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# Formational Units in Sign Languages

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# Lexical and Articulatory Influences on Phonological Processing in Taiwan Sign Language[1]

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## 1. Introduction

In spoken language research, it has become clear that the phonological processing of a word is affected by such factors as phonotactic probability, neighborhood density, articulatory difficulty and lexical (token) frequency. Phonotactic probability and neighborhood density can be taken as measures of the typicality of a word. The first is an analytic measure in that it considers parts of a word (such as phonemes) and computes the probability that the parts (or a combination of parts) will appear in a given language. By contrast, neighborhood density is a holistic measure, reflecting how many similar words ("neighbors") a target item has in the lexicon of a given language. These two measures are highly correlated with each other. Studies concerning their influence on phonological processing in spoken language include Vitevitch & Luce (1998, 1999), Luce & Large (2001), and Bailey & Hahn (2001). Articulatory difficulty - the idea that certain segments or sequences of segments are more difficult than others to articulate - is as controversial in spoken language research as it has been difficult to quantify. Attempts to do so suggest that it is connected to what articulators "want" to do, perhaps individually but especially in concert, how many articulators need to act if a particular sound or sequence is to be uttered, and even the kinds of muscular actions not produced in speech except in cases of extreme necessity (see for example Lindblom and Sundberg 1971, Gay, Lindblom and Lubker 1981, Ohala 1983, Westbury and Keating 1986, Browman and Goldstein 1992, Stevens 1971 to name a few). Despite this, a full understanding of articulatory difficulty remains elusive. Lexical (token) frequency has long been understood to interact with linguistic behavior from the phonological to syntactic and discourse levels (Bybee 2000, Bybee 2001) and beyond. Do these factors also affect phonological processing in sign languages? And if so, do they have independent effects? This study addresses these questions with an experiment on Taiwan Sign Language (TSL).

## 2. Preliminaries

Several methodological issues arose at the beginning of our work. First, articulatory difficulty and type frequency were shown to be related in Ann (2006), and thus were confounds. Second, since we do not have a large enough TSL corpus to analyze in order to establish the frequency of TSL signs, we had to find an alternative method. Next, we explain our measure of articulatory difficulty of TSL signs. Finally, we explain the reasons for the tasks we chose given our questions.

### 2.1 Articulatory difficulty and type frequency are related

Ann (2006) related articulatory difficulty of handshapes to frequency of occurrence of handshapes in TSL. Specifically, Ann (2006) found that the type frequency of a handshape (i.e. the number of signs in the lexicon containing the handshape) tends to be negatively correlated with its articulatory difficulty score (defined according to a physiology-based algorithm). To make this observation precise, we computed this correlation for the 48 handshapes in the TSL signs used in our experiment (reported below), using logarithms of the handshape type frequencies, following standard psycholinguistic practice (this transformation makes the frequency distribution more symmetrical; see e.g. Baayen, 2001). We found that the negative correlation between articulatory difficulty and log handshape type frequency was statistically significant ($r(46) = -.42$, $p < .05$) and surprisingly large (the $r^2$ value meant that 18% of the variance in handshape type frequency was accounted for by articulatory difficulty).

Handshape type frequency can be thought of as a measure of typicality, similar to phonotactic probability and neighborhood density for spoken languages. Thus its correlation with articulatory difficulty provides an important clue about the role of articulation in the coinage and evolution of signs.[2]

While this correlation is theoretically interesting in its own right, it poses a potential problem for our current purposes. If we want to know if articulatory difficulty affects phonological processing, we cannot simply test for a correlation between articulatory difficulty and reaction times, since it could be that responses are faster to more typical signs, rather than being affected by articulatory difficulty itself.

One way to deal with this potential confound is to follow the lead of Bailey & Hahn (2001), who faced a similar problem in disentangling the effects of the highly correlated phonotactic probability and neighborhood density measures in English. Their solution was to run a multiple regression analysis. The mathematics of multiple regression makes it possible to partition out the effects of one factor from the effects of another, assuming that the two factors are not completely confounded (e.g. $r^2$ close to 100%). Though correlated, articulatory difficulty and handshape type frequency are not fully confounded, so a regression-based approach may help to reveal if they indeed have distinct effects on phonological processing.



Since we are interested not only in articulatory effects, but also the effects of the lexical properties of the signs themselves, we used only real TSL signs in our study. Thus we must also consider the effects of sign token frequency, or how often the signers in our study have seen or used the signs before in their lifetimes. Token frequency has long been known to exert powerful effects in reaction time tasks (Rubenstein, Garfield, & Milliken, 1970; Whaley, 1978; Rayner & Duffy, 1986). This then raises the problem of how to estimate token frequency in a sign language, which we deal with in the next section.

### 2.2 Estimating sign frequency in TSL

In spoken languages, estimating token frequency is usually done by means of analyzing a large corpus of fluent language use. Baayen (2001) shows first, that the standardly-used corpora of major languages like English now contain millions of tokens, and second, that smaller corpora are always less reliable than larger ones. In the absence of a sufficiently large corpus for TSL, it is difficult to estimate the frequency of a sign.

We dealt with this problem by following a strategy described in Bates et al. (2003). That study found that frequencies estimated in one language can often predict response times in another (see also Dehaene and Mehler, 1992). For example, if one wants to predict how fast an English speaker will name pictures of objects, one can successfully use the token frequencies of the object names in Chinese. In our own experimental stimuli of 127 words, the (log) Chinese and the (log) English frequencies are well correlated ($r(125) = .57$, $p < .0001$, with 32% of the variance in one language's frequencies predictable from the other. This surprising result comes about, Bates et al argue, because word token frequencies reflect how often the concepts named by the words are used in everyday life, and many concept frequencies are relatively invariant across cultures. Thus, in order to estimate the frequencies of TSL signs in the experience of TSL signers, we used the frequencies of their translations into Chinese (as estimated by the number of hits on Google,

computed in October, 2005). We assume that our choice of Chinese would tend to improve accuracy, given that the aspects of the cultures of hearing and deaf people in Taiwan are similar, and so they may be expected to share similar concept frequencies. As with all frequency measures, we then took the logarithm of the Chinese frequency estimates.

### 2.3 Articulatory difficulty in sign languages

It should not be surprising that the idea of establishing a metric for determining articulatory difficulty is not particularly well-studied for sign languages. However, the literature offers a (beginning) assessment of what is difficult to articulate (Mandel 1981). Signs are said to be made up of handshape, palm orientation, location and possibly movement (Stokoe, Casterline and Croneberg 1965, Battison 1978). Though signs have not been considered in their entirety, researchers have inquired into the relative ease or difficulty of the parts of a sign, for example, palm orientation (Crasborn and van der Kooij 1997) and handshape (Ann 2006). In the present study, we computed the overall articulatory difficulty for a sign as the sum of the physiology-based ease scores of Ann (2006) of each component handshape. This measure ignored other articulatory properties of the signs (movement, location, orientation) and made the convenient (if questionable) assumption that a two-handed sign with identical handshapes doubled the articulatory difficulty

### 2.4 Perception and production tasks

Because phonological processing involves both perception and production, we therefore decided on two tasks, one primarily concerned with each of these. The purpose of the experiment involving these tasks was to investigate the independent contributions of sign token frequency, handshape type frequency, and articulatory difficulty on reaction times.

For perception, we chose the *same-different matching* task, since as Vitevitch & Luce (1999) and others have argued, this task taps a relatively early stage of phonological processing, and thus is less influenced by the other factors (e.g. semantics) affecting the lexical decision task. In this task, pairs of stimuli (e.g. signs) are presented, and participants must quickly decide if they are the same or different. Both "same" pairs and "different" pairs



are presented, though responses to the "same" pairs are the primary focus of analysis, since these involve only one item (e.g. a sign), with its own particular properties (e.g. token frequency).

For production, we chose the elicitation imitation task, in which the participant is presented with a word that the participant is asked to repeat as quickly as possible. This task allows more flexibility than the picture naming task (used by Bates et al., 2003), since the concepts associated with the words need not be concretely picturable. It clearly has a perceptual component as well (i.e., processing the stimulus), but presumably the response cannot begin until something about the production form has been mentally prepared as well.

In both tasks, the measure we are interested in is the time it takes to begin a response, not the duration of the response itself. Thus reaction times should reflect purely mental processes, not articulation. Hence, if we find that articulatory difficulty slows reaction times in the production task, this would not be a trivial matter of finding that articulatorily difficult signs are harder to articulate. Rather, it would imply that articulatorily difficult signs take longer to prepare in the mind, a potentially much more interesting finding.

## 3. Methods

For both tasks, instructions were given in TSL by a fluent signer. The experiment was controlled by E-Prime (Schneider, Eschman, & Zuccolotto, 2002). In order to ensure accurate measurements of responses using this software, we converted each video into a series of still images, each lasting 120 ms (approximately eight frames per second) before giving it to the coders. This degraded the quality of the video by slowing down the movements, but the signs were still fully recognizable. Sign durations ranged from 1200 to 3240 ms (mean 2154, SD 385).

Stimuli for the two experiments were taken from the Taiwan Sign Language Online Dictionary (Tsay, Tai, Lee, Chen and Yu 2009), which consists of short videos illustrating nearly 3000 lexical items including each of the signs in Smith & Ting (1979, 1984), with adjustments and additions based on other sources as well as recent fieldwork. All are signed by the same deaf male signer.

### 3.1 Participants

Forty fluent deaf signers who use TSL as their primary means of communication performed both perception and production tasks. Participants' ages ranged from 20 to 61 at the time of testing (mean 44, SD 10.4). Both genders were represented equally. All were from central to southern Taiwan with most of them living in the cities of Changhwa, Chiayi, Tainan, or Kaohsiung. Participants were paid for their help.

Sixteen participants attended deaf schools; the remaining subjects did not respond to that question on the form they were provided. Twenty-three participants had signing relatives (including parents, spouses or siblings). The age at which participants first learned TSL ranged from 1 to 20 years old (mean 10, SD 3.9). The majority first learned TSL by age 10, but only one participant started learning TSL by age 1 (the second youngest age was 7). Thus, we consider most of the participants non-native signers. It is by now well-established that nativeness in a sign language affects how signs are processed (e.g., Mayberry & Fischer, 1989). Hence, we included age of acquisition (i.e. the age at which participants were first exposed to TSL) as a numerical factor in our analyses to see if it modulated the effects of the other factors (e.g., whether articulatory difficulty affected processing more strongly depending on the age that the signer acquired TSL).

### 3.2 Materials

Since this experiment used a multiple regression design, it was important to choose a variety of representative materials so that effects of the various factors could be distinguished from each other.

Token frequency, handshape type frequency, and articulatory difficulty were first computed for each sign that appeared in Smith & Ting (1979, 1984). Sign token frequency was estimated via the frequency of the Chinese translations, as described above. The overall handshape type frequency for a sign was the sum of the type frequencies for the component handshapes, where these type frequencies were the number of signs in Smith & Ting (1979, 1984) containing these handshapes. The overall articulatory difficulty for a sign was the sum of the difficulty score (the ease scores of Ann 2006) for each handshape in the sign.

In an attempt to balance sign token frequency, handshape type frequency, and articulatory difficulty in the materials, signs were cross-classified as high or low according to these three measures (above and below each measure's median) so that roughly equal-sized subsets could be collected for each combination (high token frequency-high type frequency-low articulatory difficulty, low token frequency-high type frequency-low articulatory difficulty, and so on). To keep the experiment to a reasonable length, we selected 127 items from the lexicon that met these criteria as best we could. One of these items had to be dropped in the analyses, since through an oversight it contained a configuration (crossed fingers) not given an articulatory difficulty score in the Ann (2006) system.



In the production (elicitation imitation) task, all 127 items were shown, but in the perception (same-different matching) task, a subset of 114 was selected to be shown in 76 pairs. The 38 "same" pairs (the same video shown twice) were chosen so as to give roughly equal numbers of combinations of the three measures (as described above). In particular, 20 of the signs had both low or both high values for handshape type frequency and articulatory difficulty, and 18 had opposite values for them. The remaining 76 signs were then paired up to create "different pairs", choosing signs that matched each other as much as possible in low-level visual details, such as lighting.

We expected that response times might be affected by duration of the videos themselves, which might also partly correlate with at least some of our independent variables. In spoken languages, higher frequency words tend to have fewer segments (Zipf 1935), and it is also known that in fluent speech, the segments themselves are shortened more in higher-frequency words (Bybee 2000). These generalizations meant that we expected sign duration to be negatively correlated to sign frequency. At the same time, we expected sign duration to be positively correlated with articulatory difficulty, assuming that harder signs require more time to articulate. To reduce the influence of such possible confounds, we included video duration (as a measure of sign duration) as an independent variable in our analyses, so that its effects could be factored out in the regression.

### 3.3 Procedure

We were unable to use the reaction time measurements automatically recorded when participants lifted their hands off the keyboard, since all but one of the participants failed to understand the instructions; most failed to press the space key at the beginning of a trial, or pressed it again after the trial began. Hence we were forced to estimate reaction times from the video recordings of the task itself, which showed the onset of actual signing. The onset of a sign was defined to be the video frame in which the first handshape of the

sign was fully articulated, as determined by non-native research assistants. Naturally these measurements were far less accurate than we'd have liked; even under ideal conditions, our video camera could not measure durations less than 33 ms (1000 ms / 30 frames per second), and additional challenges came from properly defining and identifying the onset of a sign.

Nine participants were dropped from analyses, seven because they performed the task incorrectly (in addition to the problems noted above), one because the hand movements were too small to identify the initial handshapes in the video records, and one because of the loss of the video analysis. This left 31 participants for analysis, 17 who performed the perception task first, and 14 who performed the production task first.

Due to experimenter oversight, the order of the two tasks was not counterbalanced across participants, but as we will see in the analyses, task order had no effect on the results.

### *3.3.1 Same-different matching task*

During this task, each participant faced a computer screen, with fingers poised over keys marked YES (on the right) and NO (on the left). In each trial, a "+" symbol first appeared in the center of the screen for 1 second (to focus attention), immediately followed by the first video of the pair. When this was finished, a blank screen was shown for 50 ms, followed by the second video. Participants were asked to press, as quickly and accurately as possible, the YES key if the two signs were identical, and NO otherwise. Reaction times were measured from the onset of the second video to the onset of the key press. After a practice session with three same pairs and three different pairs, the experiment proper began. 76 pairs of videos (38 same pairs, 38 different pairs) were presented in random order. The task was broken into two blocks of trials with a brief rest between them. Participants generally required five to ten minutes to complete the task.

### *3.3.2 Elicitation imitation task*

During this task, participants faced a computer screen, with fingers pressing down the space bar. They were asked to view digital videos of TSL signs produced by a native TSL signer. Participants were asked to lift their hands from the keyboard as soon as they recognized the sign on the screen and to sign it themselves. Reaction time was measured both at the lift-off of the hands from the keyboard, and at the onset of the first handshape of the target sign in the video recording. However for the reasons noted above, only the latter measure was used in the analyses reported here. In each trial, a "+" symbol first appeared in the center of the screen for 1 second, immediately followed by the video. A video record of each trial was also made (using a Sony TRV-30 camcorder, recording at the NTSC standard of 29.7 frames per second), showing both the onset of the stimulus on the computer screen and the participants' actual signing. 127 signs were presented in random order, broken into two blocks with a brief rest in the middle. Participants generally required ten to fifteen minutes to complete the task.



## 4. Results

Reaction times in both tasks were analyzed using multiple regression. The most important independent variables were (log) sign token frequency, (log) handshape type frequency, and articulatory difficulty, but for the reasons explained in 3.1, we also included the participants' age of acquisition of TSL, as well as the durations of the stimulus videos. Because these variables showed some correlation with each other (most notably, the significant correlation between articulatory difficulty and handshape type frequency), we first computed the VIF (variance inflation factor, based on $r^2$) for each variable to confirm that these correlations didn't cause cross-variable confounds. The largest VIF was 1.22 for duration, well below the conventional threshold of 5. Thus we can be reasonably confident that effects of the different predictors are indeed independent of the others.

In order to take both cross-participant and cross-item variation into account in the regression analyses, we used a technique called linear mixed effects modeling (LME; see Baayen 2008). Results reported below are for the by-participants-and-items statistical models, which always provided a significantly better fit to the data than the simpler by-participants-only models, and significance is based on $t$ values assuming infinite degrees of freedom given the large number of observations (well over 1000).

### 4.1 Results for same-different matching

An initial LME analysis showed that the order in which the tasks were performed had no direct effect on reaction times in the perception task, as

well as no indirect effect via interaction with other factors. Age of acquisition similarly had no direct or indirect effect. Thus in the LME analysis reported in Table 1, these two factors are left out.

*Table 1.* By-participants-and-items LME analysis of reaction times in the same-different matching task

| | Coefficient | *SE* | *t* | |
|---|---|---|---|---|
| Chinese token frequency (log) | –3.723 | 23.192 | –0.161 | |
| Handshape type frequency (log) | –23.823 | 10.683 | –2.230 | * |
| Articulatory difficulty score | 27.896 | 9.395 | 2.969 | * |
| Stimulus sign duration | 0.343 | 0.043 | 8.008 | * |

Note. *SE*: standard error. *t*: t value.
* $p < .05$

All effects went in the expected directions, as shown by the signs of the coefficients. The positive correlation between stimulus sign duration and reaction times presumably merely means that participants needed some time to recognize the stimuli before they could respond to them, which took longer for longer signs. Of greater theoretical relevance were the effects of the other three factors. These effects are illustrated in Figure 1, which shows the independent contribution of each factor in the LME with other factors held constant (note that lower values on the *y* axis imply faster responses).

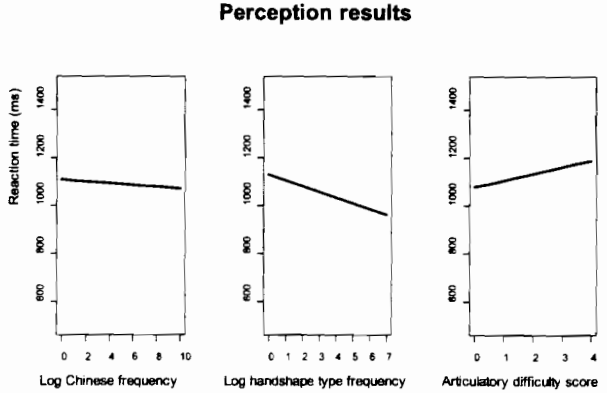


*Figure 1.* Independent contributions of log frequency of Chinese translations of the TSL items, log handshape type frequency, and articulatory difficulty scores, to reaction times in the matching task.



Higher sign token frequency was associated with somewhat faster responses, though this effect was not statistically significant. Two possible explanations for this null result come to mind. One is that our Chinese-based frequency estimates did not reflect TSL frequencies well enough. Another is that the TSL signs, being taken from an introductory textbook (the only lexicon currently available), were all relatively common and thus did not differ enough in frequency to make detection of a significant frequency effect possible. Nevertheless, the frequency effect did trend in the expected direction.

Handshape type frequency was significantly negatively correlated with reaction times, indicating that responses were sped up (shorter reaction times) for more typical signs (with higher handshape type frequencies). Articulatory difficulty was significantly positively correlated with reaction times, indicating that responses were slower for more difficult signs. These results imply that both handshape type frequency and articulatory difficulty affect perceptual processing, and do so independently of each other, as well independently of sign frequency. We return to this point in section 5.0.

### 4.2 Results for elicitation imitation

Despite the limitations in our measurements, the results were quite straightforward. As with the perception task, task order and age of acquisition had no direct or indirect effects on reaction times in the production task. Hence they are left out of the analysis reported in Table 2.

*Table 2.* By-participants-and-items LME analysis of reaction times in the elicitation imitation task

| | Estimate | *SE* | *t* | |
|---|---|---|---|---|
| Chinese token frequency (log) | –28.105 | 14.938 | –1.882 | |
| Handshape type frequency (log) | –19.331 | 6.258 | –3.089 | * |
| Articulatory difficulty score | 9.615 | 4.431 | 2.170 | * |
| Stimulus sign duration | 0.093 | 0.024 | 3.841 | * |

Note. *SE*: standard error. *t*: t value.
* $p < .05$

The effects again all trend in the expected directions. Once again, the effect of sign frequency did not reach statistical significance, though this time it came quite close ($p < .07$), perhaps because of the much greater number of

items in the production task compared with the perception task (over three times as many). The regression lines computed in the LME analysis for the three theoretically relevant factors are shown in Figure 2.

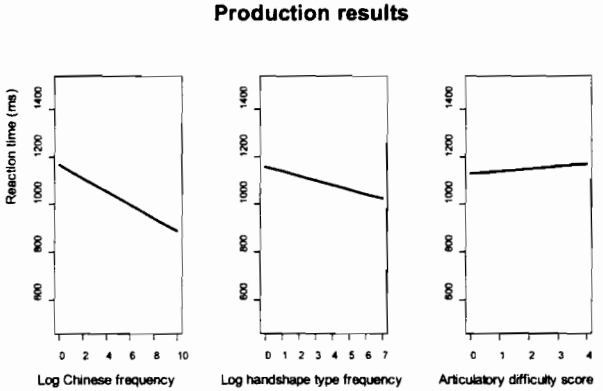


*Figure 2.* Independent contributions of log frequency of Chinese translations of the TSL items, log handshape type frequency, and articulatory difficulty scores, to reaction times (handshape onset times) in the shadowing task.

### 4.3 Cross-task comparisons

In order to help us understand what differences the task made in the influence of sign frequency, handshape type frequency, and articulatory difficulty on processing time, we conducted a further LME analysis, this time adding a factor representing the task (perception vs. production), and looking for interactions with it. This analysis was conducted using only the 24 signers who gave usable data in both tasks and the 38 items used in both tasks. Again, task order and age of acquisition had no significant effects, so they were removed from the analysis.

The tasks didn't differ in overall reaction times, but aside from sign frequency, the tasks did differ significantly in how reaction times were affected by the factors shown in the preceding tables. There were significantly stronger effects of stimulus duration ($t = 4.09$, $p < .05$) and articulatory difficulty ($t = 2.45$, $p < .05$) in the perception task than the production task, while the effect of handshape type frequency was marginally stronger in the production task than in the perception task ($t = -1.96$, $p = .05$). This difference in strength may relate to the difference in reaction time measurement sensitivity across the two tasks (1 ms. accuracy for perception vs. over 33 ms. accuracy for production), though an alternative interpretation will be noted in the discussion section.



## 5. Discussion

In both tasks, response times showed independent effects of token frequency (frequent signs were responded to more quickly), handshape type frequency (more typical signs were responded to more quickly), and articulatory difficulty (difficult signs were responded to more slowly).

Surprisingly, the cross-task analysis showed that the effect of articulation was stronger in the perceptual (same-different) task than in the production (elicitation) task. As noted above, this counterintuitive result could be due to differences in measurement sensitivity across the two tasks, but a more interesting possibility relates to the observation that the same-different task required holding the first sign in memory, whereas the elicitation imitation task did not. Wilson and Emmorey (1997) found that ASL signers hold signs in working memory using a visuospatial motoric code, analogous to the articulation-based phonological loop used by oral language speakers. Our study may have inadvertently provided new evidence for this phenomenon.

Token frequency effects were weakest in both tasks. This isn't surprising, given the problems in estimating TSL frequency and the relative uniformity of frequencies in our lexicon of mostly common signs. Nevertheless, handshape type frequency sped up responses, regardless of the task. These results were consistent with those of Carreiras, Gutierrez-Sigut, Baquero and Corina (2008) who found frequency effects in lexical decision tasks that were only significant for non-native signers. This is consistent with spoken language research on the effects of phonotactic probability and neighborhood density. But further work would be necessary to define and distinguish these two measures in sign languages.

The articulatory difficulty effect was most important finding. Our study demonstrates that articulatory difficulty of handshapes does play a role in online phonological processing in TSL, independent of the typicality and frequency of signs in the TSL lexicon. Moreover, this articulatory difficulty effect is active inside signers' minds, since the effect was observed in the time needed to prepare a response, prior to making the physical response itself.

**Notes**

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2. Crucial to our chapter is the distinction between typicality and markedness. Language users learn about typicality through their experience with their language. Markedness does not have to do with language experience. Rather, it is connected to cross-linguistic, universal or innate properties.



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