A cross-linguistic preference for torso stability in the lexicon: Evidence from 24 sign languages

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When the arms move in certain ways, they can cause the torso to twist or rock. Such extraneous torso movement is undesirable, especially during sign language communication, when torso position may carry linguistic significance, so we expend effort to resist it when it is not intended. This so-called "reactive effort" has only recently been identified by Sanders and Napoli (2016), but their preliminary work on three genetically unrelated languages suggests that the effects of reactive effort can be observed cross-linguistically by examination of sign language lexicons. In particular, the frequency of different kinds of manual movements in the lexicon correlates with the amount of reactive effort needed to resist movement of the torso. Following this line of research, we present evidence from 24 sign languages confirming that there is a cross-linguistic preference for minimizing the reactive effort needed to keep the torso stable.

Keywords: sign languages, phonetics, ease of articulation, lexical frequency, linguistic universals

1. Introduction

The many insights we have gained into the phonetics of spoken languages do not directly tell us much about the phonetics of sign languages, because of the inherent differences in the physical properties of the two modalities. Even for the fundamental concept of articulatory effort (defined generally as the sum of all articulatory forces; Kirchner 1998, 2004), the focus in phonetics has historically been only on the active effort used to move an articulator, because that is the type of articulatory effort most apparent in spoken language (Sanders & Napoli 2016:277).

Accordingly, the few studies of sign languages that delve into matters of ease of articulation also focus on active effort. Padden & Perlmutter (1987) point out variations on two-handed symmetrical signs where active effort is reduced by decreasing the number of moving articulators (i.e. freezing the non-dominant hand or leaving it out of the sign entirely). Effort can also be reduced by decreasing the number of repeated movements in a sign (Mak & Tang 2011) and by undershooting on handshape (Ortega & Morgan 2010) or on location (Mauk 2003). Additionally, articulating a sign at a lower position in space reduces effort involved in lift (Tyrone & Mauk 2010). Joint involvement is particularly relevant to effort (Mandel 1979, 1981); signers can reduce effort by transferring movement from a more proximal joint to a more distal one (Poizner et al. 2000, Crasborn and van der Kooij 2003) and by subtracting joints from the movement (Meier et al. 2008). While child signers favor the use of more proximal joints (as do new adult signers; Mirus, Rathmann & Meier 2001, Pichler 2011), they tend to distalize as their signing matures (Meier et al. 1998, Emmorey 2002, Meier et al. 2008). Signers suffering from Parkinson's disease reduce the number of movements in a sign, undershoot on handshape and location regularly, and distalize often (Brentari and Poizner 1994, Poizner et al. 2000). These various methods of reducing active effort are heightened in casual conversation among skilled signers (for undershooting, see Mauk 2003; for joint use, see Napoli, Sanders & Wright 2014).

While mention of the nonmanuals with respect to ease of articulation is rare in the literature, there has been recent relevant work. Tyrone and Mauk (2016) report that when a manual articulator moves to contact the forehead or chin, the head moves forward a bit to meet it, thus facilitating contact. But when a manual articulator moves to contact the torso, the torso does not move forward to meet it; the torso remains fixed. Their account of why the head moves but not the torso is complex, but one of the contributing factors they list is the fact that "the torso is larger and heavier, and more subject to the effects of gravity and inertia" (2016:136); in other words, it would simply take too much effort to move it.

All of this work looks only at the active effort of moving an articulator, which is an important concern in sign languages because the manual articulators are so much more massive than the vocal articulators. However, not only does it take more effort to move them, but when they do move, their greater mass can exert forces on the torso that cause it to move as well. Recent research in sign language phonetics (Sanders & Napoli 2016; henceforth S&N) has identified the effort needed to resist such incidental torso movement, which they call "reactive effort", as a second type of articulatory effort relevant to language.

S&N show that the reactive effort needed to maintain torso stability corresponds inversely to the frequency of certain types of signs in three genetically unrelated sign languages (Italian Sign Language, Sri Lankan Sign Language, and Al-Sayyid Bedouin Sign Language). They hypothesize that this correspondence is due to a universal preference for the reduction of reactive effort in the lexicon, as part of a larger preference for ease of articulation. We test and confirm S&N's hypothesis by replicating their methodology for 24 sign languages, lending further support for the existence of a cross-linguistic preference for reducing reactive effort.

We begin in §2 by outlining the biomechanical and communicative benefits of a stable torso. In §3, we then describe S&N's framework for classifying manual articulations and their predictions about how reactive effort affects the lexicon based on the physics of torso rotation. In §4, we describe the methodology we used to test these predictions, and in §5, we present and discuss the results of our study, confirming S&N's results showing that movements requiring greater reactive effort are underrepresented in the lexicon. We conclude in §6 with discussion of some limitations and possible extensions of this work, and we offer an overall summary of our key results in §7.

2. Benefits of a stable torso

Movement of the torso can occur through active effort, by activating various muscles within the torso. The torso can also be induced to move by external forces, such as how the torso may be rocked left and right when vigorously waving one arm in the air. One could certainly allow incidental movement, and thus avoid exerting reactive effort, but for a variety of reasons, humans have evolved to naturally resist incidental movement of the torso. For example, we have evolved to favor a forward-facing torso during ordinary locomotion. Development of a robust gluteus maximus muscle (Lovejoy 1988) and iliopsoas muscle (Kimura 2002) allows us to resist both rocking and twisting as the legs move (especially with the addition of swinging the arms in alternation with the legs; Witte, Preuschoft & Recknagel 1991). We expend reactive effort to activate these muscles to stabilize the torso, which would otherwise be incidentally moved by the swinging of the legs.

Another major benefit of a stable torso is that it facilitates eye-based information exchange by keeping the eyes fully visible (Kobayashi & Kohshima 2001, Tomasello et al. 2007). Our larger scleras (eye whites) allow us to indicate emotions such as fear (showing more scleral area; Morris, deBonis & Dolan 2002, Whalen et al. 2004, Smith et al. 2005) and to point (perhaps to a threat) via eye gaze (Kawashima et al. 1999, Hooker et al. 2003). Being able to see the eyes fully in a sign conversation is particularly important because sign languages use eye articulation in indicating indexicals (for example, in agreement processes) and in articulating classifier predicates, typically by gazing at a location or following the movement of the classifier (Thompson, Emmorey & Kluender 2006). Eye contact is also generally maintained in a conversation, and gaze can be used to invite others to participate (Mather 1987).

Sign languages have one more important reason for not allowing incidental movement of the torso: torso movement can carry linguistic significance in signed communication. For example, there are some signs that have no manual articulation, using only non-manual articulation instead, such as the ASL sign PUZZLED, which can be articulated non-manually with a backward movement of the torso, a lowered chin, and squinted eyebrows (Dively 2001). More importantly, torso movement also delivers non-segmental information to indicate intonational units (Nespor & Sandler 1999), discourse units (Boyes-Braem 1999), questions (Neidle et al. 1997), tenses (Aarons et al. 1992), and role shift (Engberg-Pedersen 1995, 2003; Poulin & Miller 1995; Sallandre 2003, 2007; Pfau & Quer 2010).

Thus, there are powerful motivations to prevent the torso from being destabilized by incidental movement (both in general and in signed communication specifically). Consequently, there are powerful motivations for exerting reactive effort to counteract external forces that would induce such movement. Given the general drive to reduce articulatory effort in language (see Napoli, Sanders & Wright 2014:424ff for discussion and references), we expect to see linguistic evidence for the reduction of reactive effort specifically, and S&N provide a framework for analyzing the lexicon of sign languages that does indeed find such evidence.

3. Sanders and Napoli's framework for sign categorization

We adopt S&N's notation and categorization scheme for two-handed signs with path movement, which allows signs to be easily catalogued and compared based on how they do or do not destabilize the torso. Fundamental to S&N's categorization are three cardinal axes of movement (Figure 1): a sagittal axis that runs away from and toward the torso (the AT-axis), a vertical axis that runs up and down (the UD-axis), and a transverse axis that runs left and right (the LR-axis).

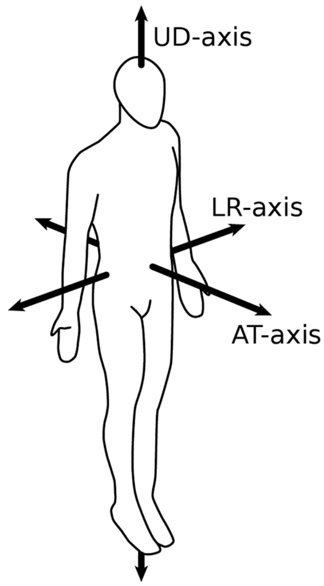

Figure 1. Three cardinal axes for manual movement (reproduced from S&N 2016:281).

For each axis, the hands may move together in the same direction defined by that axis (notated with + by S&N), in opposite directions (–), or not at all (0). For example, the ASL sign ACTIVITY in Figure 2 is coded as +LR, because the hands move together in the same direction along the LR-axis (both to the left at the same time and both to the right at the same time), while the ASL sign MAYBE in Figure 3 is coded as –UD, because the hands move in opposite directions along the UD-axis (one up and one down).

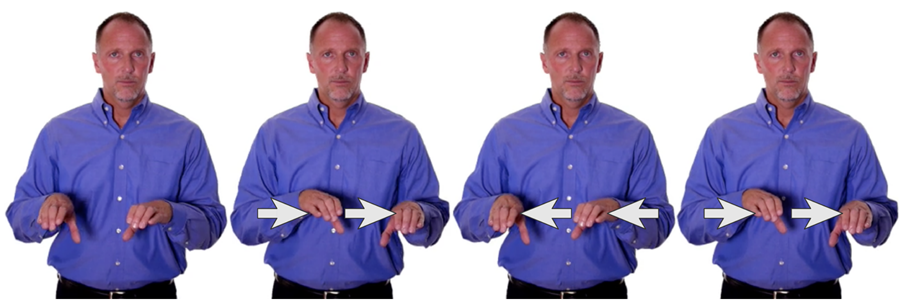

Figure 2. ACTIVITY in ASL with +LR movement.[1]

[1] All images of ASL examples used in this work are annotated versions of video stills captured from the online ASL database Signing Savvy (2016). Video for ACTIVITY available at https://www.signingsavvy.com/sign/ACTIVITY/7993/1.

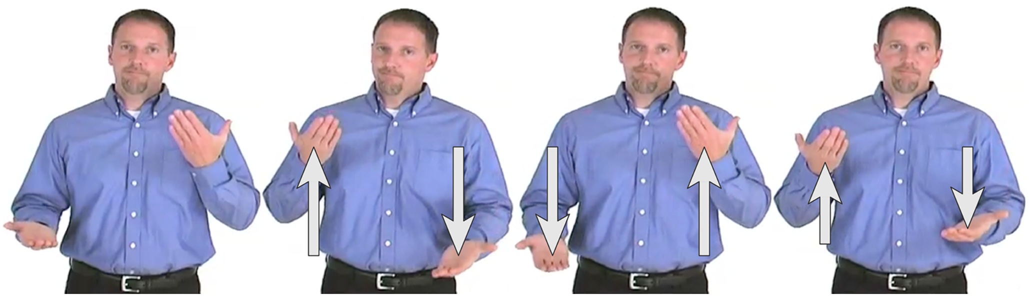

Figure 3. MAYBE in ASL with –UD movement.[2]

S&N further categorize signs by whether they are monoaxial (having manual movement along only one of the three cardinal axes, as in the ASL signs ACTIVITY and MAYBE in Figures 2 and 3) or multiaxial (movement along two or three cardinal axes, as in the ASL sign WAVE in Figure 4, in which the hands move away together (+AT), up and down together (+UD), and to the left together (+LR)).

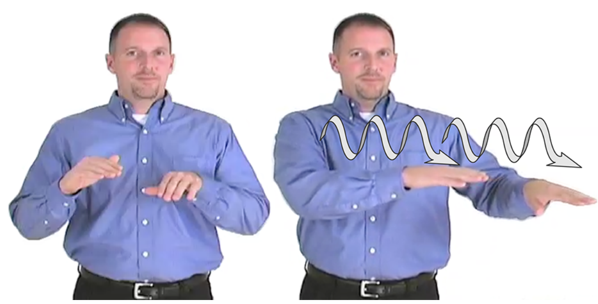

Figure 4. WAVE in ASL with +AT +UD +LR movement.[3]

Thus, there are six types of monoaxial signs (+AT, –AT, +UD, –UD, +LR, and –LR, which may be notated in expanded form explicitly showing no movement in the other two axes: +AT 0UD 0LR, –AT 0UD 0LR, etc.) and twenty types of multiaxial signs (Table 1).

Table 1. Twenty types of multiaxial signs.

AT	UD	LR	AT	UD	LR	AT	UD	LR	AT	UD	LR
+	+	+	+	–	+	0	–	+	–	0	+
+	+	0	+	–	0	0	–	–	–	0	–
+	+	–	+	–	–	–	+	+	–	–	+
+	0	+	0	+	+	–	+	0	–	–	0
+	0	–	0	+	–	–	+	–	–	–	–

As the arms move along these axes, they also exert forces on the torso. When a force acts on an object, it can cause the object to move in a straight line or create a torque that causes the object to rotate. Because the torso is fixed to the rest of the body, it cannot be moved in a straight line by arm movement, so we are concerned here only with torque. Every object has an inherent resistance to being rotated by a torque; this resistance is called its moment of inertia, which is

[2] Video available at https://www.signingsavvy.com/sign/MAYBE/261/1.
[3] Video available at https://www.signingsavvy.com/sign/WAVE/7153/1.

defined by the shape of the object, the way mass is distributed within it, and which axis it is being rotated around. We focus on the moments of inertia of the torso because it can be easily approximated across arbitrary signers in a way that other factors relevant to torque (such as magnitude and distance) cannot.

If we treat the human torso as a uniform cylinder (as in Figure 5) with sensible assumptions about dimensions ($r < h$), we can calculate that it takes less force to cause a torso-like cylinder to twist than it does to cause it to rock. Consider the difference between rolling a full keg across a lawn versus trying to repeatedly flip it end over end the same distance; rolling the keg is easier than flipping it. This is the effect of the different moments of inertia the cylinder has to being rotated for the different axes it is being rotated around. In particular, just like for a keg, the moment of inertia for twisting a torso-like cylinder (I_{twist} in Figure 5) is lower than the moment of inertia for rocking it (I_{rock} in Figure 5); see S&N 2016:290 for a mathematical proof.

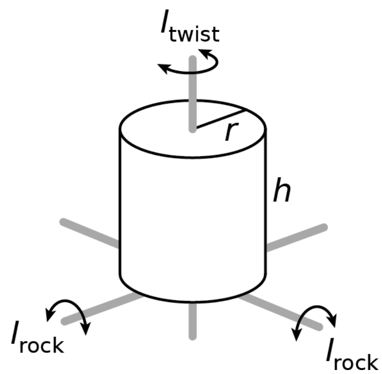

Figure 5. Cylindrical approximation of the human torso and its moments of inertia for twisting and rocking (reproduced from S&N 2016:289).

Since humans have an innate biological drive to maintain a stable torso, especially during sign language conversation (as discussed in the §2), and since arm motion can create torque on the torso (which would lead to the torso rotating about an axis), we must exert reactive effort to prevent this incidental movement. Given that sign languages, like spoken languages, have a drive for ease of articulation via effort reduction (Napoli, Sanders & Wright 2014), sign languages should, therefore, avoid signs that call for expending reactive effort to maintain torso stability. Further, since twisting, with the lowest moment of inertia, is the easiest torque to initiate, it therefore requires the most reactive effort to resist. S&N therefore predict that the lexicon might be biased against torque-inducing signs, with those signs that induce twisting being the least frequent. Their study confirms that prediction. Their findings further suggest, though without statistically significant data, that we might expect to find the lexicon biased against signs with a changing center of mass, since moving the center of mass is also destabilizing.

S&N look at signs in three languages in which both hands have path movement, since these signs have the greatest potential to induce destabilizing torque on the torso, given the large masses of both arms. They show that, with respect to torque, signs fall into three types, characterized by direction of path movement along the cardinal axes. First, –LR and +UD movements do not induce torque. For –LR movements (as in the ASL sign STRETCH in Figure 6), the individual torques induced separately by each hand point in opposite directions, so they cancel each other out, resulting in no net torque.

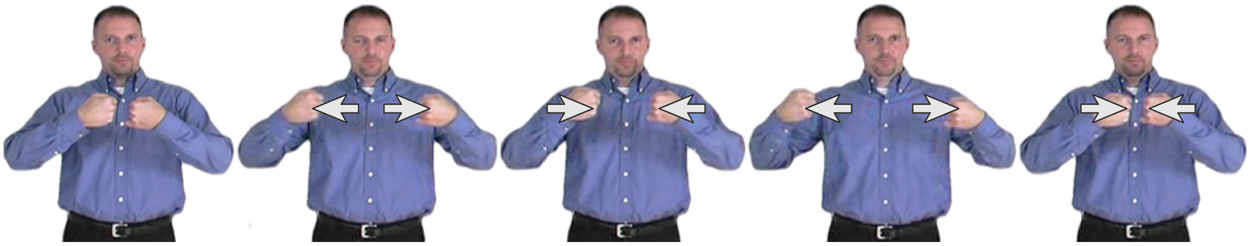

Figure 6. STRETCH in ASL with –LR movement, which induces no torque.[4]

For +UD movement (as in the ASL sign LIFT in Figure 7), the torso is pushed upward and/or downward. Since upward torso movement is resisted by gravity and downward torso movement is resisted by the ground (via the legs, a chair, etc.), +UD movement results in no torso movement. Even if the torso were to move as the result of +UD movement, such movement would be linear rather than rotational, so no torque is induced.

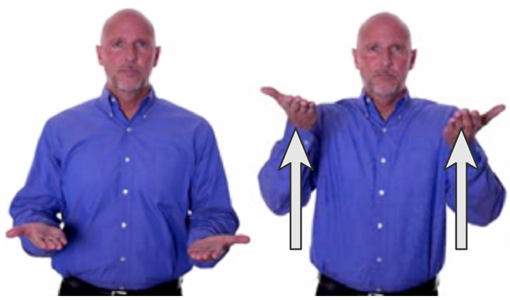

Figure 7. LIFT in ASL with +UD movement, which induces no torque.[5]

Second, –UD and +AT movements induce a rocking torque (side-to-side or forward-and-backward). For –UD movement (as in the ASL sign MAYBE in Figure 3), each hand movement separately induces a torque on the torso causing it to rotate around the sagittal axis pointing out through the waist. Since both torques rock the torso in the same direction at the same time, the net torque is a side-to-side rocking torque. For +AT movement (as in the ASL sign TEACH in Figure 8), each hand movement separately induces a torque on the torso causing it to rotate around the transverse axis pointing out through the sides. Since both torques rock the torso in the same direction at the same time, the net torque is a forward-and-backward rocking torque.

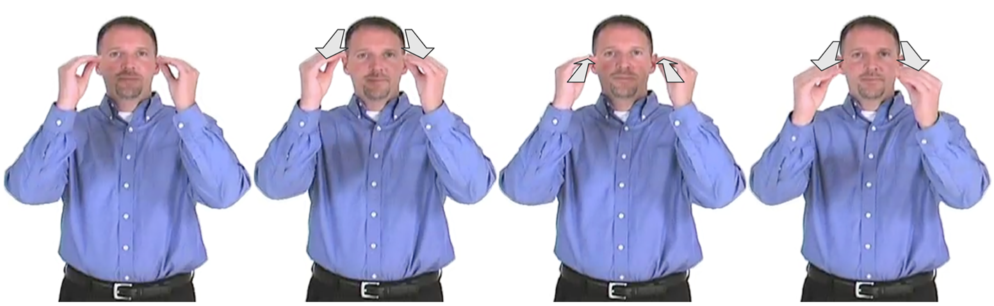

Figure 8. TEACH in ASL with +AT movement, which induces a rocking torque.[6]

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[4] Video available at https://www.signingsavvy.com/sign/STRETCH/4606/1.
[5] Video available at https://www.signingsavvy.com/sign/LIFT/3796/1.

Third, –AT and +LR movements induce a twisting torque (around the axis that goes vertically up the center of the body). For both –AT movement (as in the ASL sign WALK-FAST in Figure 9) and +LR movement (as in the ASL sign ACTIVITY in Figure 1), each hand movement separately induces a torque on the torso causing it to rotate around the craniocaudal axis pointing up and down. Since both torques twist the torso in the same direction at the same time, the net torque for both –AT and +LR movement is a twisting torque.

Figure 9. WALK-FAST in ASL with –AT movement, which induces a twisting torque.[7]

The three languages S&N studied are not genetically related to each other, and they cut across the age and stability factors that are sometimes used for characterizing languages (Aronoff et al. 2008): one is a national language in Italy that dates back to the late 1700s, one is a national language in Sri Lanka that dates back to the early 1900s, and one is a village sign language of a Bedouin community in Israel that dates back to the 1930s. Given that S&N report the same pattern across all three languages, we expect their findings to hold of sign languages in general, which led us to replicate their methods and confirm their results for a larger set of languages.

4. Data collection

We chose the online repository of sign language videos at Spreadthesign (henceforth STS; 2012) as the source of our data because of its size, search functionality, ease of use, and inventory of signs from many understudied languages. STS is run by the European Sign Language Centre in Örebro, Sweden, and contains signs mostly from European sign languages, though there are also signs from American Sign Language, Brazilian Sign Language, Indian Sign Language, Japanese Sign Language, and Ugandan Sign Language. The STS database contains 281,676 total videos from 26 sign languages for 15,000 main entries (as of July 8, 2015), which may be individual signs (THINK), phrases consisting of multiple signs (CHILDREN'S TV PROGRAM), or even full sentences (THE BACON IS OVERDONE). These main entries are presented in whichever language the user has selected for reading the website (we selected American English, the default setting). The database can be searched by main entry in this selected language in any of over 200 categories, which may be syntactic (Nouns, Verbs, Sentences, etc.) or semantic (Architecture, Military & Weaponry, At the hair salon, etc.). While main entries are displayed in lowercase on

[6] Video available at https://www.signingsavvy.com/sign/TEACH/704/1.
[7] Video available at https://www.signingsavvy.com/sign/WALK%20FAST/9263/1.

STS, we follow a standard convention in sign language linguistics literature of using small capitals to indicate signs.

Note that these main entries do not reflect well-defined lexemes, a problem with most sign language databases (Johnston and Schembri 1999). For example, the STS main entries EXCITED and ENTHUSIASTIC would be grouped into the same lexeme in a properly lemmatized dictionary of British Sign Language (Fenlon, Cormier & Schembri 2015:176), but in STS, they are separate entries containing different videos depicting different signers, with no indication that the two signers are in fact signing the same lexeme. It seems unlikely that this lexicographical shortcoming would be systematically skewed to favor or disfavor reactive effort in any language, let alone all of them. Thus, we take the STS database to adequately represent the distribution of reactive effort across each language's lexicons, with the understanding that properly lemmatized dictionaries would yield more reliable results and should be used when available.

The 26 languages are not equally represented in STS (see Table 2); in particular, Finnish Sign Language and Ugandan Sign Language are distinctly underrepresented. The exact count for Ugandan Sign Language is not listed on the STS website, though we found about one-fourth as many videos for Ugandan Sign Language as for Finnish Sign Language among the main entries we analyzed, so we estimate that there are probably no more than about 80 main entries with videos for Ugandan Sign Language. Note that since many of the main entries have two or more variants in some of the languages, STS's total number of videos is larger than the sum of the main entries counted in Table 2.

Table 2. Number of main entries with at least one video for each of 26 languages in the STS database. Data from http://www.spreadthesign.com/us/statistics/, accessed July 8, 2015.

Czech	15,000	American	13,421
Estonian	15,000	Icelandic	11,115
Italian	15,000	Portuguese	10,641
Latvian	15,000	Russian	10,097
Lithuanian	15,000	Romanian	8,807
Turkish	15,000	Ukrainian	8,208
Austrian	14,619	Brazilian	5,091
Swedish	14,382	Indian	4,744
Spanish	14,217	Greek	3,399
German	14,007	Bulgarian	2,492
British	13,781	Japanese	1,248
French	13,585	Finnish	325
Polish	13,430	Ugandan	~80

There are not enough signs in the database for Finnish Sign Language or Ugandan Sign Language to draw any statistically significant conclusions about them with the methodology and analyses used for this study (they yielded only 8 and 2 usable signs, respectively), so we exclude them from further consideration and analyze only the remaining 24 languages in the STS database.

STS does not provide direct access to the entire list of 15,000 main entries, and many of them are phrases or sentences that would not be suitable for our analysis, so we began our data collection by randomly selecting 500 total main entries from the five main grammatical categories that STS presents (Nouns, Verbs, Adjectives, Prepositions, and Adverbs), as these categories consist mostly of individual words, rather than phrases or sentences. Since the purpose of this work is to replicate S&N's methodology, we used their criteria for including and excluding signs. Thus, we included only those signs for the 500 main entries in which (i) both hands trace a route through space due to movement at the elbow and/or shoulder (i.e. the signs have path movement), (ii) the hands may touch for part of the sign but are not in continuous contact with each other throughout the duration of the sign (which means that they have the potential to move differently from one another), and (iii) the hands each trace (and potentially retrace) one single path (which means they can be described with a single movement parameter); all other signs were discarded.

In a small number of cases, two of the main entries we used were explicitly identified in STS as belonging to the same lexeme in a language (e.g. SQUEEZE and PUSH in German Sign Language are both identified as PUSH), in which case, we counted the sign only once and listed it under the main entry that STS identified as primary (here, PUSH). In addition, many signs in STS have two or more variants, some identified with descriptive language (e.g. *Inte så vanligt* 'not so common' and *Vanligast* 'most common' for MISUNDERSTAND in Swedish Sign Language), though many are simply called variants without further explanation. Thus, for a given main entry, we include all relevant variant signs separately in our data set, because there is often no way to determine which (if any) should be considered somehow primary. (To confirm that sign variation had no appreciable effect on our results, we performed our statistical analysis once with all variants included and then again multiple times with a single variant randomly selected for each sign; the statistical outcomes were the same in all cases).

From 500 original main entries, there were 430 with at least one language having a sign for that main entry that satisfied S&N's criteria (two-handed single or retraced path movement and hands not connected the entire duration of the sign). From those 430 main entries, we collected a total of 2,570 signs, distributed among the 24 languages as shown in Table 3 (the languages in Table 3 are ordered by total number of signs collected; for ease of comparison, the order arrived at in Table 3 is used in all tables for the rest of this work).

Table 3. Number of signs analyzed per language.

Austrian	172	British	120	Romanian	94
German	165	Icelandic	120	Portuguese	85
Polish	154	Spanish	118	Turkish	72
Estonian	145	Ukrainian	118	Brazilian	64
Czech	140	Russian	117	Indian	50
American	139	Italian	114	Bulgarian	36
Latvian	132	Lithuanian	113	Greek	31
Swedish	132	French	103	Japanese	26

All signs were coded (as +, –, or 0 along the AT-, UD-, and LR-axes) by two researchers, with a third researcher resolving any discrepancies between the first two. Following S&N, we further divided the signs into monoaxial and multiaxial signs for separate analysis.

5. Results

In this section, we report the results of analyzing the same four distinctions among signs in our data set that S&N analyzed in theirs: destabilizing versus stable for monoaxial signs (§4.1), destabilizing versus stable for multiaxial signs (§4.2), twisting versus rocking for monoaxial signs (§4.3), and changing versus fixed center of mass for monoaxial signs (§4.4). For each analysis, we follow S&N by calculating the *p*-value for Pearson's χ^2 test for goodness of fit to the proportions expected by the null hypothesis, using the chisq.test() function in the R programming language (R Core Team 2016); when direct computation of the *p*-value is unreliable or impossible due to limitations of the data, we compute the *p*-value using Monte Carlo simulation with 100,000 replicates. A result is considered statistically significant for $p < 0.05$.

5.1 Stability in monoaxial signs

For the monoaxial signs in our data set, we tallied how many of them destabilize the torso (i.e. those with +AT, –AT, –UD, or +LR movement) and how many of them keep the torso stable (i.e. those with +UD or –LR movement). If these six total monoaxial movements are uniformly distributed by random chance among monoaxial signs in a language's lexicon, we would expect roughly two-thirds of the monoaxial signs to be destabilizing (and thus, one-third should be stable). Such a uniform distribution is the null hypothesis for the χ^2 test. For each language in our data, the raw counts of the destabilizing signs (D) and stable signs (S), the percentage of monoaxial signs that are destabilizing (%D), and the *p*-value of the relevant χ^2 test are given in Table 4.

Table 4. Number of destabilizing (D) and stable (S) signs among monoaxial signs. %D = D/(D+S), and *p* measures significance of difference of %D from expected 66.7.

	D	**S**	**%D**	***p***		**D**	**S**	**%D**	***p***
Austrian	12	53	18.5	< 0.001	Russian	15	25	37.5	< 0.001
German	14	30	31.8	< 0.001	Italian	8	13	38.1	0.005
Polish	11	23	32.4	< 0.001	Lithuanian	11	18	37.9	0.001
Estonian	9	23	28.1	< 0.001	French	11	18	37.9	0.001
Czech	16	21	43.2	0.003	Romanian	12	18	40.0	0.002
American	10	19	34.5	< 0.001	Portuguese	8	13	38.1	0.005
Latvian	14	39	26.4	< 0.001	Turkish	7	19	26.9	< 0.001
Swedish	14	30	31.8	< 0.001	Brazilian	10	12	45.5	0.035
British	8	20	28.6	< 0.001	Indian	8	5	61.5	0.771
Icelandic	11	23	32.4	< 0.001	Bulgarian	1	10	9.1	< 0.001
Spanish	12	20	37.5	< 0.001	Greek	3	7	30.0	0.019
Ukrainian	13	17	43.3	0.007	Japanese	3	8	27.3	0.009

For every language, the proportion of destabilizing signs is less than what would be expected by the uniform distribution of the null hypothesis (i.e. %D is less than 66.7 for all 24 languages). In all but one, this is a statistically significant result; there are not enough relevant signs for Indian Sign Language to support a significant difference from the null hypothesis, but it does exhibit the same pattern as the other 23 languages.

These results are graphed in Figure 10 to better highlight the overall trend and its statistical significance in 23 of the languages. The thin white horizontal line across the graph indicates the uniform distribution of the null hypothesis, marking the expected proportional split between destabilizing signs (across the bottom) and stable signs (across the top). The null hypothesis is also graphed vertically with a yellow bar graphed upward for the destabilizing signs and a white bar graphed downward for the stable signs, with both meeting at the white horizontal line. For the 23 languages that differ significantly from the null hypothesis, the proportion of destabilizing signs is graphed in pink and the proportion of stable signs is graphed in blue; the remaining language is graphed in gray, with dark gray for destabilizing signs and light gray for stable signs.

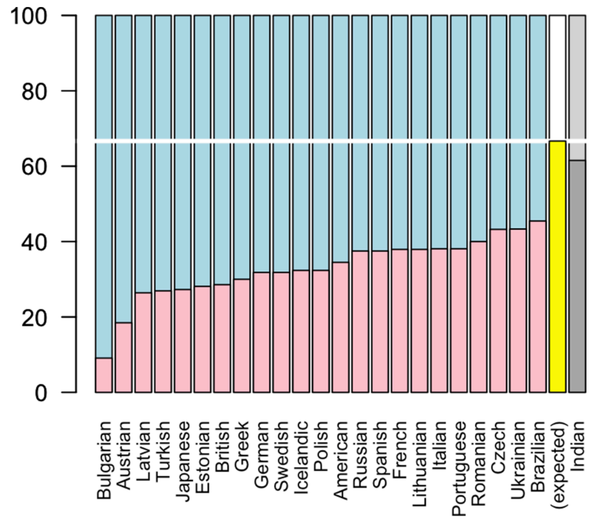

Figure 10. Percentage distribution of destabilizing (pink and dark gray across the bottom) versus stable (blue and light gray across the top) monoaxial signs.

From these results, there appears to be a strong cross-linguistic preference for destabilizing signs to be less frequent (and thus, for stable signs to be more frequent) among monoaxial signs in the lexicon than would be expected by random chance. This matches what is predicted by taking reactive effort into consideration with respect to overall torso stability: destabilizing signs require more reactive effort to prevent the torso from twisting or rocking, so they are predicted to be avoided.

In addition, as with the three languages in S&N's study, there is no statistical distinction across the languages in our study ($p = 0.45$ for a χ^2 test of homogeneity) or across the languages covered by our study conflated with S&N's ($p = 0.58$; note that conflating our study with S&N's must be interpreted with caution, since the corpora of the two studies were gathered in different ways). That is, not only are destabilizing signs underrepresented among monoaxial signs in the lexicon, but the degree to which they are underrepresented does not differ significantly across languages, suggesting a universal optimal proportion of destabilizing signs (approximately 34%, the average %D across the 24 languages here).

5.2 Stability in multiaxial signs

As with the monoaxial signs, we divided the multiaxial signs into those involving stable movement (i.e. 0AT +UD –LR only) and destabilizing movement (all other combinations). Of the 20 total multiaxial combinations (given in Table 1), six should be rare to non-existent for physiological and/or neurological reasons having nothing to do with reactive effort: periodic movement of both arms is most stable when it has midsagittal symmetry and either phasic or antiphasic homologous muscle activation, with phasic movement being even more prone to stability (Spencer et al. 2005:2901). That is, periodic bimanual movement is most stable when it traces two paths that are left-right reflections of each other; when the hands trace those paths in the same direction (both clockwise or both counterclockwise, as viewed from the right); and when the manual articulators' corresponding muscles are performing the same tasks, either at the same time (as in the ASL sign ROWING in Figure 11) or, less optimally, in cyclic alternation (as in the ASL sign BICYCLE in Figure 12).

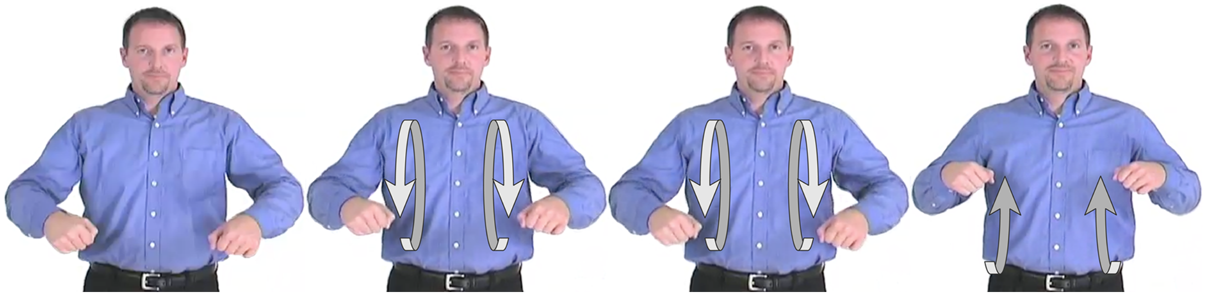

Figure 11. ROWING in ASL with laterally symmetric path movement and phasic homologous muscle activation.[8]

Figure 12. BICYCLE in ASL with laterally symmetric path movement and antiphasic homologous muscle activation.[9]

The problematic combinations are those in which movements along the AT- and UD-axes have opposite polarity (+AT –UD or –AT +UD), such as trying to articulate a sign like ROWING or BICYCLE, but with one hand moving counterclockwise while the other moves clockwise. In such a case, the homologous muscles in the arms are never performing exactly the same tasks, either at the same time or as part of a cyclic alternation. There are six such combinations (two for each of the three values for LR). There may be other multiaxial combinations that are also disfavored for reasons other than consideration of reactive effort, but these six are particularly difficult, so following S&N, we also exclude them from consideration. As expected, we found almost no signs in our data that had these problematic movements (only six out of 2,790 total signs), and given that there are other known factors that disfavor them besides reactive effort, including these disfavored combinations would artificially bias the results in our favor. Thus, excluding them makes it harder to find statistically significant differences due to reactive effort,

[8] Video available at https://www.signingsavvy.com/sign/ROWING/5029/1.
[9] Video available at https://www.signingsavvy.com/sign/BICYCLE/3041/1.

so we can be more confident in the differences we do find. This leaves us with 14 multiaxial combinations for consideration here, one stable and 13 destabilizing.

Given this, in the null hypothesis in which each of these 14 multiaxial combinations are uniformly distributed, we expect approximately 92.9% (that is, 13 out of 14) of the multiaxial signs in a language to be destabilizing and 7.1% (1 out of 14) to be stable. For each language in our data, the raw counts of the destabilizing signs (D) and stable signs (S), the percentage of monoaxial signs that are destabilizing (%D), and the *p*-value of the relevant χ^2 test are given in Table 5.

Table 5. Number of destabilizing (D) and stable (S) signs among multiaxial signs. %D = D/(D+S), and *p* measures significance of difference of %D from expected 92.9.

	D	**S**	**%D**	***p***		**D**	**S**	**%D**	***p***
Austrian	78	29	72.9	< 0.001	Russian	69	8	89.6	0.269
German	89	32	73.6	< 0.001	Italian	74	19	79.6	< 0.001
Polish	97	23	80.8	< 0.001	Lithuanian	67	17	79.8	< 0.001
Estonian	91	22	80.5	< 0.001	French	59	15	79.7	< 0.001
Czech	72	31	69.9	< 0.001	Romanian	52	12	81.2	0.002
American	89	21	80.9	< 0.001	Portuguese	53	11	82.8	0.006
Latvian	61	18	77.2	< 0.001	Turkish	27	19	58.7	< 0.001
Swedish	64	24	72.7	< 0.001	Brazilian	28	14	66.7	< 0.001
British	71	21	77.2	< 0.001	Indian	30	7	81.1	0.015
Icelandic	62	24	72.1	< 0.001	Bulgarian	23	2	92.0	1.000
Spanish	62	24	72.1	< 0.001	Greek	12	9	57.1	< 0.001
Ukrainian	72	16	81.8	< 0.001	Japanese	11	4	73.3	0.020

As for the monoaxial signs, for every language, the proportion of destabilizing signs is less than what would be expected by the uniform distribution of the null hypothesis (i.e. %D is less than 92.9 for all 24 languages), and again, in nearly all of them, this is a statistically significant result; only two (Russian and Bulgarian) do not have enough data to support a significant difference from the null hypothesis, but they still follow the same pattern as the other 22 languages. These results are graphed in Figure 13, following the same conventions established in Figure 10.

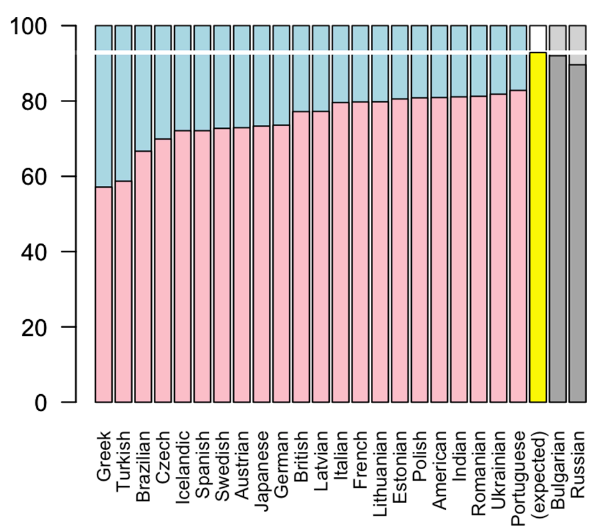

Figure 13. Percentage distribution of destabilizing (pink and dark gray across the bottom) versus stable (blue and light gray across the top) multiaxial signs.

From these results, there appears to be a strong cross-linguistic preference for destabilizing signs to be less frequent (and thus, for stable signs to be more frequent) among multiaxial signs in the lexicon than would be expected by random chance. This matches what is predicted by taking reactive effort into consideration with respect to overall torso stability: destabilizing signs require more reactive effort to prevent the torso from twisting or rocking, so they are predicted to be avoided.

Unlike with the monoaxial signs, there is a statistically significant difference in the patterns across the 24 languages for multiaxial signs ($p = 0.01$), with the languages breaking into two clear groups based on Figure 13: Greek and Turkish form one group (with the lowest proportion of destabilizing signs), and the remaining 22 languages form the other group. Within these two groups, there is no statistical distinction across languages ($p > 0.99$ and $p = 0.14$, respectively). Thus, if we set aside Greek and Turkish as outliers, we again find that not only are destabilizing signs underrepresented, but the degree to which they are underrepresented does not differ across languages, about 76% on average (and again, there is no statistically significant difference between S&N's data and the 22 non-outlier languages here, with $p = 0.13$). The suggestion of a universal optimal proportion is thus not as strong as for monoaxial signs, but it is still strong, with only two outliers. Perhaps not coincidentally, Greek and Turkish have two of the lowest total number of multiaxial signs in our data set (Greek has the second lowest and Turkish has the fifth lowest); a larger data set may push them closer to patterning with the other languages.

5.3 Types of instability in monoaxial signs

Following S&N, we further divided the destabilizing monoaxial signs into those that induce twisting of the torso (i.e. those with –AT or +LR movement) and those that induce rocking of the torso (i.e. those with +AT or –UD movement). If the four total destabilizing monoaxial movements are uniformly distributed (the null hypothesis), we expect to see approximately one-half of the destabilizing monoaxial signs in a language induce twisting and one-half induce rocking. For each language in our data, the raw counts of the twisting signs (T) and rocking signs (R), the percentage of destabilizing monoaxial signs that induce twisting (%T), and the p-value of the relevant χ^2 test are given in Table 6.

Table 6. Number of twisting (T) and rocking (R) signs among monoaxial signs. %T = T/(T+R), and p measures significance of difference of %T from expected 50.0.

	T	**R**	**%T**	***p***		**T**	**R**	**%T**	***p***
Austrian	2	10	16.7	0.021	Russian	3	12	20.0	0.021
German	5	9	35.7	0.285	Italian	2	6	25.0	0.288
Polish	1	10	9.1	0.007	Lithuanian	1	10	9.1	0.007
Estonian	0	9	0.0	0.004	French	2	9	18.2	0.035
Czech	2	14	12.5	0.003	Romanian	1	11	8.3	0.004
American	0	10	0.0	0.002	Portuguese	3	5	37.5	0.727
Latvian	3	11	21.4	0.033	Turkish	2	5	28.6	0.453

Swedish	2	12	14.3	0.008	Brazilian	4	6	40.0	0.527
British	1	7	12.5	0.071	Indian	2	6	25.0	0.290
Icelandic	4	7	36.4	0.366	Bulgarian	0	1	0.0	1.000
Spanish	2	10	16.7	0.021	Greek	0	3	0.0	0.249
Ukrainian	2	11	15.4	0.013	Japanese	1	2	33.3	1.000

For every language, the proportion of twisting signs is less than what would be expected by the uniform distribution of the null hypothesis (i.e. %T is less than 50.0 for all 24 languages), though this result is statistically significant for only slightly more than half of the languages (13 out of 24). These results are graphed in Figure 14, with twisting signs in red and dark gray across the bottom and rocking signs in pink and light gray across the top; statistically significant results are in red and pink. Otherwise, the same conventions are used as in Figures 10 and 13.

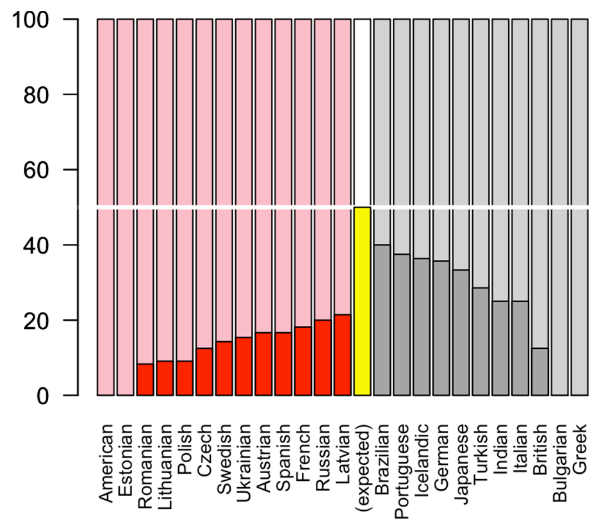

Figure 14. Percentage distribution of twisting (red and dark gray across the bottom) versus rocking (pink and light gray across the top) monoaxial signs.

From these results, there appears to be a strong cross-linguistic preference among destabilizing monoaxial signs for those that induce twisting to be less frequent in the lexicon, in comparison to those that induce rocking, than would be expected by random chance. This matches what is predicted by taking reactive effort into consideration with respect to overall torso stability: it requires more reactive effort to prevent twisting than rocking, so twisting is predicted to be avoided more than rocking is.

Here, there is no statistical difference across the languages in our study ($p = 0.68$) or across the languages in our study conflated with S&N's ($p = 0.63$), so again, not only are the disfavored (twisting) signs underrepresented, but the degree to which they are underrepresented does not differ across languages (the average %T is approximately 18%).

4.4 Center of mass in monoaxial signs

When the arms move, they can change the signer's center of mass (CM). For monoaxial signs, if both hands move in the same direction (i.e. +AT, +UD, and +LR), the CM will move along the relevant axis. If the hands move in opposite directions (i.e. –AT, –UD, and –LR), they balance each other out and the CM will remain fixed. Since a change in CM could cause us to topple in one direction or another, S&N raise the possibility that the body might expend reactive effort to combat changes in CM (2016:292–294). While they do not find any statistically significant patterns, they note an overall suggestive pattern: when comparing two monoaxial movements that induce the same torque (twisting, rocking, or none), where one movement involves change of CM and the other does not, the type with changing CM is almost always the less frequent. That is, for the two monoaxial movements that induce twisting (–AT and +LR), the movement that changes the CM (+LR) is the less frequent. Likewise, for the two movements that induce rocking (–UD and +AT) and the two that induce no torque (–LR and +UD), the movement in each pair that changes the CM (+AT and +UD, respectively) is usually the less frequent. They further suggest that the effect may be stronger for twisting movements than for rocking movements, and weakest for stable movements. Despite their lack of statistically significant results, the pattern suggests the need to explore a larger data set, which we do here.

If the two twisting monoaxial movements are uniformly distributed (the null hypothesis), we expect to see approximately one-half of the twisting monoaxial signs in a language change the CM and one-half keep the CM fixed. For each language in our data, the raw counts of the twisting monoaxial signs with changing CM (C) and with fixed CM (F), the percentage of twisting monoaxial signs that change the CM (%C), and the *p*-value of the relevant χ^2 test are given in Table 7.

Table 7. Number of changing CM (C) and fixed CM (F) signs among twisting monoaxial signs. %C = C/(C+F), and *p* measures significance of difference of %C from expected 50.0.

	C	**F**	**%C**	***p***		**C**	**F**	**%C**	***p***
Austrian	1	1	50.0	1.000	Russian	1	2	33.3	1.000
German	3	2	60.0	1.000	Italian	1	1	50.0	1.000
Polish	1	0	100.0	1.000	Lithuanian	1	0	100.0	1.000
Estonian	0	0	–	–	French	1	1	50.0	1.000
Czech	2	0	100.0	1.000	Romanian	0	1	0.0	1.000
American	0	0	–	–	Portuguese	0	3	0.0	1.000
Swedish	0	2	0.0	0.501	Turkish	1	1	50.0	1.000
Latvian	1	2	33.3	1.000	Brazilian	1	3	25.0	0.626
British	0	1	0.0	1.000	Indian	0	2	0.0	0.501
Icelandic	1	3	25.0	0.626	Bulgarian	0	0	–	–
Spanish	1	1	50.0	1.000	Greek	0	0	–	–
Ukrainian	1	1	50.0	1.000	Japanese	0	1	0.0	1.000

Four of the languages have no twisting monoaxial signs at all, and there is no significant difference between changing and fixed CM for twisting monoaxial signs in any of the remaining 20 languages. Furthermore, unlike in S&N's data, there is no clear pattern here across the languages: half of the 20 languages with twisting monoaxial signs follow S&N's prediction for changing CM to be underrepresented, six have an equal amount of changing and fixed CM, and four show a preference for changing CM. These results are graphed in Figure 15, with changing CM signs in dark gray across the bottom and fixed CM signs in light gray across the top. Otherwise, the same conventions are used as in Figures 10, 13, and 14.

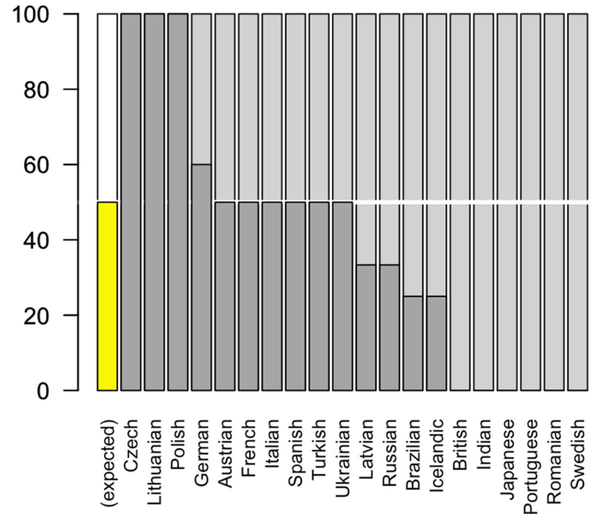

Figure 15. Percentage distribution of twisting monoaxial signs with changing CM (dark gray across the bottom) versus fixed CM (light gray across the top).

The distribution of monoaxial twisting signs is not statistically significantly different across these 20 languages alone ($p > 0.99$) or conflated with those in S&N's study that also have monoaxial twisting signs ($p = 0.66$), but there are too few signs in our data to draw any meaningful conclusions.

Similarly, if the two rocking monoaxial movements are uniformly distributed (the null hypothesis), we expect to see approximately one-half of the rocking monoaxial signs in a language change the CM and one-half keep the CM fixed. For each language in our data, the raw counts of the rocking monoaxial signs with changing CM (C) and with fixed CM (F), the percentage of rocking monoaxial signs that change the CM (%C), and the *p*-value of the relevant χ^2 test are given in Table 8.

Table 8. Number of changing CM (C) and fixed CM (F) signs among rocking monoaxial signs. %C = C/(C+F), and *p* measures significance of difference of %C from expected 50.0.

	C	F	%C	*p*		C	F	%C	*p*
Austrian	8	2	80.0	0.108	Russian	8	4	66.7	0.388
German	7	2	77.8	0.182	Italian	3	3	50.0	1.000
Polish	7	3	70.0	0.344	Lithuanian	4	6	40.0	0.754
Estonian	6	3	66.7	0.508	French	5	4	55.6	1.000
Czech	8	6	57.1	0.790	Romanian	2	9	18.2	0.066
American	8	2	80.0	0.110	Portuguese	3	2	60.0	1.000
Latvian	7	4	63.6	0.547	Turkish	4	1	80.0	0.374
Swedish	3	9	25.0	0.145	Brazilian	5	1	83.3	0.219
British	5	2	71.4	0.452	Indian	6	0	100.0	0.031
Icelandic	2	5	28.6	0.452	Bulgarian	1	0	100.0	1.000
Spanish	8	2	80.0	0.110	Greek	2	1	66.7	1.000
Ukrainian	5	6	45.5	1.000	Japanese	1	1	50.0	1.000

There is only one language with a statistically significant difference from the null hypothesis (Indian Sign Language), and it contradicts S&N's prediction by having all of its rocking monoaxial signs involve a change in CM. For the remaining 23 languages, only five follow

S&N's prediction in having a preference for fixed CM, while 16 show a preference for changing CM, and two show no preference. These results are graphed in Figure 16, with changing CM signs in purple and dark gray across the bottom. Otherwise, the same conventions are used as in Figures 10 and 13–15.

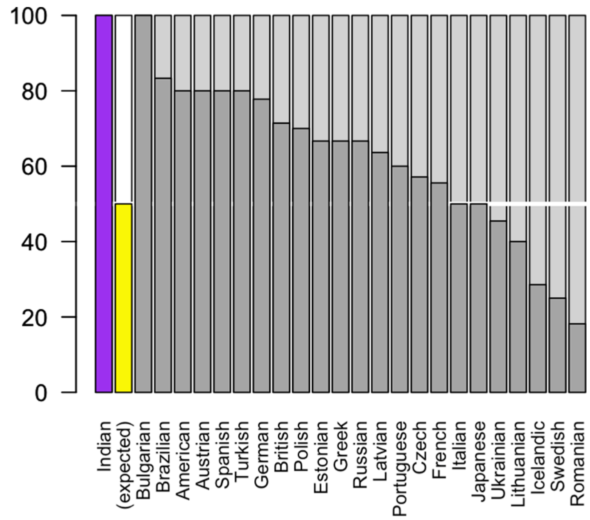

Figure 16. Percentage distribution of rocking monoaxial signs with changing (dark purple and dark gray across the bottom) versus fixed (light gray across the top) center of mass.

Here, there is a statistically significant difference across the languages in our study (p = 0.04) and also across the languages in our study conflated with S&N's (p = 0.03), which is evidence that there is no consistent cross-linguistic pattern in the relationship between CM and monoaxial rocking, though again, there are not enough signs in our data to support a strong hypothesis.

As with twisting and rocking monoaxial movements, if the two stable monoaxial movements are uniformly distributed (the null hypothesis), we expect to see approximately one-half of the stable monoaxial signs in a language change the CM and one-half keep the CM fixed. For each language in our data, the raw counts of the stable monoaxial signs with changing CM (C) and with fixed CM (F), the percentage of stable monoaxial signs that change the CM (%C), and the p-value of the relevant χ^2 test are given in Table 9.

Table 9. Number of changing CM (C) and fixed CM (F) signs among stable monoaxial signs. %C = C/(C+F), and p measures significance of difference of %C from expected 50.0.

	C	F	%C	*p*		C	F	%C	*p*
Austrian	23	30	43.4	0.410	Russian	13	12	52.0	1.000
German	17	13	56.7	0.583	Italian	4	9	30.8	0.269
Polish	5	18	21.7	0.011	Lithuanian	8	10	44.4	0.816
Estonian	14	9	60.9	0.405	French	5	13	27.8	0.097
Czech	14	7	66.7	0.188	Romanian	2	16	11.1	0.001
American	9	10	47.4	1.000	Portuguese	8	5	61.5	0.583
Latvian	28	11	71.8	0.010	Turkish	11	8	57.9	0.645
Swedish	13	17	43.3	0.588	Brazilian	3	9	25.0	0.145
British	4	16	20.0	0.012	Indian	0	5	0.0	0.062
Icelandic	11	12	47.8	1.000	Bulgarian	5	5	50.0	1.000

Spanish	11	9	55.0	0.824	Greek	3	4	42.9	1.000
Ukrainian	12	5	70.6	0.145	Japanese	4	4	50.0	1.000

For stable monoaxial signs, there is no significant difference between fixed and changing CM for 20 of the 24, and of the four that do have a significant difference, three follow S&N's prediction by having change of CM being underrepresented among stable monoaxial signs, and one does not. For the remaining 20 languages, exactly half follow S&N's prediction in having a preference for fixed CM, while eight show a preference for changing CM, and two show no preference. These results are graphed in Figure 17, with fixed CM signs in light purple and light gray across the top. Otherwise, the same conventions are used as in Figures 10 and 13–16.

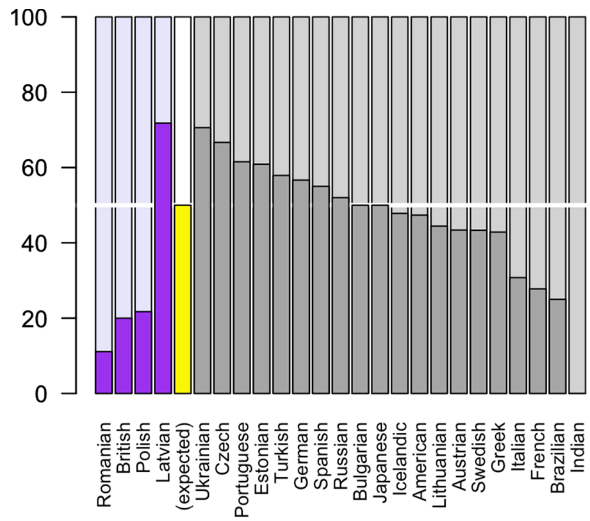

Figure 17. Percentage distribution of stable monoaxial signs with changing (dark purple and dark gray across the bottom) versus fixed (light purple and light gray across the top) center of mass.

As with rocking monoaxial signs, there is a statistically significant difference in changing versus fixed CM in stable monoaxial signs across the languages in our study ($p < 0.001$) and across the languages in our study conflated with S&N's ($p < 0.001$), pointing to a lack of a consistent cross-linguistic pattern in how a changing versus fixed CM is distributed across stable monoaxial signs.

Overall, across these three types of monoaxial signs, there is little evidence to support S&N's prediction concerning the underrepresentation of a changing CM: only three out of 68 total comparisons show a statistically significant agreement with this prediction, while two showed statistically significant disagreement. Of the remaining comparisons, slightly more contradict S&N's prediction than follow it (38 versus 25). Thus, at least at the level of these three subtypes of monoaxial signs based on torso stability, there seems to be no effect of whether the CM is changing or fixed. Indeed, the subtype of monoaxial signs that showed the strongest effect of avoiding changing CM are the stable signs, which S&N predicted should show the weakest effect.

As a final test to find support for S&N's prediction, we split up all monoaxial signs in each language regardless of torso stability based simply on whether the CM is changing (i.e. those with +AT, +UD, or +LR movement) or fixed (i.e. those with –AT, –UD, or –LR movement). There are six total monoaxial movements, so in the null hypothesis in which CM plays no role in the frequency of movements across signs in the lexicon, we expect to see monoaxial signs split approximately equally between those with a changing CM and those with a fixed CM. The raw counts of the monoaxial signs with changing CM (C) and fixed CM (F), the percentage of monoaxial signs with changing CM (%C), and the *p*-value of the relevant χ^2 test are given in Table 10.

Table 10. Number of monoaxial signs with changing (C) and fixed (F) center of mass among. %C = C/(C+F), and *p* measures significance of difference of %C from expected 50.0.

	C	F	%C	*p*		C	F	%C	*p*
Austrian	32	33	49.2	0.901	Russian	22	18	55.0	0.527
German	27	17	61.4	0.132	Italian	8	13	38.1	0.275
Polish	13	21	38.2	0.170	Lithuanian	13	16	44.8	0.577
Estonian	20	12	62.5	0.157	French	11	18	37.9	0.194
Czech	24	13	64.9	0.071	Romanian	4	26	13.3	< 0.001
American	17	12	58.6	0.353	Portuguese	11	10	52.4	0.827
Latvian	36	17	67.9	0.009	Turkish	16	10	61.5	0.239
Swedish	16	28	36.4	0.070	Brazilian	9	13	40.9	0.394
British	9	19	32.1	0.059	Indian	6	7	46.2	0.782
Icelandic	14	20	41.2	0.303	Bulgarian	6	5	54.5	0.763
Spanish	20	12	62.5	0.157	Greek	5	5	50.0	1.000
Ukrainian	18	12	60.0	0.273	Japanese	5	6	45.5	0.763

There is little evidence of an overall pattern in these results. Only two languages have a statistically significant difference from the null hypothesis (Latvian and Romanian), and while Romanian Sign Language does follow S&N's prediction in having a lower proportion of changing CM than expected by random chance, Latvian Sign Language does not. Of the remaining 22 languages, exactly half follow S&N's prediction in having a lower proportion of changing CM signs than would be expected by the uniform distribution of the null hypothesis, while 10 contradict S&N's prediction, and one shows no preference. These results are graphed in Figure 18, with the same conventions used in Figures 10 and 13–17.

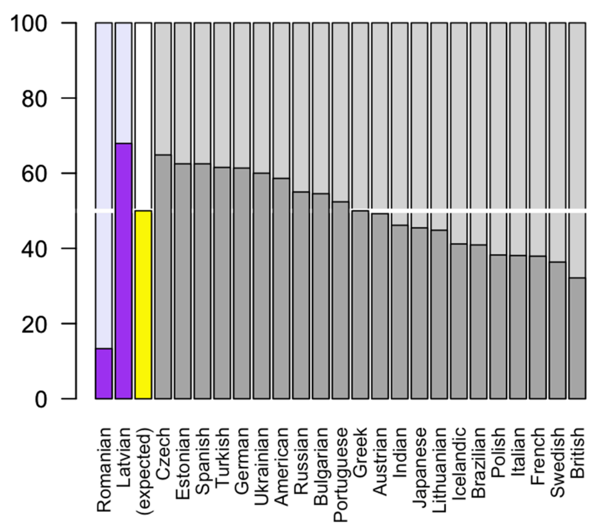

Figure 18. Percentage distribution of monoaxial signs with changing (dark purple and dark gray across the bottom) versus fixed (light purple and light gray across the top) center of mass.

As expected by previous results, there is no statistically significant difference across the languages in our study alone or conflated with those in S&N's study ($p < 0.001$ for both comparisons). Thus, contrary to the tentative suggestion by S&N that minimization of reactive effort might be sensitive to movement of the CM, in the results here, there appears to be no overall cross-linguistic preference among monoaxial signs for a changing CM to be less frequent than would be expected by random chance. This suggests that whatever reactive effort is needed to resist destabilization caused by a changing CM is likely too small to have a noticeable effect on the distribution of types of movement in the lexicon.

6. Limitations and extensions

Despite our robust cross-linguistic results, the present study is limited in a number of ways. First, we look here only at biomechanics, but six mathematically possible types of signs (those with different polarity for AT and UD) were excluded from consideration because of cognitive constraints on motor coordination (§5.2). An examination of what those constraints might look like would reveal information about effort more broadly, contributing to an understanding of the relative roles of cognitive effort and biomechanical effort.

Second, the signs in this study were categorized solely on the basis of movement along the cardinal axes, but that gross approach loses crucial information relevant to torso stability. S&N note this for multiaxial signs, but we note here that it is a problem for monoaxial signs as well. For example, –UD movement induces side-to-side rocking when the hands are horizontally separated, as in ASL MAYBE. (Figure 3). But when the hands are stacked vertically, as in ASL ALLIGATOR (Figure 19), no rocking is induced.

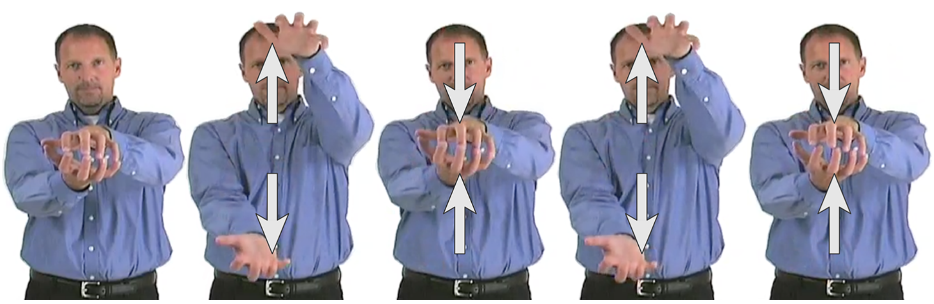

Figure 19. –UD movement in ALLIGATOR in ASL, which induces no rocking torque.

There were no relevant signs in S&N's data, so this issue did not arise for them. But in replicating their methodology, we discovered a few examples of these non-rocking –UD monoaxial signs: one each in six languages (Austrian PERSUASION, Italian MUST, Japanese RIGHT, Portuguese SAME, Spanish DECEIVE, and Swedish TEST), and two each in three languages (Lithuanian ACCURATE and COMMIT; Romanian IMPLEMENT and WHY; and Russian ACCURATE and BEHAVE). The number of such examples is so small that, if we exclude them, the fundamental statistical results of the present work do not change. However, the mere existence of such signs introduces the larger issue of how the position of the hands relative to each other and to the body may affect the kind of torso movement induced by a given cardinal movement. Thus, future applications of this approach need to consider more factors than just cardinal movement.

Third, both S&N and the present work consider only matters of production in accounting for the observed lexical frequencies and do not consider matters of perception, which is also a factor that shapes language. The drive for ease of articulation, for example, is tempered by the fact that movement of the more proximal joints requires less visual acuity to perceive and thus is favored perceptually (Brentari 1998:133ff, Poizner et al. 2000:447). Perhaps this is the reason why joint freezing is more prevalent than distalization as a method of reducing effort (Napoli, Sanders & Wright 2014). Additionally, that drive is tempered by the need to maintain intelligibility and sign recognizability. Thus, if a strategy for reducing effort would interfere with a morphological process, it might not be employed when it otherwise would be. For example, trilling occurs in deriving activity nouns from verbs in ASL (Klima et al. 1979) and in deriving approximative adjectives from ordinary adjectives in ASL (Bellugi 1980, Padden & Perlmutter 1987), but when other non-morphological effort is reduced, trilling is ordinarily preserved, regardless of how fast or casual the conversation is. Likewise, though finger movement requires much less active effort than other manual movement, distalization down to the joints internal to the hand is rare, probably because it would interfere with the handshape and, thus, with recognition of the sign (Napoli, Sanders & Wright 2014:448).

Furthermore, movement along the AT-axis relies much more heavily on stereoscopic cues and image size on the retina (Regan, Erkelens & Collewijn 1986; Regan and Kaushal 1994), which makes it more difficult to perceive than movement along the UD- and LR-axes. This could cause movement along the AT-axis to be underrepresented beyond considerations of torque (note that both +AT and –AT are destabilizing, so they are already underrepresented). In Napoli, Mai & Gaw's (2011) Adaptive Modularity Hierarchy, movement away from the body (which occurs along the AT-axis) is more likely than any other movement to combine with movement along other axes, which suggests that perceptual and torque considerations that disfavor monoaxial movement along the AT-axis may be mitigated in multiaxial signs. The difficulty in perceiving movement along the AT-axis may also affect coding signs using two-dimensional video, leading to ±AT being disproportionately coded incorrectly as 0, in comparison to ±UD and ±LR. Thus, we expect that ±AT movement should be even more underrepresented in studies of this type than would be expected simply by reduction of reactive effort, and this effect should be even stronger for monoaxial signs. Preliminary analysis of our data suggests that these expectations may be true: movement along the AT-axis is found in fewer monoaxial and multiaxial signs than either the UD-axis or LR-axis, and the average difference Δ between the amount of AT movement and the amount of UD and LR movement is greater for monoaxial signs than for multiaxial signs (Table 11).

Table 11. Percentage of monoaxial and multiaxial signs with movement along each of the three cardinal axes. $\Delta = (UD + LR)/2 - AT$.

	AT	**UD**	**LR**	**Δ**
monoaxial	20.1	42.0	37.9	19.6
multiaxial	68.4	85.2	81.8	15.1

Another perceptual issue that could affect the distribution of types of movement is the horizontal-vertical illusion, in which humans tend to overestimate the length of vertical lines in comparison to horizontal lines (Avery & Day 1969). If this illusion extends to path movement in sign languages, then we might expect the hands to move further on average for horizontal movement (to compensate for the illusion), and thus, be underrepresented in the lexicon (since moving longer distances would require more effort). Again, our preliminary analysis in Table 11 supports this prediction, since horizontal movement along the LR-axis is less frequent in our data than movement along the UD-axis, for both monoaxial and multiaxial signs. However, this difference could also simply be due to reactive effort, since ±UD is either stable or rocking, while ±LR movement is either stable or twisting, and twisting requires more reactive effort than rocking does. Comparing only the stable directions (+UD and –LR), we find that horizontal movement is less frequent in multiaxial signs but not in monoaxial signs (Table 12). Further research on the interaction of perception and articulation is clearly warranted.

Table 12. Percentage of monoaxial and multiaxial signs with stable horizontal movement (–LR) and stable vertical movement (+UD).

	–LR	**+UD**
monoaxial	35.6	31.3
multiaxial	58.3	63.8

Finally, though it may be the case that the pressure to reduce reactive effort is simply a static constraint on the lexicon, it is more likely to be a factor that influences diachronic change. Thus, this study also opens possibilities for new ways of approaching the question of how sign languages change over time. In ongoing work, we are looking at the comparative method in sign language reconstruction, and how one might judge whether the movement parameter of two signs, in terms of cardinal movement, can be considered sufficiently similar to have come from the same source (as in McKee & Kennedy 2000). The whole area is complex (see Woodward 1978, 2011 for discussion), but examination of the movement parameter in terms of effort reduction could shed light on typical kinds of diachronic change.

7. Conclusion

This study replicates the methodology of S&N concerning their discovery of a previously unrecognized factor in language production: reactive effort. Their study finds evidence that reactive effort shapes the lexicon in three languages, and our study confirms their results with a larger sample of 24 languages. With respect to torso twisting and rocking in monoaxial signs, and basic torso stability in both monoaxial and multiaxial signs, each language in both studies exhibits a lexicon that disfavors signs calling for greater reactive effort and favors signs calling for less reactive effort. Further, nearly every case shows that reactive effort is disfavored to the same degree across languages. Thus, we conclude that there is a linguistic universal for reduction of reactive effort at play here, as part of a larger drive to reduce articulatory effort.

Additionally, we followed up on S&N's suggestion that CM might also play a cross-linguistic role in shaping the lexicon through reduction of reactive effort. However, we do not find enough evidence to support this suggestion, likely because any destabilizing effect produced by movement of the CM would be so small as to have no notable impact on the lexicon.

The literature on sign language phonetics, which is regrettably small (Crasborn 2012:4–5, Tyrone 2012:61), has repeatedly discussed the effects of the drive for ease of articulation, and the present work contributes to this literature in an important way by noting the potential cross-linguistic effects of biomechanics on which types of movement are expected to be more or less frequent in the lexicon.

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