Scales of effort in sign language articulation and perception

Nathan Sanders

Haverford College

work done partially in collaboration
with Donna Jo Napoli from Swarthmore College

April 7th, 2017
invited talk at
University of Delaware

Roadmap of the talk

1. Background
2. Articulatory effort scales
3. Perceptual effort scales
4. Combined effort scales
5. Summary

Background

Sign language phonetics

"Sign language phonetics"?

Sign language phonetics

"Sign language phonetics"?

- *phonetics* < Greek *φωνή (phōnē)* 'sound'

Sign language phonetics

"Sign language phonetics"?

- *phonetics* $<$ Greek *φωνή (phōnē)* 'sound'
- *language* $<$ Latin *lingua* 'tongue'

Sign language phonetics

"Sign language phonetics"?

- *phonetics* < Greek *φωνή (phōnē)* 'sound'
- *language* < Latin *lingua* 'tongue'
- but despite etymology, *language* refers to any language, regardless of its modality (i.e. both sign and speech)

Sign language phonetics

"Sign language phonetics"?

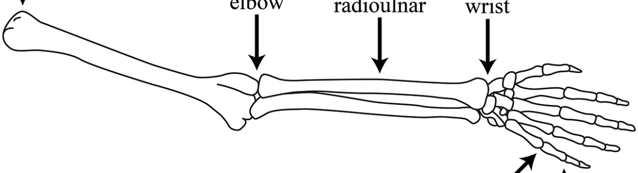
- *phonetics* < Greek *φωνή (phōnē)* 'sound'
- *language* < Latin *lingua* 'tongue'
- but despite etymology, *language* refers to any language, regardless of its modality (i.e. both sign and speech)
- similarly, despite etymology, *phonetics* refers to the physical properties of any language, regardless of its modality

Sign language articulators

manual: arms, hands, fingers, thumbs

nonmanual: eyebrows, nostrils, lips, tongue, head, torso

Manual joints



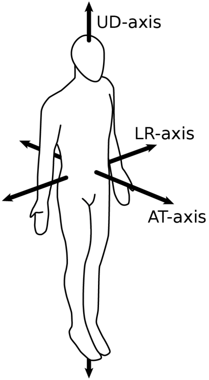
Manual movement

path: at the shoulder or elbow (e.g. ASL STAY and SAME)

local: at the radioulnar, wrist, base, or interphalangeal (e.g. ASL YES and YELLOW)

Axes of movement

Sanders and Napoli (2016a) introduce notation for three cardinal axes of movement (away-toward (AT), up-down (UD), left-right (LR)), and for two-handed signs, the relative direction of the hands: + for the same direction, – for the opposite direction, and 0 for no movement.



Axes of movement

For example, ACTIVITY in ASL would be notated as +LR, since the hands move in the same direction along the LR-axis, while ALLIGATOR in ASL would be notated as −UD because the hands move in opposite directions along the UD-axis.

Signs like these, in which movement occurs along only one axis, are called monoaxial.

Axes of movement

Signs can also be multiaxial. For example, PACK in ASL would be notated as 0AT −UD +LR, while BICYCLE in ASL would be notated as −AT −UD 0LR.

Axes of movement

For one-handed signs, such as SEE in ASL, $+$ and $-$ lose their meaning, so we can notate a sign with just the bare axis (here, AT) or with some sort of modifying symbol to clearly indicate one-handed movement (we're currently toying with $\sqrt{\text{AT}}$, but we're open to suggestions!).

Articulatory effort scales

Articulatory effort

Long tradition of functional work recognizing the importance of reducing articulatory effort in (spoken) language:

Passy 1891, Jespersen 1894, Martinet 1952, 1955, Kiparsky 1968, King 1969, Lindblom and Maddieson 1988, Lindblom 1990, Vennemann 1993, Willerman 1994, Flemming 1995, Boersma 1998, Hayes 1999, etc.

Articulatory effort

Kirchner 1998, 2004: Sum of all articulatory forces involved throughout the duration of the articulation, both those which result in movement and those which isometrically hold an articulator in place.

$$\text{total articulatory effort} = \int_{t_i}^{t_j} |\mathbf{F}(t)| \, \mathrm{d}t$$

Articulatory effort

Strategies for reducing articulatory effort:

- reduce number of moving articulators
- reduce distance moved
- reduce mass moved
- reduce isometric (stabilizing) forces
- and probably others

Articulatory effort

Strategies for reducing articulatory effort in sign:

- **reduce number of moving articulators:**
  e.g. simplification of two-handed signs to one-handed (ASL COW used to be two-handed)

Articulatory effort

Strategies for reducing articulatory effort in sign:

- **reduce number of moving articulators:** e.g. simplification of two-handed signs to one-handed (ASL COW used to be two-handed)
- **reduce distance moved:** e.g. location undershoot (ASL KNOW is sometimes articulated under the eye)

Articulatory effort

Strategies for reducing articulatory effort in sign:

- **reduce number of moving articulators:** e.g. simplification of two-handed signs to one-handed (ASL COW used to be two-handed)
- **reduce distance moved:** e.g. location undershoot (ASL KNOW is sometimes articulated under the eye)
- **reduce mass moved:** e.g. joint freezing (ASL RELAX can be articulated with both the shoulders and elbows or with just the elbows, freezing the shoulders)

Articulatory effort

Strategies for reducing articulatory effort in sign:

- **reduce number of moving articulators:** e.g. simplification of two-handed signs to one-handed (ASL COW used to be two-handed)
- **reduce distance moved:** e.g. location undershoot (ASL KNOW is sometimes articulated under the eye)
- **reduce mass moved:** e.g. joint freezing (ASL RELAX can be articulated with both the shoulders and elbows or with just the elbows, freezing the shoulders)
- **reduce isometric (stabilizing) forces:** **stay tuned!**

Reactive effort

I am concerned here with reactive effort, first identified recently by Sanders and Napoli (2016a). It contrasts with **active effort**, which is the effort used within an articulator to move it.

This is the traditional conception of what articulatory effort is.

Reactive effort

Sanders and Napoli (2016a) define **reactive effort** as the effort used to isometrically resist incidental movement of one part of the body caused by movement elsewhere in the body.

Reactive effort

Sanders and Napoli (2016a) define **reactive effort** as the effort used to isometrically resist incidental movement of one part of the body caused by movement elsewhere in the body.

For manual movement in a sign language, this is the effort needed to prevent the manual articulators from destabilizing (twisting or rocking) the torso, which we resist by engaging the abdominals, back muscles, obliques, etc.

Reactive effort

Phonetics research has long focused on spoken language, and the speech articulators are too small to induce movement elsewhere in the body under normal circumstances, so reactive effort was never a consideration.

Reactive effort

Phonetics research has long focused on spoken language, and the speech articulators are too small to induce movement elsewhere in the body under normal circumstances, so reactive effort was never a consideration.

But the manual articulators are much more massive and can easily cause incidental movement of the torso, especially when they have path movement.

Reactive effort

Why is reactive effort important?

Reactive effort

Why is reactive effort important?

Humans generally prefer to maintain an upright, forward-facing torso orientation.

- bipedal locomotion induces twisting, which is destabilizing, but the human muscles evolved differently from other great apes to resist this twisting (the other great apes rock side to side to stabilize themselves) (Lovejoy 1988)

Reactive effort

Why is reactive effort important?

Humans generally prefer to maintain an upright, forward-facing torso orientation.

- bipedal locomotion induces twisting, which is destabilizing, but the human muscles evolved differently from other great apes to resist this twisting (the other great apes rock side to side to stabilize themselves) (Lovejoy 1988)
- humans use eye gaze for nonverbal communication, and a fixed torso position helps (Kobayashi and Kohshima 2001)

Reactive effort

An upright, forward-facing torso orientation is also specifically preferred in signing, because torso movement often carries a linguistic function, such as surprise (Sze 2008), marking topic boundaries (Winston and Monikowski 2003), role shifting (Engberg-Pedersen 1993), etc. So extraneous torso movement could be misinterpreted by the addressee as meaningful.

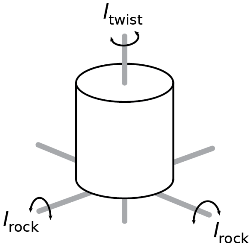
Reactive effort

An upright, forward-facing torso orientation is also specifically preferred in signing, because torso movement often carries a linguistic function, such as surprise (Sze 2008), marking topic boundaries (Winston and Monikowski 2003), role shifting (Engberg-Pedersen 1993), etc. So extraneous torso movement could be misinterpreted by the addressee as meaningful.

Thus, torso stability is a crucial concern for humans in general, but especially within the context of sign language communication.

Reactive effort

Rotational inertia is how much an object resists being rotated (roughly speaking, this is the rotational equivalent of mass). Approximating the torso as a cylinder, we have:



Reactive effort

The formulas for these two moments of inertia are:

$$I_{\text{twist}} = \frac{mr^2}{2} \qquad I_{\text{rock}} = \frac{m(3r^2 + 4h^2)}{12}$$

Reactive effort

The formulas for these two moments of inertia are:

$$I_{\text{twist}} = \frac{mr^2}{2} \quad < \quad I_{\text{rock}} = \frac{m(3r^2 + 4h^2)}{12}$$

Reactive effort

The formulas for these two moments of inertia are:

$$I_{\text{twist}} = \frac{mr^2}{2} \quad < \quad I_{\text{rock}} = \frac{m(3r^2 + 4h^2)}{12}$$

This inequality means that twisting is more easily induced than rocking, because the torso has less inherent resistance to twisting, requiring us to expend more reactive effort to resist it.

Predictions

Given consideration of articulatory effort, we expect that:

Predictions

Given consideration of articulatory effort, we expect that:

- **destabilizing** signs (those which induce either twisting or rocking) should be dispreferred to **stable** signs (which induce no torso movement)

Predictions

Given consideration of articulatory effort, we expect that:

- **destabilizing** signs (those which induce either twisting or rocking) should be dispreferred to **stable** signs (which induce no torso movement)
- signs that induce **twisting** (which has a lower moment of inertia and thus, less inherent resistance to offer) should be dispreferred to signs that induce **rocking**

Predictions

For monoaxial and multiaxial signs with both hands moving, this means:

$$\underset{\text{(destabilizing)}}{+\text{AT}, -\text{AT}, -\text{UD}, +\text{LR}} < \underset{\text{(stable)}}{+\text{UD}, -\text{LR}}$$

$$\underset{\text{(destabilizing)}}{\text{all others}} < \underset{\text{(stable)}}{0\text{AT} +\text{UD} -\text{LR}}$$

Predictions

And further, for monoaxial signs with both hands moving:

$$\underset{\text{(twisting)}}{-\text{AT}, +\text{LR}} < \underset{\text{(rocking)}}{+\text{AT}, -\text{UD}}$$

(Twisting versus rocking is too difficult to determine for multiaxial signs.)

Our reactive effort studies

In joint work with Donna Jo Napoli (Sanders and Napoli 2016a and Sanders and Napoli 2016b), these predictions were tested.

Our reactive effort studies

We compiled signs with **free, single or retraced two-handed path movement.**

In our original study, we looked at the lexicons of Italian Sign Language (Romeo 1991), Sri Lankan Sign Language (Sri Lanka Central Federation of the Deaf 2007), and Al-Sayyid Bedouin Sign Language (Meir et al. 2012).

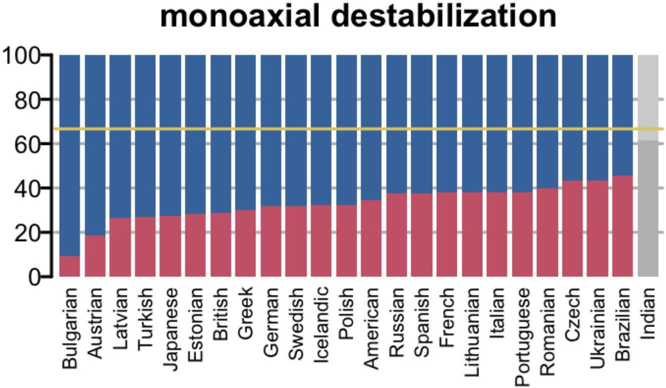
The results were solid and suggestive, so we followed up with 24 languages from the online database Spreadthesign (2012).

Our reactive effort studies

$$+\text{AT}, -\text{AT}, -\text{UD}, +\text{LR} < +\text{UD}, -\text{LR}$$

Our reactive effort studies

$$+\text{AT}, -\text{AT}, -\text{UD}, +\text{LR} < +\text{UD}, -\text{LR}$$

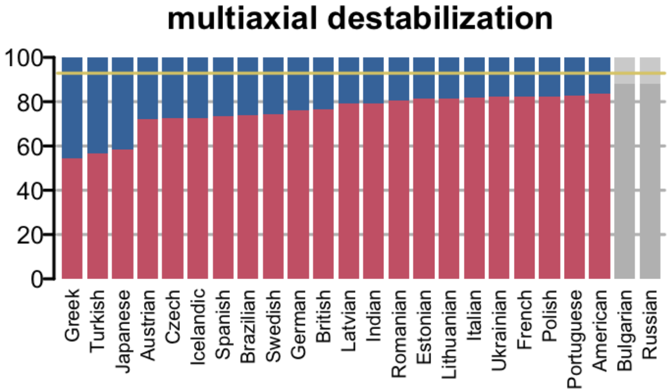


Our reactive effort studies

all others $<$ 0AT $+$UD $-$LR

Our reactive effort studies

all others $<$ 0AT $+$UD $-$LR



Our reactive effort studies

We find that for both monoaxial and multiaxial signs, in all languages, destabilizing signs are less common than would be expected by chance frequency (nearly all comparisons, 45 out of 48, are statistically significant). First prediction fulfilled!

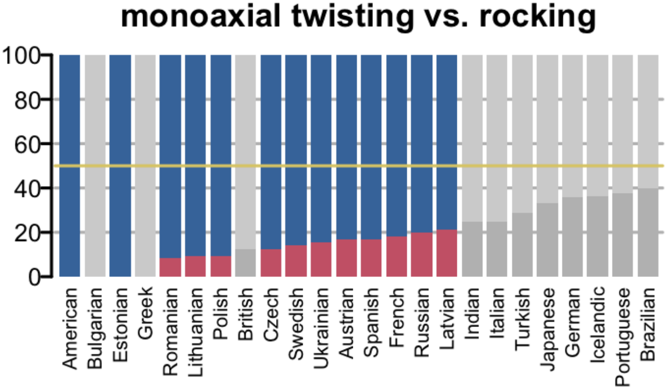
Furthermore, in both cases, the languages are statistically indistinguishable from each other (except Greek and Turkish in the multiaxial comparison), which points to a **cross-linguistic universal**.

Our reactive effort studies

$$-\text{AT}, +\text{LR} < +\text{AT}, -\text{UD}$$

Our reactive effort studies

$$-\text{AT}, +\text{LR} < +\text{AT}, -\text{UD}$$



Our reactive effort studies

We find that for destabilizing monoaxial signs, in all languages, twisting signs are less common than would be expected by chance frequency (about half of the comparisons, 13 out of 24, are statistically significant). Second prediction fulfilled!

Again, the languages are statistically indistinguishable from each other, which points to a **cross-linguistic universal**.

Perceptual effort scales

Motion in depth

Motion in depth (movement along the AT-axis) is more difficult to perceive than vertical (UD) or horizontal (LR) movement (Regan et al. 1986, Regan and Kaushal 1994).

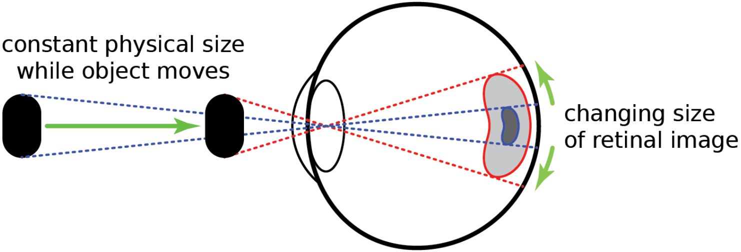
Motion in depth

Motion in depth (movement along the AT-axis) is more difficult to perceive than vertical (UD) or horizontal (LR) movement (Regan et al. 1986, Regan and Kaushal 1994).

This is because, unlike UD and LR, we do not view AT movement directly, but must instead infer it from indirect cues.

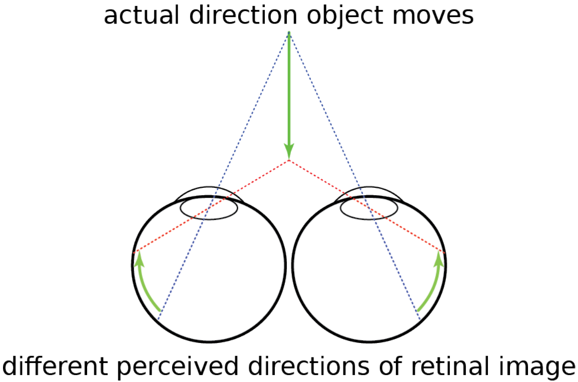
Motion in depth

One such cue is change in apparent size of an object as it moves along the AT-axis.



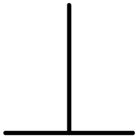
Motion in depth

Another cue to AT movement is parallax.



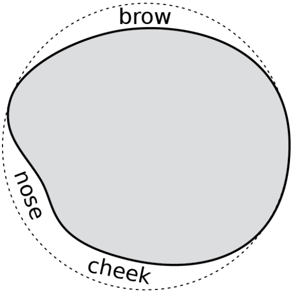
The horizontal-vertical illusion

Although they are directly observed, UD and LR movement are also perceived slightly differently. One example of this is the **horizontal-vertical illusion** (Fick 1851, Bailey and Scerbo 2002):



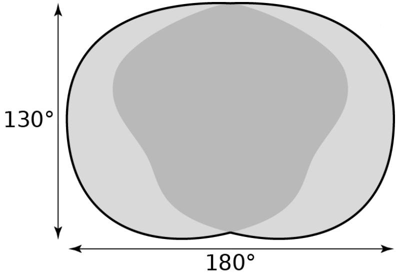
The horizontal-vertical illusion

This illusion can be explained by the geometry of our visual field (Künnapas 1957). Each individual eye has a roughly circular visual field (Webb 1964, Parker and West 1973):



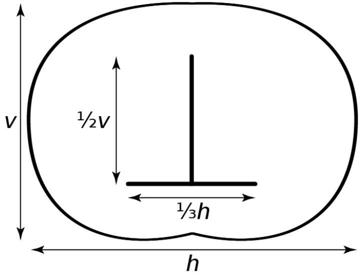
The horizontal-vertical illusion

Our ambinocular visual field is the result of both monocular fields of view combined, which is roughly elliptical because of the horizontal placement of the eyes:



The horizontal-vertical illusion

Distances or movements take up different proportions of the visual field, depending on whether they are oriented vertically or horizontally, with vertical appearing larger:



Predictions

Given consideration of perceptual effort, we expect that:

Predictions

Given consideration of perceptual effort, we expect that:

- **AT** movements (which require extra cues to perceive) should be dispreferred to **UD** and **LR**

Predictions

Given consideration of perceptual effort, we expect that:

- **AT** movements (which require extra cues to perceive) should be dispreferred to **UD** and **LR**
- **LR** movements should be dispreferred to **UD** because of the horizontal-vertical illusion

Predictions

For monoaxial and multiaxial signs with both hands moving, this means:

+AT, −AT	<	+UD, −UD, +LR, −LR
(indirectly cued)		(directly observed)

+LR, −LR	<	+UD, −UD
(horizontal)		(vertical)

My preliminary perceptual effort study

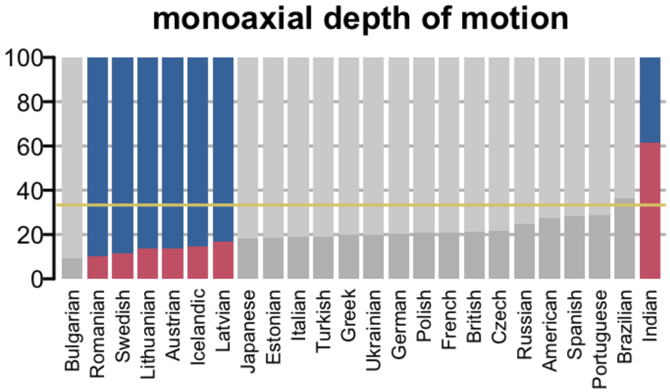
I tested these predictions against the same data from the 24 languages in Sanders and Napoli (2016b).

My preliminary perceptual effort study

$$+\text{AT}, -\text{AT} < +\text{UD}, -\text{UD}, +\text{LR}, -\text{LR}$$

My preliminary perceptual effort study

$+\text{AT}, -\text{AT} < +\text{UD}, -\text{UD}, +\text{LR}, -\text{LR}$

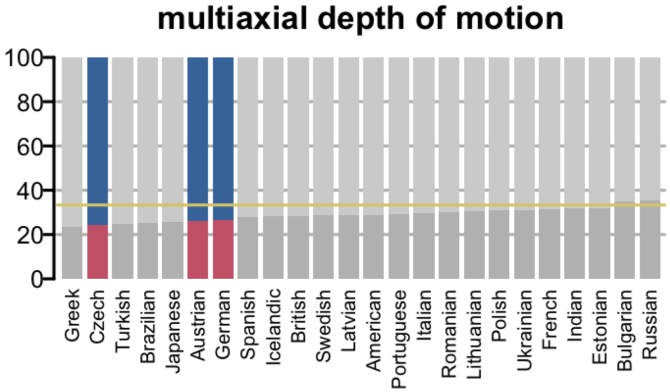


My preliminary perceptual effort study

$$+\text{AT}, -\text{AT} < +\text{UD}, -\text{UD}, +\text{LR}, -\text{LR}$$

My preliminary perceptual effort study

+AT, −AT < +UD, −UD, +LR, −LR



My preliminary perceptual effort study

I find that for both monoaxial and multiaxial signs, in nearly all languages (22 out of 24 for each case), AT movement is less common than would be expected by chance frequency (though only 10 out of 48 comparisons are statistically significant, one of which contradicts the prediction). First prediction fulfilled?

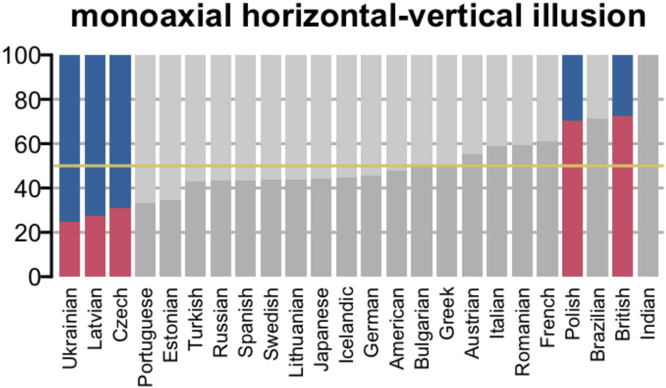
Furthermore, in both cases, the languages are statistically indistinguishable from each other, which points to a **cross-linguistic universal**.

My preliminary perceptual effort study

$$+\text{LR}, -\text{LR} < +\text{UD}, -\text{UD}$$

My preliminary perceptual effort study

$$+\mathrm{LR}, -\mathrm{LR} < +\mathrm{UD}, -\mathrm{UD}$$

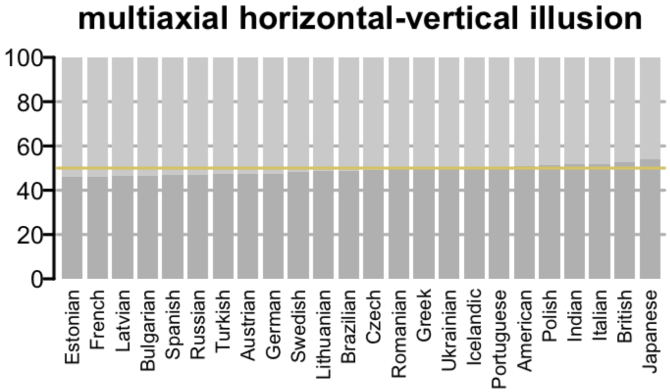


My preliminary perceptual effort study

$$+\text{LR}, -\text{LR} < +\text{UD}, -\text{UD}$$

My preliminary perceptual effort study

$$+\text{LR}, -\text{LR} < +\text{UD}, -\text{UD}$$



My preliminary perceptual effort study

I find that for both monoaxial and multiaxial signs, in only about half of the languages (14 and 10 out of 24 for each case), LR movement is less common than would be expected by chance frequency (though only 5 out of 48 comparisons are statistically significant, two of which contradict the prediction). Second prediction fails?

Combined effort scales

Articulatory and perceptual effort interleaved

For monoaxial signs, $+$UD is the most preferred on both scales (stable and vertical), so it should be the most preferred on the combined scale.

Articulatory and perceptual effort interleaved

For monoaxial signs, $+$UD is the most preferred on both scales (stable and vertical), so it should be the most preferred on the combined scale.

$-$AT is the least preferred on both scales (twisting and depth in motion), so it should be the least preferred on the combined scale.

Articulatory and perceptual effort interleaved

$-$UD is only slightly less preferred than $+$UD: like $+$UD, it is vertical, so it is also perceptually ideal, but it involves rocking, which is articulatorily suboptimal.

Articulatory and perceptual effort interleaved

$-$UD is only slightly less preferred than $+$UD: like $+$UD, it is vertical, so it is also perceptually ideal, but it involves rocking, which is articulatorily suboptimal.

Similarly, $-$LR is also only slightly less preferred than $+$UD: like $+$UD, it is articulatorily stable, but it is horizontal, which is perceptual suboptimal.

Articulatory and perceptual effort interleaved

+AT is only slightly more preferred than −AT: like −AT, it is depth in motion, so it is also perceptually dispreferred, but it involves rocking, which is articulatorily better than twisting.

Articulatory and perceptual effort interleaved

$+$AT is only slightly more preferred than $-$AT: like $-$AT, it is depth in motion, so it is also perceptually dispreferred, but it involves rocking, which is articulatorily better than twisting.

Similarly, $+$LR is also only slightly more preferred than $-$AT: like $-$AT, it involves twisting, which is articulatorily dispreferred, but it is horizontal, which is perceptually better than depth in motion.

Articulatory and perceptual effort interleaved

Putting it all together, we have:

$$+\text{UD} \;>\; -\text{UD}, -\text{LR} \;>\; +\text{AT}, +\text{LR} \;>\; -\text{AT}$$

Articulatory and perceptual effort interleaved

Putting it all together, we have:

$$+\text{UD} \;>\; -\text{UD}, -\text{LR} \;>\; +\text{AT}, +\text{LR} \;>\; -\text{AT}$$

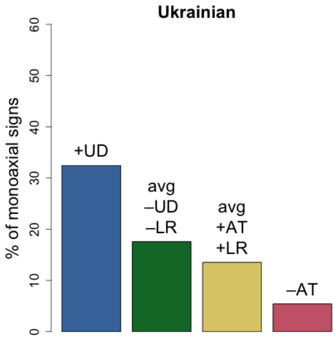
Note, this only takes into account the reactive effort of minimizing torso movement and the perceptual effort due to motion in depth and the horizontal-vertical illusion. Other factors (active effort, iconicity) may alter this scale or subvert it entirely.

My preliminary combined effort study

To test the combined effort scale, I matched it to the distribution of signs in the 24 languages in the Sanders and Napoli (2016b) dataset.

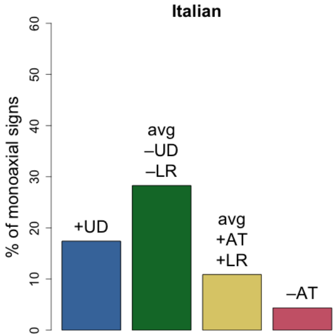
My preliminary combined effort study

Half of the 24 languages fit the combined scale as predicted:



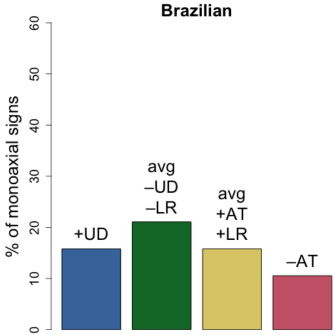
My preliminary combined effort study

Three languages fit the combined scale, except that $+$UD is under-represented in comparison to $-$UD and $+$LR:



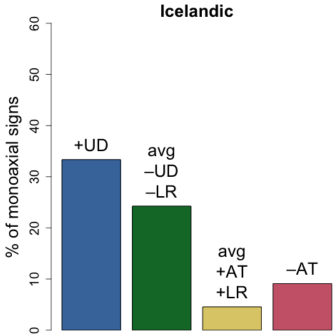
My preliminary combined effort study

Three languages fit the combined scale, except that +UD is under-represented in comparison to −UD and +LR, and is tied or nearly so with +AT and +LR:



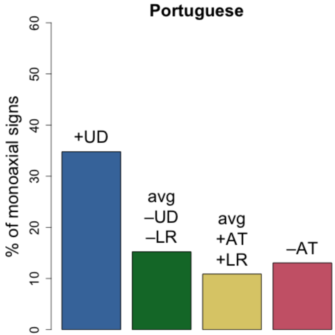
My preliminary combined effort study

Three languages fit the combined scale, except that −AT is over-represented in comparison to +AT and +LR:



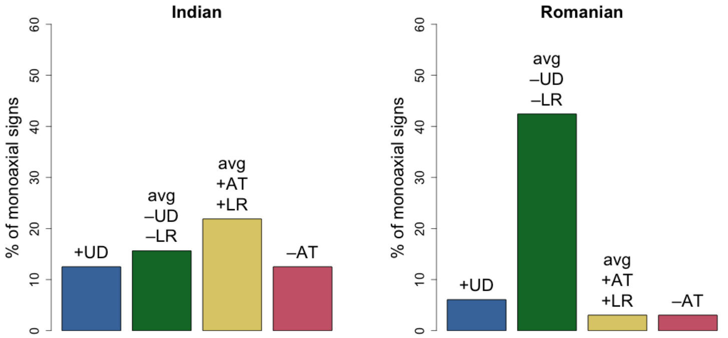
My preliminary combined effort study

One language fits the combined scale, except that −AT is over-represented in comparison to +AT and +LR, and is nearly tied with −UD and +LR:



My preliminary combined effort study

The remaining two languages are just odd:

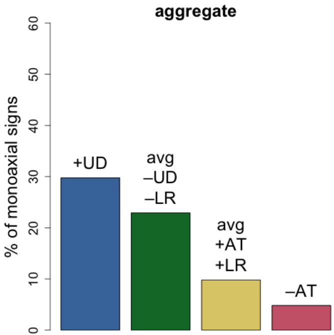


My preliminary combined effort study

So overall, 12 of the languages fit the effort scale exactly, 10 fit it fairly closely, and 2 have odd patterns. Though there is no hard cross-linguistic universal, there is evidence of a strong tendency towards obeying the combined effort scale so that both articulatory and perceptual effort are reduced together.

My preliminary combined effort study

This can be seen in the aggregate pattern averaged across all 24 languages:



Problems with the combined scale

- Since the perceptual scale showed little to no effect on its own, are we seeing a synergistic effect in the combined scale, or is the articulatory scale sufficient on its own to account for the data?

Problems with the combined scale

- Since the perceptual scale showed little to no effect on its own, are we seeing a synergistic effect in the combined scale, or is the articulatory scale sufficient on its own to account for the data?
- No statistical testing done on the combined scale. It turns out to be a hard problem to solve! How can we verify that the observed patterns are in fact statistically significant?

Problems with the combined scale

- Since the perceptual scale showed little to no effect on its own, are we seeing a synergistic effect in the combined scale, or is the articulatory scale sufficient on its own to account for the data?
- No statistical testing done on the combined scale. It turns out to be a hard problem to solve! How can we verify that the observed patterns are in fact statistically significant?
- Is it fair to average the two movements in the intermediate categories? In each, one member turns out to generally be more common than the other.

Summary

Reactive effort results

Reactive effort is a previously unstudied facet of articulatory effort that needs to be distinguished from active effort. It is reduced in various ways in the lexicons of 24 languages, following essentially the same mathematical pattern across languages (which suggests a cross-linguistic universal):

Reactive effort results

Reactive effort is a previously unstudied facet of articulatory effort that needs to be distinguished from active effort. It is reduced in various ways in the lexicons of 24 languages, following essentially the same mathematical pattern across languages (which suggests a cross-linguistic universal):

- among both monoaxial and multiaxial signs, destabilizing movements are less common than would be expected by random chance

Reactive effort results

Reactive effort is a previously unstudied facet of articulatory effort that needs to be distinguished from active effort. It is reduced in various ways in the lexicons of 24 languages, following essentially the same mathematical pattern across languages (which suggests a cross-linguistic universal):

- among both monoaxial and multiaxial signs, destabilizing movements are less common than would be expected by random chance
- among monoaxial signs, twisting movements are less common than rocking movements than would be expected by random chance

Perceptual effort results

Reduction of perceptual effort was not nearly as strongly apparent as for reactive effort:

Perceptual effort results

Reduction of perceptual effort was not nearly as strongly apparent as for reactive effort:

- among both monoaxial and multiaxial signs, depth in motion was moderately less common than horizontal and vertical movement than would be expected by random chance

Perceptual effort results

Reduction of perceptual effort was not nearly as strongly apparent as for reactive effort:

- among both monoaxial and multiaxial signs, depth in motion was moderately less common than horizontal and vertical movement than would be expected by random chance
- among monoaxial and multiaxial signs, the horizontal-vertical illusion seems irrelevant, with horizontal and vertical movement being about equally likely

Combined effort results

Among monoaxial signs, $+$UD movement was generally more common than the average of $-$UD and $-$LR, which was generally more common than the average of $+$AT and $+$LR, which was generally more common than $-$AT, though there was a lot of variation.

It's hard to tell if these results are statistically significant, and whether these results are better than looking at just articulation alone.

What's next?

- find more evidence for reduction of reactive effort in the lexicon (we've looked at resistance to movement of center of mass, but there seems to be no pattern)

What's next?

- find more evidence for reduction of reactive effort in the lexicon (we've looked at resistance to movement of center of mass, but there seems to be no pattern)
- find evidence for reduction of reactive effort in spoken languages (maybe reduction of jaw movement to prevent incidental head movement)

What's next?

- find more evidence for reduction of reactive effort in the lexicon (we've looked at resistance to movement of center of mass, but there seems to be no pattern)
- find evidence for reduction of reactive effort in spoken languages (maybe reduction of jaw movement to prevent incidental head movement)
- use effort reduction to look at other aspects of sign: frequency in conversation, order of acquisition, etc.

What's next?

- in particular, use effort reduction to help do historical reconstruction on sign languages (currently ongoing work with Donna Jo)

What's next?

- in particular, use effort reduction to help do historical reconstruction on sign languages (currently ongoing work with Donna Jo)
- compare path movement to local movement; perhaps path movement is more sensitive to articulatory effort (bigger masses are harder to move), while local movement is more sensitive to perceptual effort (smaller movements are harder to see) (probably my next project)

Thank you!

References I

Bailey, Nathan R. and Mark W. Scerbo. 2002. The horizontal-vertical velocity illusion: Implications for the design of dynamic displays. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 46:1556–1559.

Boersma, Paul. 1998. *Functional Phonology: Formalizing the Interactions Between Articulatory and Perceptual Drives*. The Hague: Holland Academic Graphics.

Engberg-Pedersen, Elisabeth. 1993. *Space in Danish Sign Language: The Semantics and Morphosyntax of the Use of Space in a Visual Language*. Hamburg: Signum.

Fick, Adolf. 1851. *De errore quodam optico asymmetrica bulbi effecto*. Marburg: J. A. Kochin.

Flemming, Edward. 1995. *Auditory Representations in Phonology*. Doctoral dissertation. University of California, Los Angeles.

References II

Hayes, Bruce. 1999. Phonetically driven phonology: The role of Optimality Theory and inductive grounding. In Michael Darnell, Edith Moravcsik, Michael Noonan, Frederick Newmeyer, and Kathleen Wheatly, eds. *Functionalism and Formalism in Linguistics. Volume I: General Papers*. Amsterdam: John Benjamins. 243–285.

Jespersen, Otto. 1894. *Progress in Language with Special Reference to English*. London: Swan Sonnenschein.

King, Robert D. 1969. *Historical Linguistics and Generative Grammar*. Englewood Cliffs, NJ: Prentice-Hall.

Kiparsky, Paul. 1968. Linguistic universals and language change. In Emmond Bach and Robert T. Harms, eds. *Universals in Linguistic Theory*. New York: Holt, Rinehart, and Winston. 170–202.

Kirchner, Robert. 1998. *An Effort-Based Approach to Lenition*. Doctoral dissertation. University of California. Los Angeles.

References III

Kirchner, Robert. 2004. Consonant lenition. In Bruce Hayes, Robert Kirchner, and Donca Steriade, eds. *Phonetically Based Phonology*. Oxford: Oxford University Press. 313–345.

Kobayashi, Hiromi and Shiro Kohshima. 2001. Unique morphology of the human eye and its adaptive meaning: Comparative studies on external morphology of the primate eye. *Journal of Human Evolution* 40:419–435.

Künnapas, Theodor M. 1957. The vertical-horizontal illusion and the visual field. *Journal of Experimental Psychology* 53:405–407.

Lindblom, Björn. 1990. Explaining phonetic variation: A sketch of the H&H theory. In William J. Hardcastle and Alain Marchal, eds. *Speech Production and Speech Modeling*. Dordrecht: Kluwer Publishers. 403–439.

References IV

Lindblom, Björn and Ian Maddieson. 1988. Phonetic universals in consonant systems. In Larry M. Hyman and Charles N. Li, eds. *Language, Speech, and Mind: Studies in Honour of Victoria A. Fromkin*. London: Routledge. 62–78.

Lovejoy, C. Owen. 1988. Evolution of human walking. *Scientific American* 259:118–125.

Martinet, André. 1952. Function, structure, and sound change. *Word* 8:1–32.

Martinet, André. 1955. *Économie des changements phonétiques: Traité de phonologie diachronique*. Bern: Francke Verlag.

Meir, Irit, Wendy Sandler, Carol Padden, and Mark Aronoff. 2012. *Al-Sayyid Bedouin Sign Language Dictionary*. Haifa, Israel, and Chicago: University of Haifa and University of Chicago.

Parker, Jr., James F. and Vita R. West. 1973. *Bioastronautics Data Book*. Washington, DC: Scientific and Technical Information Division, National Aeronautics and Space Administration. second ed.

References V

Passy, Paul. 1891. *Étude sur les changements phonétiques et leurs caractères généreaux*. Paris: Libraire Firmin-Didot.

Regan, David, Casper J. Erkelens, and Han Collewijn. 1986. Necessary conditions for the perception of motion in depth. *Investigative Ophthalmology & Visual Science* 27:584–597.

Regan, David and Suneeti Kaushal. 1994. Monocular discrimination of the direction of motion in depth. *Visual Research* 34:163–177.

Romeo, Orazio. 1991. *Dizionario dei segni*. Zanichelli.

Sanders, Nathan and Donna Jo Napoli. 2016a. Reactive effort as a factor that shapes sign language lexicons. *Language* 92:275–297.

Sanders, Nathan and Donna Jo Napoli. 2016b. A cross-linguistic preference for torso stability in the lexicon: Evidence from 24 sign languages. *Sign Language & Linguistics* 19:197–231.

Spreadthesign. 2012. http://www.spreadthesign.com.

References VI

Sri Lanka Central Federation of the Deaf. 2007. *Sri Lanka sign dictionary*. Colombo, Sri Lanka: Graphitec.

Sze, Felix. 2008. Blinks and intonational phrasing in Hong Kong Sign Language. In Josep Quer, ed. *Signs of the Time: Selected Papers from TISLR 2004 (International Studies on Sign Language and Communication of the Deaf 51*. Hamburg: Signum.

Vennemann, Theo. 1993. Language change as language improvement. In Charles Jones, ed. *Historical Linguistics: Problems and Perspectives*. London: Longman. 319–344.

Webb, Paul. 1964. *Bioastronautics Data Book*. Washington, DC: Scientific and Technical Information Division, National Aeronautics and Space Administration.

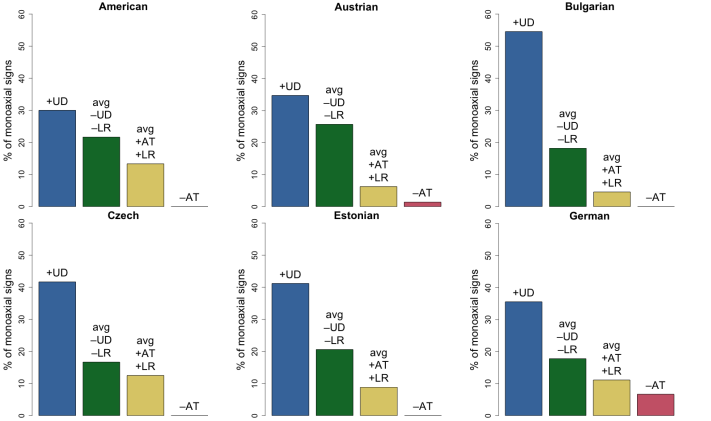
Willerman, Raquel. 1994. *The Phonetics of Pronouns: Articulatory Bases of Markedness*. Doctoral dissertation. University of Texas at Austin. Austin, TX.

References VII

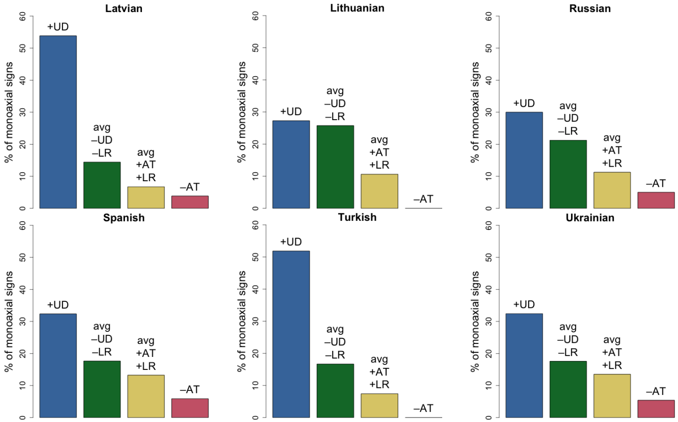
Winston, Elizabeth and Christine Monikowski. 2003. Marking topic boundaries. In Melanie Metzger, Steven D. Collins, Valerie Dively, and Risa Shaw, eds. *From Topic Boundaries to Omission: New Research on Interpretation 1*. Washington, DC: Gallaudet University Press. 187–227.

Appendix

12 languages fit the expected pattern: American, Austrian, Bulgarian, Czech, Estonian, German, Latvian, Lithuanian, Russian, Spanish, Turkish, and Ukrainian

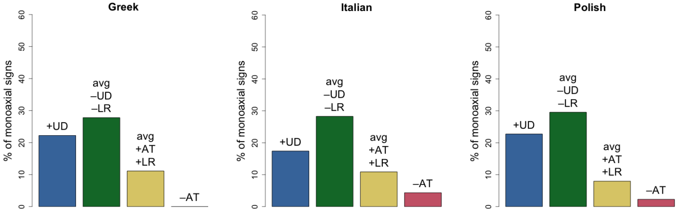


Appendix


Latvian
Lithuanian
Russian
Spanish
Turkish
Ukrainian
% of monoaxial signs
0
10
20
30
40
50
60
+UD
avg
–UD
–LR
avg
+AT
+LR
–AT

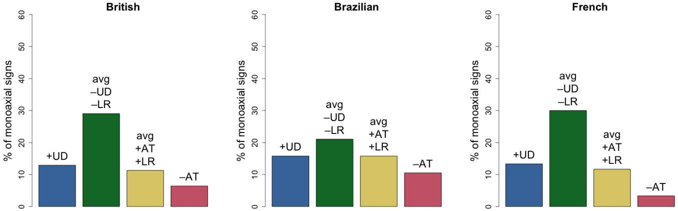
Appendix

3 languages almost fit the expected pattern except $+$UD is under-represented in comparison to $-$UD&$+$LR: Greek, Italian, and Polish



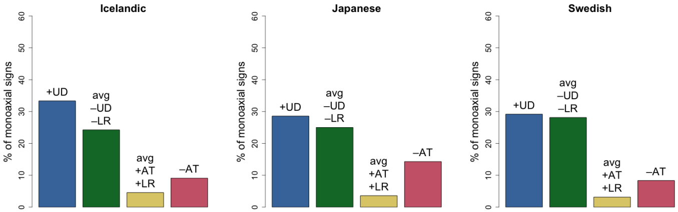
Appendix

3 languages almost fit the expected pattern except $+$UD is under-represented in comparison to $-$UD&$+$LR and is (nearly) tied with $+$AT&$+$LR: British, Brazilian, and French



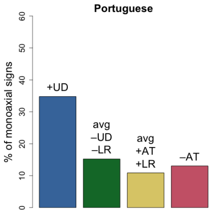
Appendix

3 languages almost fit the expected pattern except $-$AT is over-represented in comparison to $+$AT&$+$LR: Icelandic, Japanese, and Swedish



Appendix

1 language almost fits the expected pattern except $-$AT is over-represented in comparison to $+$AT&$+$LR and is nearly tied with $-$UD&$+$LR: Portuguese



2 languages have odd distributions: Indian and Romanian