Coarticulation in ASL fingerspelling *

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1. Introduction

There has been much work on coarticulation in speech, however ASL fingerspelling has been explored less. Using a new data set of ASL fingerspelling, we have annotated pinky extension as a first step to look for coarticulation on a larger scale. We aim to answer three broad questions: Does the extension of the pinky finger spread across multiple units? If so, what environments condition this coarticulation: previous handshape, following handshape, transition time? Do all handshapes with an extended pinky condition coarticulation equally?

1.1 Background

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). Every letter used in English is given a unique combination of handshape, orientation, and in a few cases path movement[1] (Wilcox (1992), Padden (1998), Cormier et al. (2008) among others). These fingerspelled-letters (henceforth: FS-letters) are used sequentially to represent each letter in an English word. Figure 1 shows the FS-letters for ASL. The orientation of each FS-letter is altered in this figure for ease of learning. In reality, all FS-letters are articulated with the palm facing forward, away form the signer, except for -H- and -G- (in, towards the signer), -P- and -Q- (down) and the end of -J- (to the side).[2]

Fingerspelling is used more frequently in ASL than in other sign languages (Padden 1991). Fingerspelling is a part of the ASL lexicon, and is used as one method of borrowing words from English (Brentari and Padden 2001). Fingerspelling is also 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

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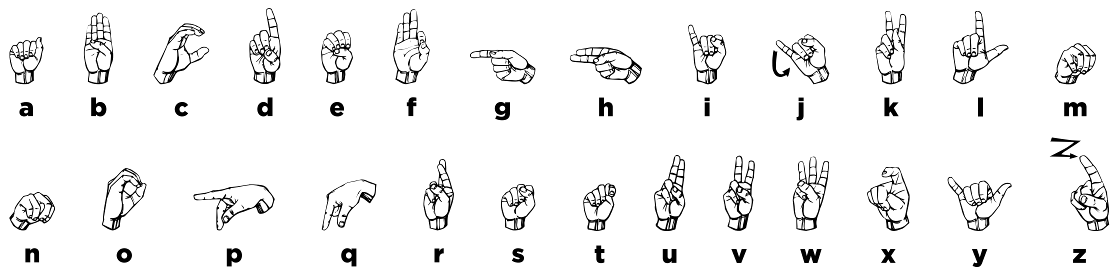

Figure 1: FS-letters for ASL fingerspelling.

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 (Padden and Le Master 1985). On further investigation, it has been discovered that this is not the whole story. Fingerspelling can be used for emphasis as well as when the ASL sign for a concept is at odds with the closest English word, especially in bilingual settings. One often cited example of the first is the use of Y-E-S-Y-E-S[3] 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, because the ASL sign PROBLEM has a separate meaning that is not quite compatible with the English sense of the word. 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).

1.2 The phonetics and phonology of fingerspelling

The phonetics and phonology of fingerspelling are in some ways related to the phonetics and phonology of ASL, because it uses many of the same articulators, but there are important differences. 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), and (Quinto-Pozos 2010) there is little literature on the phonetics of fingerspelling. Wilcox (1992) looks at a very small set of words (~ 7) and attempts

possible without the help of the signers who fingerspelled for many hours for us. Although all of these people helped immensely, any mistakes or omissions are entirely our own.

[1]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.

[2]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.

[3]I'm choosing to adopt the clear and elegant 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-).

to describe the dynamics of movement in fingerspelling. This study is mainly limited by its small size and method of data collection involving infrared emitters and infrared sensitive cameras, but no standard video. Tyrone et al. (1999) looks at fingerspelling in Parkinsonian signers, and what phonetic features are compromised in parkinsonian fingerspelling. Emmorey et al. (2010) studied segmentation of fingerspelling perception 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. Additionally, there is already some literature on the nativization process from fingerspelled form to lexicalized sign (Brentari and Padden 2001, Cormier et al. 2008).

There has been a small amount of work on coarticulation in fingerspelling. 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 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.

We have found that there is, indeed, coarticulation with respect to pinky extension (compare the two images of hands fingerspelling -R- in figure 2b and 2a). 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-).

2. Methods

We recorded nearly 3 hours of 2 native ASL signers, one 65 year old woman and one 32 year old man. The word list used had 300 words: 100 names, 100 nouns, and 100 non-English[4] words. 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 data was collected across different sessions that consisted of all of the words on the word list. 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.[5] For a small number of sessions the signers were asked to fingerspell at a careful speed, which was supposed to

[4]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.

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

be slow and deliberate.[6] Each session lasted between 25–40 minutes and there was a self timed break in the middle of each session for the signer to stretch and rest.

Video was recorded using two cameras, both at 45 degree angles from straight on. Each of these cameras recorded video that was 1920×1080 pixels, 60 fields per second, interlaced, 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.

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. We will use the term *handshape* to refer to the canonical configuration of the articulators for each FS-letter and the term *hand configuration*[7] to refer to the actual realization of handshape for a specific FS-letter in our data (combined with orientation, what we call an *apogee*). Neither of these makes reference to orientation, which, for our purposes here, is fine because orientation is not the focus of this study. We call the period of hand configuration and orientation stability for each letter an *apogee* (i.e. 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. Two letters defied definition in this manner, namely -J- and -Z-, since they have movement. Both will have periods of hand configuration stability, as well as landmarks in hand orientation that allow for classification similar to that of other FS-letters, although we expect the apogees here to be longer than other FS-letters.

Once the video was processed, 3–4 human coders identified the approximate location of each apogee while watching the video at around half of the real time speed. In order to determine the more precise apogee locations 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 in the correct location, and the FS-letter associated with it matched the FS-letter being fingerspelled. At this time a single frame was selected as the location 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 ori-

[6] 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.

[7] 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).

entation 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. We had a total of 15,125 apogees, of which 7,317 are at a normal conversational speed, where we expect to find the most coarticulation.

We extracted still images at each apogee and then hand annotated pinky extension. This annotation was meant to determine if the pinky was extended regardless of other factors of the apogee. We approached this annotation with two goals in mind: 1. we wanted the task to be simple so that there was only a minimal amount of training that was needed for annotators, and 2. we wanted to design a metric that would apply regardless of how canonical the handshape of a given apogee was. 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). In order to make the annotations as objective as possible, no context was provided for the image when it was annotated, so the annotators didn't know what the target canonical handshape was, or what apogees surrounded the one to be annotated. 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.

(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**

3. 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-. 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

		handshape	
		+pinky extension	−pinky extension
hand configuration	+pinky extension	1438	295
	−pinky extension	49	5870

Table 1: Counts for pinky extension: where the columns are handshapes with and without pinky 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.

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.[8] Two contextual factors are the handshape of the surrounding signs, or in this case apogees, as well as the transition times to and from the surrounding apogees. The hypothesis here is that surrounding apogees that have handshapes with pinky extension will increase the chance of an apogee's hand configuration exhibiting pinky extension even thought 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 others that might affect 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 more instances with pinky extension than those that have any other letter on either side, including -B-, -C-, and -F- (see figure 3).

Using a mixed effects logistic regression with varying intercepts for the FS-letter of the apogee, and 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

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

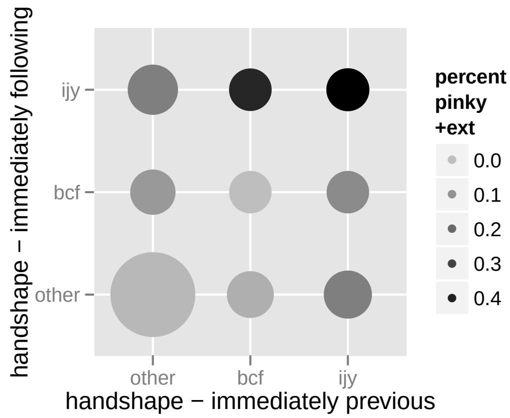

Figure 3: A plot showing the percent of apogees with hand configurations that have pinky extension, despite their handshapes not specifying pinky extension, based on surrounding handshapes. Darker colors represent a higher percentage of pinky extension, and the size of the dots represents the number of apogees that fall into each group.

both the following apogee's handshape was -I-, -J-, -Y-, -B-, -C-, or -F- and the following transition time was shorter (see table 2 for effect size estimates).

Additionally the model predictions from the regression are visualized in figure 4. Here we can see that apogees with handshapes that specify pinky extension (-B-, -C-, -F-, -I-, -J-, or -Y-) 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 also see the effect that

	Estimate	Std. Error	z value	Pr(> |z|)
(Intercept)	−5.82	0.60	−9.72	< 0.0001**
apogee of interest: -B-, -C-, -F-, -I-, -J-, or -Y-	12.14	1.28	9.50	< 0.0001**
previous -B-, -C-, or -F-	0.77	0.42	1.85	0.065·
previous -I-, -J-, or -Y-	3.38	0.30	11.31	< 0.0001***
previous transition time (zscore of log(time))	.06	0.15	0.41	0.68
following -B-, -C-, or -F-	1.16	0.59	1.96	0.05·
following -I-, -J-, or -Y-	2.52	0.29	8.79	< 0.0001***
following transition time (zscore of log(time))	−0.08	0.15	−0.50	0.62
word type foreign	−0.68	0.32	−2.10	0.03*
word type name	−0.28	0.29	−0.96	0.34
signer s1	−0.11	0.24	−0.47	0.64
previous -B-, -C-, or -F-×previous transition time	−0.33	0.38	−0.87	0.38
previous -I-, -J-, or -Y-×previous transition time	0.10	0.22	0.45	0.65
following -B-, -C-, or -F-×following transition time	−2.15	0.47	−4.56	< 0.0001***
following -I-, -J-, or -Y-×following transition time	−2.19	0.28	−7.95	< 0.0001***

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

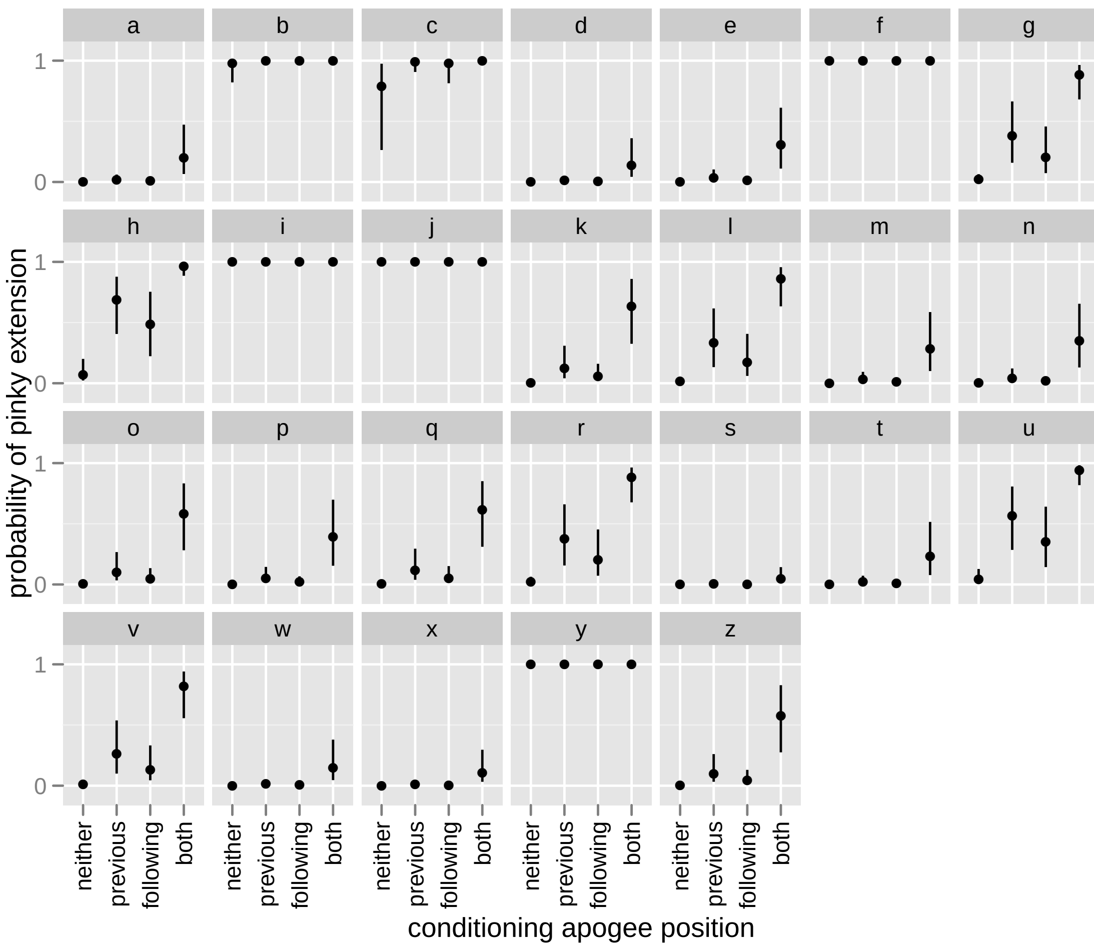

Figure 4: A plot showing the effect of conditioning apogees (-I-, -J-, and -Y-) on the probability of pinky extension at mean transition times for both previous and following positions. Dots are model predictions for an apogee with a condition apogee in the previous position, following position, both,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

a conditioning, surrounding apogee (FS-letter: -I-, -J-, or -Y-) has 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 -G-, -H-, -L-, -R-, -U-, and -V-), that probability greatly increases if there is an -I-, -J-, or -Y- apogee before or after, and even more 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. The generalization is that when a pinky is extended along with other fingers (especially the ring and middle fingers), there 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, whereas 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 these muscular asymmetries account 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, whereas flexion would be acting in concert with it.

Figure 5 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[9] 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 conditioning handshape in the previous apogee do not vary much at different previous transition times. 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 conditioning handshapes in following and both positions).

Additionally, when the word type is non-English, there is less pinky extension. This makes sense because both of the signers have some familiarity with English, and thus the

[9] 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.

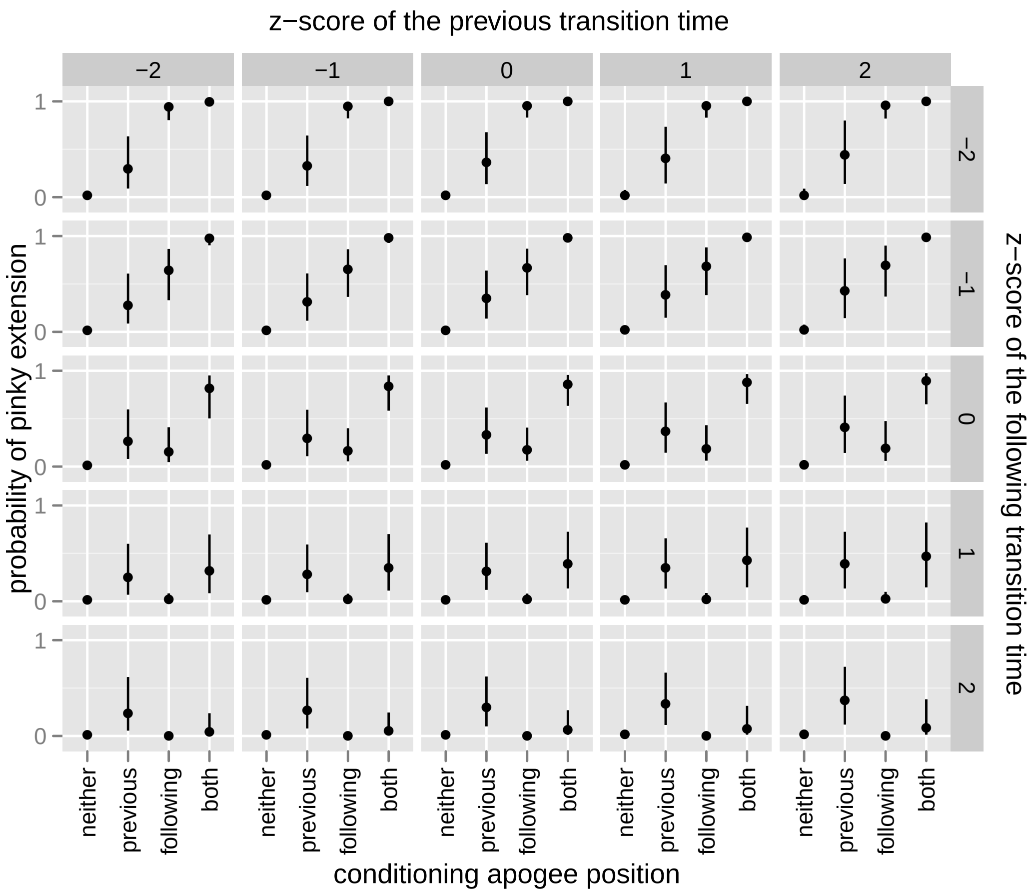

Figure 5: A plot showing the effect of conditioning apogees (-I-, -J-, and -Y-) on the probability of pinky extension for the FS-letter -L- only, faceted by previous and following transition time (z-scores of the log transform, where smaller values are shorter transitions).

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 additionally 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), and it would not be surprising if signers exhibited less coarticulation with non-English words beyond what is predicted by the longer transitions. 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 (Keane 2010). Finally, there is not a significant difference between the two signers we have data for with respect to these measures.

4. Discussion

We have seen that there does appear to be coarticulation with respect to the pinky finger: an extended pinky in the handshape of a neighboring apogee will increase the probability that an apogee for an FS-letter with a handshape with no 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-). Using a task dynamic modeling of speech and sign (Tyrone et al. 2010, Saltzman and Kelso 1987) this is expected, 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.

Future work is needed to gather more data from more signers, with more words in order to be able to make more nuanced conclusions. Previous and following apogees that are -B-, -C-, and -F- show some indication of causing similar coarticulation; with more data we will be able to determine if this tendency is robust, or is just noise. More signers are needed to confirm that these results hold across a wider language community, as well as further test the amount of individual variation (although we didn't find a significant amount in this study, we don't expect that there is none at all). Finally, more words with more apogees in diverse environments will allow us to determine how different FS-letters vary with respect to how much pinky extension coarticulation they participate in.

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