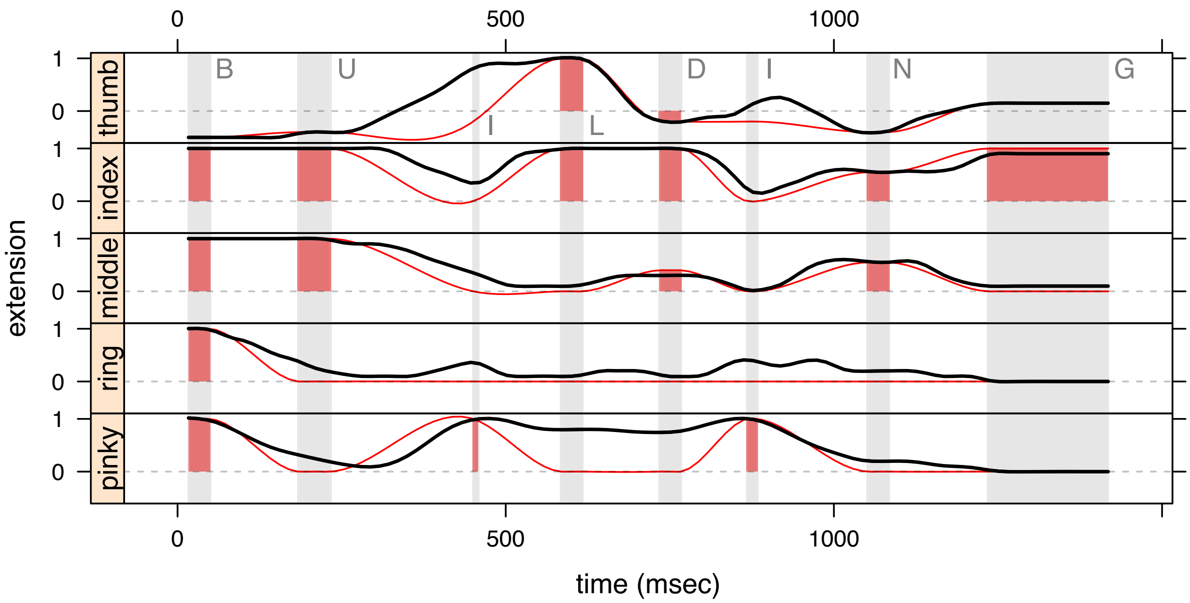


Figure 12: Articulator trajectories for B-U-I-L-D-I-N-G. Similar to figure 10.

that, however, there is quite a bit of deviation: the next apogee, -V-, has unexpected pinky extension, as well as some articulatory undershoot for the two selected fingers (the index and the middle finger). After that the next period of stability is actually two apogees (-I- and -T-) fused together to form -IT-. The selected fingers for these two FS-letters do not clash: for the -I- the only selected finger is the pinky, whereas for the -T- only the index finger is selected. The two sets of selected fingers are separate, and thus do not conflict. The observed extension for the index and pinky fingers reach the extension targets for -I- and -T- at the same time, and thus the two apogees occupy the same period of time. In figure 14, a period of stability has been inserted halfway between the -V- and -IT- to show what the articulators are expected to do if the fusion did not occur. The last apogee, -Y- matches the expected configuration This case study shows to things: First, during the period of time between the two -I- apogees (including the fused -IT- apogee), the pinky does not ever completely flex, but rather stays at least partially extended as a result of coarticulation, and the fact that it is not selected except in any of the intervening apogees. Second, in some extraordinary cases apogees that do not have conflicting selected fingers can be fused temporally, where the articulators reach their phonologically specified targets at the same time.

Although rare, the apogee fusion seen here is not a solitary example. There are also examples of -TI-, -NI-, and -OI-; the last one is even documented as one strategy that is used in rapid lexicalization (Brentari,

(a) -A- (b) -C- (c) -T- (d) -I- (e) -V- (f) -IT- (g) -Y-

Figure 13: Still images at apogees for A-C-T-I-V-I-T-Y.

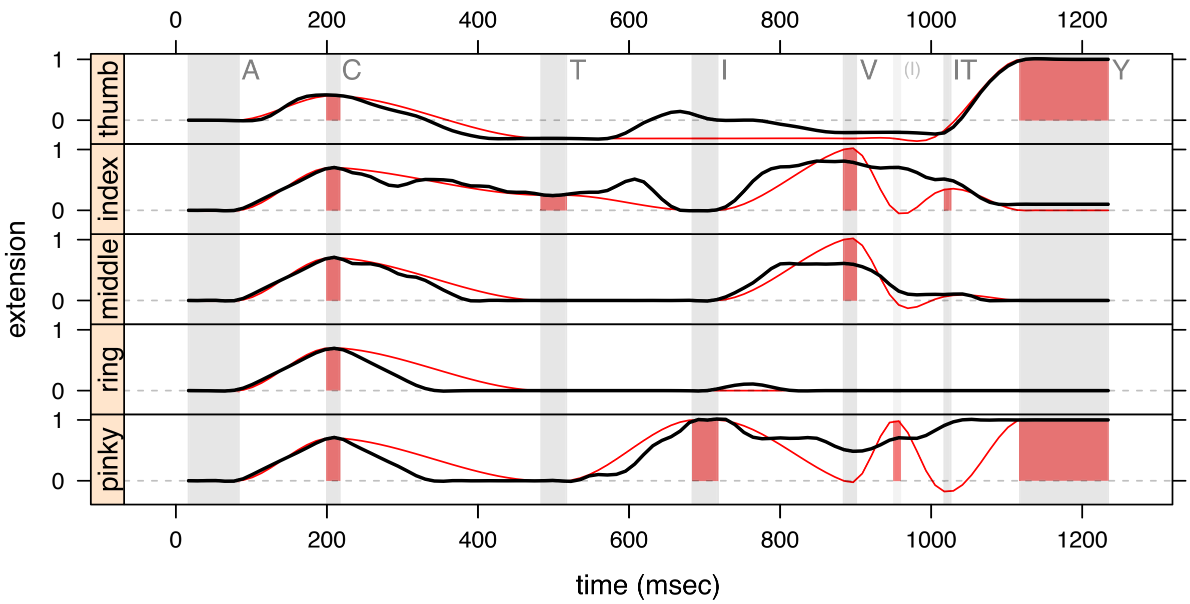


Figure 14: Articulator trajectories for A-C-T-I-V-I-T-Y. Similar to figure 10, the only exception is that the light gray associated with the second -I-, is placed halfway between the -V- and -TI- apogees in order to show the trajectories expected for canonical realization.

1998). Two out of three of these share the property that the selected fingers of the two FS-letters are distinct, and thus there is no conflict. The -OI-, however seems to present a problem because a canonical -O- should have all fingers selected. There is some work (Keane et al., 2012) that shows that there are instances of -O- where the ulnar digits (typically the pinky and ring fingers) are completely flexed rather than having the same configuration as the radial digits (typically the index and the middle fingers). This happens in approximately 25% of -O-s in this corpus. The analysis of these variants are that these handshapes have different selected fingers than the canonical forms, that is, only the index and middle fingers are selected, while the pinky and ring fingers are nonselected. Additionally the one example of -OI- shows increased flexion of the ring finger, just like with the -D- in the B-U-I-L-D-I-N-G case study, suggesting that this case of -OI- fusion might involve an -O- variant that does not have the pinky finger selected. More work, and more data, are needed to fully understand and model how these two different types of variation interact.

Given a model of segmentation that looks at handshape as a whole these fusions would have to represent examples of new kinds of segments in the inventory of FS-letters. However, if only the selected fingers are used as a basis for segmentation, these fused apogees can still be analyzed as two apogees, that just happen to occupy the same time. Why this fusion occurs is outside of the scope of this work, however many (*eg* Wilcox (1992); Emmorey and Petrich (2011)) have noted that fingerspelling often has a rhythmic pattern. We have observed what appear to be consistent rhythmic patterns in our corpus and we speculate that the fusion process might be a way to maintain the rhythm when two apogees are too close together, and don't have conflicting selected fingers. More data and analysis is required to understand this possibility fully.

4 Conclusions

Using data from the phonetic configuration of the pinky finger, we can explore the question of what constitutes a segment in ASL fingerspelling. The pinky shows clear evidence of phonetic variation as a result of coarticulatory pressures. We have observed that there are situations where there is a higher probability of having a phonetically extended pinky finger in handshapes that are not phonologically specified for an extended pinky. The main contextual factor is that there is more pinky extension when there is a surrounding handshape where the pinky is selected and extend, compared to when there is a surrounding handshape where the pinky is not extended. This coarticulation does not occur across the board: There is temporal variation; regressive coarticulation is time-sensitive, where as progressive coarticulation does not seem to be. Familiar words exhibit more coarticulation. Finally, not all FS-letters exhibit pinky extension coarticulation at the same rates. A trend is observed that when the pinky finger is selected and flexed, it resists pinky extension coarticulation much more than when it is nonselected and flexed.

Because of this coarticulation, defining fingerspelling segments in discreet temporal terms is not possible; that is, the articulatory gestures associated with one apogee sometimes stretch across multiple apogees. Further, as a result of the coarticulation described here, not every articulator reaches the phonologically specified canonical target for a given handshape. Which articulators reach canonical configuration depends on their phonological status: selected fingers typically attain their phonological specification, where as nonselected fingers show more variation, and do not always reach their phonological target. Three case studies were conducted that show how this segmentation can be implemented using ideas from work on Articulatory Phonology in spoken and signed languages. Additionally, this model of segmentation can accomodate a process of apogee (or segment) fusion that is observed in fingerspelling. During this process two apogees are executed at the same time. This is possible because the handshapes observed here have two distinct sets of selected fingers. This being the case, there is no conflict in reaching the articulatory target for the selected fingers; in order to maintain the overall rhythmic timing the apogees for each of the two individual FS-letter in the word are collapsed into a single period of stability. The model of fingerspelling segmentation proposed accounts this process of apogee fusion, as well as the effects of coarticulation being limited in selected fingers because the core of the segment is restricted to the selected fingers: that is the element of handshape that carries the most contrast and information about the identity. Other parts of handshape are allowed to, and do vary to ease the articulatory effort needed to produce fingerspelling, or maintain its overall rhythmic structure.

A Regression model of pinky extension coarticulation

The model was fit with pinky extension as the outcome variable, as well as all and only the predictors listed in table 2. We included varying intercepts for the FS-letter of the apogee because we expect that there will be variation among different FS-letters with respect to the amount of pinky extension. We included varying intercepts for word because we expect that there is variation among words with respect to the amount of pinky extension. The model was fit on only word internal apogees, since the first and last apogee lack a previous and a following apogee respectively.

	coeficient (standard error)
Intercept	$-5.82(0.60)^{***}$
apogee of interest: -B-, -C-, -F-, -I-, -J-, or -Y-	$12.14(1.28)^{***}$
previous -B-, -C-, or -F-	$0.77(0.42)^{\cdot}$
previous -I-, -J-, or -Y-	$3.38(0.30)^{***}$
previous transition time (zscore of log(time))	$0.06(0.15)$
following -B-, -C-, or -F-	$1.16(0.59)^{*}$
following -I-, -J-, or -Y-	$2.52(0.29)^{***}$
following transition time (zscore of log(time))	$-0.08(0.15)$
word type: foreign	$-0.68(0.32)^{*}$
word type: name	$-0.28(0.29)$
signer: S1	$-0.11(0.24)$
previous -B-, -C-, or -F-×previous transition time	$-0.33(0.38)$
previous -I-, -J-, or -Y-×previous transition time	$0.10(0.22)$
following -B-, -C-, or -F-×following transition time	$-2.15(0.47)^{***}$
following -I-, -J-, or -Y-×following transition time	$-2.19(0.28)^{***}$
AIC	1028.59
BIC	1138.44
Log Likelihood	−497.29
Deviance	994.59
Num. obs.	4730
Groups: word	300
Groups: verLetter	26
Variance: word	0.94
Variance: verLetter	4.59
Variance: Residual	

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Table 2: Mixed effects logistic regression coefficient estimates and standard errors.

Notes

[1]These numbers range widely across many sources which was documented by Mitchell et al. (2006).

[2]Which will be defined in more detail later in section 2.1. For now, they can be assumed to be synonymous with segments.

[3]Traditionally movement is said to only be used for the letters -J- and -Z- as well as to indicate some instances of letter doubling. Although in fluent fingerspelling many letters have movement of some type.

[4]This figure was generated using a freely available font created by David Rakowski. This figure is licensed under a Creative Commons Attribution-ShareAlike 3.0 Unported License and as such can be reproduced freely, so long as it is attributed appropriately. Contact jonkeane@uchicago.edu for an original file.

[5]I'm choosing to adopt the typographic conventions of Brentari and Padden (2001). Fingerspelled forms are written in smallcaps (an adaptation from Cormier et al. (2008)), with hyphens: A-T-L-A-N-T-I-C and ASL native signs are written in only smallcaps: GROUP. Single finger spelled letters will be flanked by hyphens on either side (*eg* -T-).

[6]These are also called foreign, although that is not entirely accurate, since all fingerspelled words are in some sense not part of the native ASL lexicon. These words were selected specifically for sequences that are not generally found in English.

[7]The instructions, given in ASL were to: "proceed at normal speed and in your natural way of fingerspelling."

[8]Again, in ASL "be very clear, and include the normal kind of transitional movements between letters." The signers were also specifically asked not to punch the letters with forward movements, as is often done for emphatic fingerspelling.

[9]Differentiating between *handshape* and *hand configuration* follows others (Whitworth, 2011), although it uses the term *hand configuration* in a way that is quite different from how it is used in the Hand-Tier model (Sandler, 1989).

[10](Cheek, 2001) for environment; (Mauk, 2003) for speed and environment; (Lucas et al., 2002) for grammatical category

[11]Where 0 represents the mean value, -1 represents a transition that is one standard deviation shorter than the mean, and $+1$ represents one standard deviation longer than the mean.

[12]For the thumb the extension should be slightly less than zero because it is crossing over the palm.

[13]What fingers are selected for the FS-letter -D- are not actually a settled matter. In some models the thumb as well as the middle, ring, and pinky fingers are selected, the index finger is either nonselected and extended, or secondary-selected. However, Keane et al. (2012) has shown that -D- is frequently realized as what is referred to as baby-D, that is with the pinky and middle fingers completely flexed, the middle finger and the thumb forming a loop, and the index finger fully extended. The apogee here, shows this pattern with flexion in the ring finger, although the pinky is extended because of coarticulation from -I- apogees around it. With that configuration the middle finger and thumb would be selected, and the index finger secondary-selected, while the ring and pinky fingers are nonselected.

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