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Documenting a Reduction in Signing Space in Nicaraguan Sign Language Using Depth and Motion Capture

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Abstract

In this paper, we use motion tracking technology to document the birth of a brand new language: Nicaraguan Sign Language. Languages are dynamic entities that undergo change and growth through use, transmission, and learning, but the earliest stages of this process are generally difficult to observe as most languages have been used and passed down for many generations. Here, we observe a rare case of language emergence: the earliest stages of the new sign language in Nicaragua. By comparing the signing of the oldest and youngest signers of Nicaraguan Sign Language, we can track how the language itself is changing. Using motion tracking technology, we document a decrease in the size of articulatory space of Nicaraguan Sign Language signers over time. The reduction in articulatory space in Nicaraguan Sign appears to be the joint product of several decades of use and repeated transmission of this new language.

Keywords: Nicaraguan Sign Language; Language emergence; Motion tracking; Language evolution; Sign language

1. Introduction

All languages are dynamic entities that undergo change and growth through use, transmission, and learning, but the earliest stages of this process are generally difficult to observe. Most languages have been used so much, passed down so many times, and learned by so many

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child learners that the earliest fingerprints of these processes are obscured by their iteration. However, occasionally, we have the opportunity to document these changes as they occur by observing the growth of a new natural language. Here, we investigate changes in such a young language: Nicaraguan Sign Language (NSL).

NSL emerged in the late 1970s when new schools for special education were opened in Managua, Nicaragua. The language of instruction in these schools was Spanish (written and spoken), and none of the original teachers had experience with any sign language. Deaf students generally had minimal success in learning to read and speak Spanish at the school, but they gained something invaluable upon school entry: a community of other individuals with whom they could co-create[1] a new language. Though no one was teaching the children to sign, they were not prohibited from using their hands to communicate with one another. Students spontaneously began to manually communicate with one another at school, and later outside as well within their growing Deaf Community. Though there is no systematic documentation of the signing at the school in the earliest days, reports from the time indicate that after only a short while, hearing teachers no longer understood the children's manual communication with one another (Polich, 2005).

Each year since this time, new deaf children have entered the school in Managua and have encountered a different situation than those children who first entered. As in the 1970s, children entering school today still join a language community when they begin school, but now they also encounter a sign language already in use. Each year, deaf children entering the school learn to sign NSL from older signing students through natural interaction inside and outside the classroom. And each year, students graduate from the school system and continue to use NSL in their daily lives. As NSL is used in the school and larger community, passed down to new students, and learned by wave after wave of child learners, the language itself grows and changes. By comparing the signing of the oldest and youngest signers, each of whose signing reflects the language as it existed when they first learned it in childhood, we can rigorously document change as it happens in this new language.

One way in which new sign languages may change as they grow and develop is in overall size of signing space. Signing space is the area in front of the body in which signs are generally produced. Though the literature does not contain extensive quantitative information about cross linguistic variation in signing space, many contend that significant variation exists. One important factor in characterizing the size of a language's signing space appears to be whether the language is used primarily in more urban or more rural environments. Sign languages, such as Kata Kolok in Bali and Adamorobe Sign Language in Ghana, both used in primarily rural communities, are described as being larger in overall signing space than more urban sign languages (de Vos, 2012; Nyst, 2007). Urban sign languages, like American Sign Language (ASL) and other western urban sign languages, are described as being generally smaller in signing space (e.g., Perniss, Pfau, & Steinbach, 2007). This variation may be related to the fact that signers in rural environments tend to point toward real locations in space, rather than set up arbitrary referential loci as has been documented in languages like ASL. Sandler, Belsitzman, and Meir (2020) also report potentially relevant articulation differences between Israeli Sign Language (ISL), an urban sign language, and Al-Sayyid Bedouin Sign Language (ABSL), a rural sign language. They find that ABSL signers learning ISL produce ISL signs in ways that reflect typical articulation of ABSL (their ABSL accent), such as reduced contact between the hands (occlusion) and increased hand laxness. If features such as these are more common in rural sign languages, they might also contribute toward larger signing space in those languages.

Variation in signing space within a sign language also serves important sociolinguistic and discourse pragmatic purposes. In Japanese Sign Language, for example, altering the size of the signing space allows a signer to mark increased politeness (George, 2011), with smaller signing space being associated with polite signing. Increasing or decreasing the size of one's signing space in many languages also affects the number of potential message recipients, similar to "shouting" or "whispering" in spoken languages (Crasborn, 2001; Liddell et al., 2003). The temporal duration of signs (signing speed), which may be related to the size of signing space, has also been reported to decrease with repeated mention of a given sign or sequence of signs (Lepic, 2019).

The size of signing space may interact with other factors, such as whether signers select more proximal joints (larger joints, closer the body's midline) or more distal joints (small joints, further from the body's midline) in their signing. A tendency to select more proximal joints may result in a larger overall signing space than the selection of small, more distal joints. Signers' selection of joints may also be influenced by factors, such as their age of exposure to a sign language, stage of sign language learning, as well as formality versus casualness of signing. For example, Mirus, Rathmann, and Meier (2001) report proximalization errors in adult language learning. When learning signs from an unfamiliar sign language, both hearing nonsigners and signers learning another sign language substitute more proximal joints for the more distal joints used in the new sign language. However, hearing nonsigners proximalize more often (35.5% of productions) than do signers learning a second sign language (up to 8.5% of productions). Earlier work points to deaf child learners also producing more proximalization errors early in learning a sign language (i.e., Meier, Mauk, Mirus, & Conlin, 1998; Meier, Mauk, Cheek, & Moreland, 2008). Napoli, Sanders, and Wright (2014), report a tendency by signers to use more distal joints, rather than larger, more proximal joints, in conversational signing as opposed to more formal citation form signing. As proximal joints require more biomechanical effort to move than more distal joints, the authors argue that this distalization leads to increased articulatory ease.

Size of signing space may also vary over the history of a language. In studying signing space in ASL, Frishberg (1975) describes a diachronic tendency for signs to move from locations on the periphery of signing space to more central space (in front of the body), thus reducing the overall signing space of the language. The way in which this type of change can lead to a reduction in signing space is nicely illustrated by Frishberg's example of the ASL sign BIRD. In older versions of ASL, this sign contained two separate parts: first, the dominant hand articulated a beak-like sign by closing forefinger and thumb together in front of the nose, and then second, both hands articulated flapping motions above shoulder level to either side of the body. Over the course of just several decades, however, the sign for BIRD in ASL has changed to include only the first, more central and also much smaller sign.[2] Mineiro et al. (2017) provide a preliminary report of a similar tendency for reduction in size over time in a young sign language: Sao Tome and Principe Sign Language. The authors report that signs using smaller joints are more prevalent in later forms of this language than in earlier forms, but do not provide a quantitative characterization of these results.

Importantly, on its own, a smaller signing space is not a marker of an older language that has passed through more generations of learners. Varieties of a given sign language with different overall signing space sizes can and do coexist, as is the case for White ASL and Black ASL (see McCaskill, Lucas, Bayley, & Hill, 2011, Hill, McCaskill, Lucas, & Bayley, 2009), though the size of signing space in these two varieties may be converging in younger signers (Hill & McCaskill, 2010).

In newly emerging sign languages like NSL, we might expect diachronic change in the size of the signing space to differ by the language's urban versus rural origins. The categories of urban versus rural sign languages themselves are, however, more complicated than they may first appear. In their introduction to a special issue of *Sign Language Studies*, Kusters and Hou (2020) describe the cline of manual communication implicit in much of this work: with gesture at one end of the spectrum, homesign and rural/village/shared sign languages in the middle, and national/urban sign languages at the other end. In some ways, NSL is a classic urban sign language. It arose in a school environment within a dense urban area that does not appear to have an unusually high incidence of deafness. NSL is generally learned at school entry from peers, and NSL signers are primarily deaf. Furthermore, NSL is a national sign language, used in many widely separated areas of the country. As an urban sign language, we might expect NSL to have a relatively constrained signing space.

However, in other ways, NSL does not neatly fit the national/urban sign language template. Urban sign languages are often referred to as being "Western" sign languages or those of the "Global North." Despite the fact that Nicaragua is located in the Northern Hemisphere and is further West than two-thirds of the United States, the terms "Western" and "Global North" generally do not include Central and South America. This disparity makes it clear that "West" and "North" are not what scholars really mean when they describe the ecology of urban sign languages. As Braithwaite (2020) points out, the term "urban sign language" is primarily used to refer to European sign languages and sign languages used in other areas of the world that were colonized by Europeans and especially by the British (i.e., Australian Sign Language also known as Auslan, ASL). Despite originating in an urban center, NSL is a young sign language and so the size of its signing space may not immediately resemble that of other urban sign languages. Here, we document the size of signing space of Nicaraguan signers ranging from some of the oldest signers in the community, whose signing reflects the earliest version of NSL, to signers who are 30 years younger and who learned NSL language only after it had undergone several decades of use and change.

While very few equivalent quantitative, semi-automated assessments of the size of signing space exist for any sign language (see, e.g., Stamp et al. (2022)[3]), a parallel investigation of how repeated use may change the size of the articulatory space of communicative gestures has been carried out with striking results. Namboodiripad and colleagues (2016) asked hearing nonsigners to participate in a communication game that required them to produce silent gesture descriptions for meanings (English words) to another hearing nonsigner. As this game continued for several rounds, participants produced silent gesture descriptions for each meaning multiple times. The authors used a Microsoft Kinect Motion Tracker to quantify gesture size across rounds, using the proxy of total distance traveled by the wrists, and found that the size of the gestures' articulatory space decreased over time. This result may further suggest that size of signing space in a young language like NSL will also decrease over time, as the language itself continues to be used. Trujillo and colleagues (2018, 2019) have also used the Kinect to characterize the kinematic features of hearing people's gestures and have found that the Kinect data largely match up with nonautomated by eye coding, further supporting the Kinect's ability to characterize manual movements.[4]

Converging evidence for a decrease in articulatory space as a communicative system comes from laboratory studies of emergent communication systems. For example, in pictionary-like drawing communication and transmission tasks, a reduction in graphical complexity is observed both as the communication task is repeated with a single group of participants (Garrod, Fay, Rogers, Walker, & Swoboda, 2010), as well as if new communication participants are introduced in each round (Caldwell & Smith, 2012). Other studies (e.g., Motamedi, Schouwstra, Smith, Culbertson, & Kirby, 2019) also find the length of gesture utterances to be reduced through the process of interaction, but in this study, transmission to new learners alone did not have the same effect.

In this paper, we quantitatively document change in the size of signing space between some of the oldest and youngest signers of NSL. In keeping with Labov (1963)'s Apparent Time Construct, we take differences in the signing of older versus younger signers to reflect the diachronic change NSL has undergone between the time the oldest and youngest signers learned the language. Because the exact size of signing space is challenging to quantify by eye, we employ the same methodology as Namboodiripad et al. (2016): a Microsoft Kinect Motion Tracker. To our knowledge, this is the first time this technology has been employed to characterize the signing space of a young natural language in the first few decades after its birth. Though different from methods used in previous investigations of signing space in other languages, this tool allows us to precisely and consistently quantify variation in signing space among Nicaraguan signers.

2. Method

2.1. Participants

Seventeen signers of NSL (8 women, 9 men; range 20–51 years old, mean age 34.7 years; median age 36 years) were recruited via the first author's contacts to participate in the task. All signers first learned NSL before the age of 6 upon first entry to school. Participants entered school during a nearly 30-year period, between 1975 and 2003. Unlike previous studies, we do not divide signers into groups or cohorts. Instead, we treat their year of entry into the community as a continuous variable. A brief description of the study procedure along with possible consequences was provided to all participants in order to obtain informed consent as approved by the University of Edinburgh Ethics Board. All recruited participants provided their signed consent before proceeding. Participants were monetarily compensated for their time.

2.2. Video elicitation materials

Participants viewed a series of 36 short video vignettes. The vignettes depicted a set of 18 actions (approach, crawl to, cycle to, feed, give ball to, hop to, jump to, poke, pull, punch, push, roll ball, run to, skip to, tap/touch, throw ball to, throw confetti on, cycle to) between two entities. Each action had two vignettes, one in which an animate entity (a man or a woman) acted on another animate entity (a man or woman) and one in which an animate entity acted on an inanimate entity (a chair or a plant). For the poking events then, for example, the animate-animate version would consist of a woman poking a man. The animate-inanimate version of poking would consist of a woman poking a plant. These events were selected to be easily depictable in live action video stimuli, so as to minimize verbal demands of the task.

2.3. Procedure

Participants viewed the 36 target events in one of two semi-random orders (with the constraint that no two same action events were presented in direct succession) on a laptop. After viewing each item, participants were asked to describe what they saw to a signer peer (communication partner) who could not see the laptop screen. Importantly, we did not attempt to tightly control the elicited responses, as, for example, Namboodiripad et al. (2016) did in their study of gesture space size using the Kinect, because our goal here was to characterize this new sign language as it is typically produced by signers in their every day lives. Variation across (and within) individual language users is the norm in all languages (see Pyers et. al. (2020) for a discussion on how iconicity is affecting lexical change in NSL) and we did not wish to suppress this variation. We aimed to strike a balance between experimental control (by providing carefully controlled elicitation stimuli) and naturalistic communication (by conducting our analysis at the utterance level, no matter what the utterance provided to describe an event was for each participant). This means that it is entirely possible that one person may have described an event using different constructions, lexical items, and stylistic choices than another person. Nonetheless, in comparing their responses, we are comparing like to like in that they were each providing utterances to describe the same set of stimuli. All our analyses are, therefore, performed at the utterance level rather than at the level of individual lexical items.

The last frame of each vignette remained visible on the screen while participants produced their descriptions. Communication partners were instructed to indicate if they did not understand the descriptions and could ask for clarification. However, only signers' first responses were analyzed. All responses were both videotaped for later offline coding as well as recorded using a Microsoft Kinect 3D camera (Fig. 1). The Kinect tracked the position of signers' wrists by using depth and motion sensors to return the inferred XYZ position of 21 joints in the body at a target frame rate of 30 fps (Wang, Kurillo, Ofli, & Bajcsy, 2015).

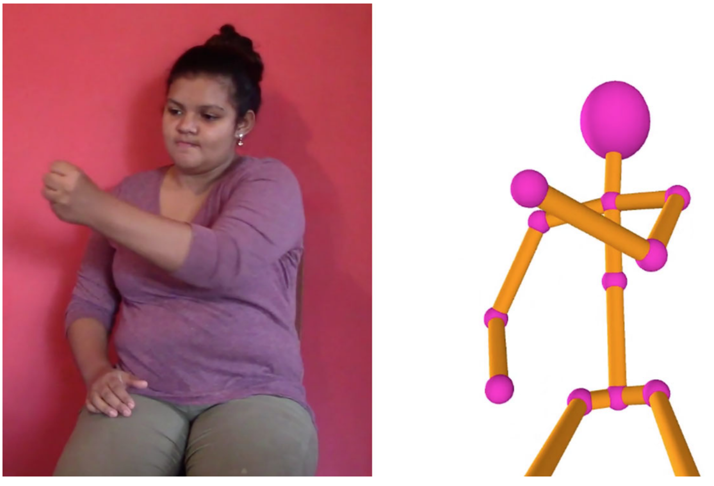

Fig. 1. An RBG frame (left) and a visualization of the corresponding XYZ body data tracked by Kinect (right).

3. Results

The first step in analyzing these data was identifying utterance beginning and end points. The first author, who has over 15 years of experience coding NSL data, glossed each utterance and identified the first and last frame of each utterance from the video data. The utterance onset frame was identified as the frame in which the participant's hand or hands first began to move from rest in an articulatory movement (generally when the hands ceased to be in contact with the legs where they had previously rested). Offset frame was identified as the frame in which the hand or hands returned to rest (generally the frame in which the hands contacted the legs, coming back to rest). A second coder also identified first and last utterance frames based on these criteria for 10% of the data. The two coders' decisions differed by an average of 1.75 frames for the first frame and 3.25 frames for the last frame. Given the average utterance in the reliability subset was 162.5 frames long, this represents an utterance first and last frame identification agreement rate of 98–99%.

Prior to the analyses reported below, it was necessary to preprocess the body tracking data in several ways. First, we time-aligned the video and body-tracking data streams in order to establish correspondence between frames from the two data sources. The body tracking data were then median filtered to reduce noise. Crucially, we also transform the body tracking data to enable comparison between participants with differing body sizes. To do this, we find the upper arm length (the average euclidian distance between the tracked shoulder and elbow joints) of each participant. Each participant's data are then transformed by a scaling factor obtained by dividing their upper arm length by the average upper arm length of all participants in the data set. This results in a normalized data set in which the upper arm length is the same for all participants, though their individual relative body proportions remain unchanged.

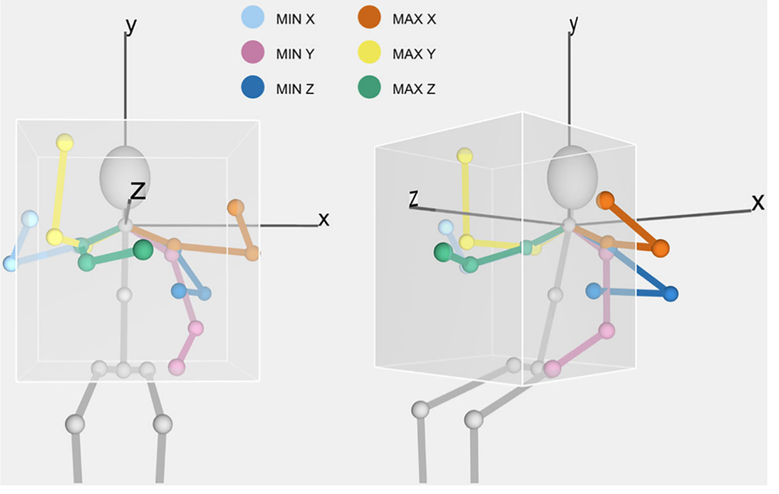

Fig. 2. An illustration of the bounding box for a single participant. The position of the shoulder, elbow, and wrist for each contributing frame is overlaid to show how the bounding box delimits the space used. The position of the rest of the figure drawn in gray is averaged over the six contributing frames. An interactive version can be accessed online (see Supplementary Materials).

Production of the Kinect device was discontinued in 2018 and the API is no longer supported by Microsoft, but the principles underlying our data processing and analysis are general and should be transferable to any other system that produces 3D joint position data.

We report three measures of signing space: the bounding box, the distance of the wrists to the average position of the wrists, and the distance of the wrists to a fixed point on the body.

3.1. *Level of analysis*

In all of the analyses described below, the utterance is our level of analysis. As NSL is changing so rapidly and in so many domains, this macro-level measure allowed us to best seek out global change in the language and characterize it continuously. As all participants responded to the same vignettes, comparing each participant's response to each vignette allowed us to focus on naturalistic descriptions produced by each signer, rather than the less naturalistic responses that can result from more tightly controlled experimental conditions.[5]

3.2. *Bounding box*

The first measure of signing space we constructed was the volume (in m^3) of the bounding box. The bounding box takes into account the minimum and maximum tracked X, Y, and Z positions of the wrists over a given window of frames and delineates the outer limits or bounds of the space used by a participant over those frames (Fig. 2). The bounding box is given by formula 1:

$$vol = (maxX - minX) * (maxY - minY) * (maxZ - minZ) \tag{1}$$

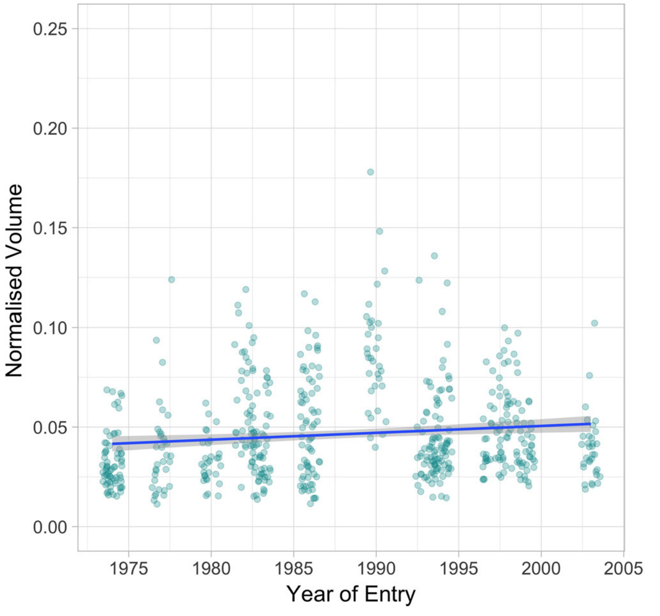

Fig. 3. Normalized volume of the bounding box by year of entry. The unit of measurement corresponds to m^3 after the participants' measurements are normalized so that each is the size of the average participant. Each point represents an utterance. There is no significant change in the bounding box measure by year of entry.

The bounding box is based on the position of the wrists in a maximum of six frames of data: in some cases, the most extreme value on more than one axis may be given by the same frame, meaning the bounding box sometimes uses even fewer than six frames of data. Because of this it is a measure that is highly sensitive to noise and could be heavily affected by nonlinguistic movements outside of the signing space (such as stretching, tying shoelaces, etc.). We, therefore, computed the bounding box for frames belonging to utterances only.[6]

Frames belonging to a coded utterance account for 40.83 % of the 238,253 total recorded frames.[7] The volume of the bounding box by year of entry computed for each utterance is shown in Fig. 3. The unit of measurement is given as m^3 but note that this corresponds to the volume of the bounding box if each participant was scaled to the size of the average participant. Values range between 0.01 and 0.17. We assess the relationship between the normalized volume of the bounding box and year of entry into the community with a mixed effects model. We include a fixed effect of year of entry and random intercepts per signer. Year of entry was centered so that the model intercept corresponds to 1975, the first year in our data set. Likelihood ratio testing by comparison to the null model suggests that our model does not perform better than chance ($X^2(3) = 0.68$, $p = .40$)), suggesting no change over time in the average volume of the bounding box of utterances.

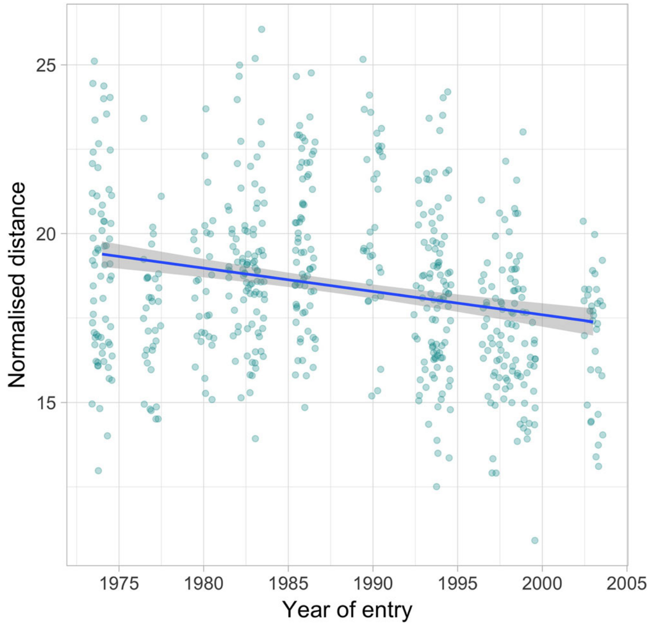

Fig. 4. The average distance between the average position of the wrists, and the position of the wrists at each frame (averaged over both wrists) by year of entry into the community. The unit of measurement corresponds to *cm* after normalization of participant body size. Each point represents an utterance.

3.3. Distance to average position of the wrists

Although the bounding box is a useful measure to find the outer limits of the space used by a participant over a range of frames, as mentioned above, it is based on a maximum of six frames. The bounding box then fails to take into account the vast majority of available frames, and provides no information about the use of space within that delimited area. We, therefore, constructed a second measure of signing space to be more comprehensive, taking into account all available frames: First, we found the average position of both wrists over all frames produced by each participant to use as an individual signer's reference point. This reference point is intended to be a proxy for the center of their overall signing space. Then, for each frame, we computed the euclidean distance of the wrists to that reference point.[8] (Fig. 4). The distance between two points (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) in three-dimensional space is yielded by the distance formula in (2) derived from the Pythagorean theorem:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (2)$$

The unit of measurement for the distance from the mean position of the wrists corresponds to *cm* after participants' measurements are normalized so that each is the size of the average participant, ranges from 10.91 to 26.05 and appears to show a downward trend. To assess this, we constructed a mixed effects model predicting the distance between the reference point and the wrists with a fixed effect of year of entry into the community (centered so that the model intercept corresponds to the first year in our data set) and random intercepts per participant. Likelihood ratio testing by comparison to the null model (with random effects only) suggests that the model performs marginally better than chance ($X^2(3) = 4.03$, $p = .04$). The model estimates a decrease in distance ($\beta = -.07$, standard error = 0.03) per year relative to the model intercept of 19.43.

3.4. Body-wrist distance

The measure of distance between the reference point and the wrists reported above provides some indication that a reduction in signing space is happening, but rests entirely on the position of the wrists with respect to a reference point that does not take into account the relationship between the position of the wrists and the body. It is possible to imagine a case where the average position of the wrists is far from the body, yet the distance of the wrists to that average position is small. As an extreme example, if a person were to extend their hands far above their head without moving their hands apart, the measure above would yield a small distance. It is clear that this does not capture the fact that signing space, at least in sign languages used by large urban communities like that in Nicaragua, is generally anchored to the space directly in front of the body, rather than that overhead, a fully extended arm's length in front of the body, behind the body, or similar. Movement of sign articulation to the space in front of the body has also been documented over historical time in at least one sign language, ASL (Frisberg, 1975), further bolstering the appeal of a measure incorporating not only the location of the wrist, but also their relative positions to the trunk of the body. Here, we report an additional measure of the signing space which takes the euclidean distance (formula 2) between the position of the wrists in each frame and a fixed point on the body (the Kinect tracked joint between the shoulders) (Fig. 5).

Fig. 6 shows the mean computed distance to the body for each utterance produced by each participant by year of entry. The unit of measurement corresponds to *cm* after normalization of participant body size. The mean distance (averaged over both wrists) to the origin of the body data ranges from 23.29 to 52.03 and appears to show a downward trend. To assess this, we ran a mixed effects model predicting the distance between the body and the wrists with a fixed effect of year of entry into the community (centered so that the model intercept corresponds to the first year in our data set) and random intercepts per participant. Likelihood ratio testing by comparison to the null model (with random intercepts only) suggests that the model performs better than chance ($X^2(3) = 14.59$, $p < .001$), with an estimated decrease in the body-wrist distance ($\beta = -0.32$, standard error = 0.08) per year relative to the model intercept of 44.67.

4. Discussion

In this paper, we have documented a decrease in the size of signing space of NSL signers over time. Both the average distance between the estimated center of the signing space and the position of the wrists, and the average body-wrist distance, which together we take to index

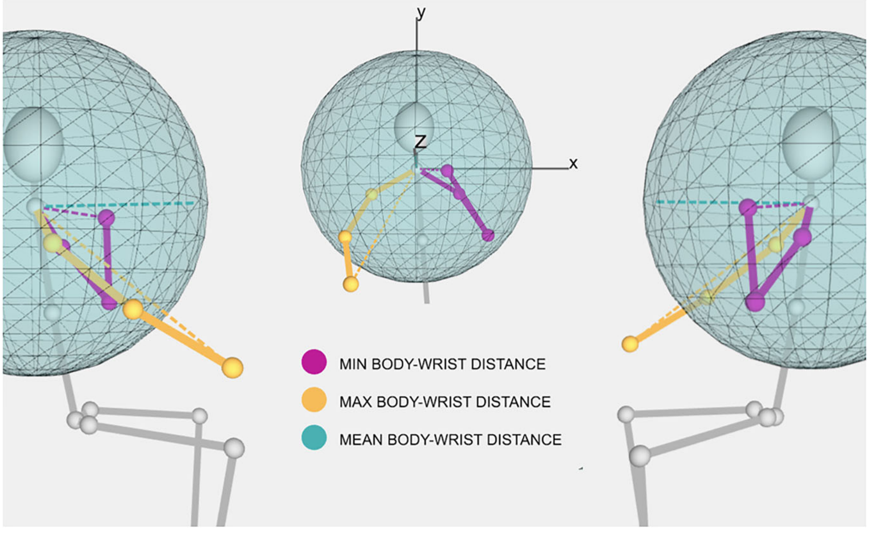

Fig. 5. An illustration of the body-wrist distance on the two frames (overlaid) contributing the minimum and maximum distance from the origin of the body data. The mean body wrist distance over all frames of this participant's data is shown as a sphere. http://astewa12.ppls.ed.ac.uk/Visualizations/wristdist/ An interactive version can be accessed online (see Supplementary Materials).

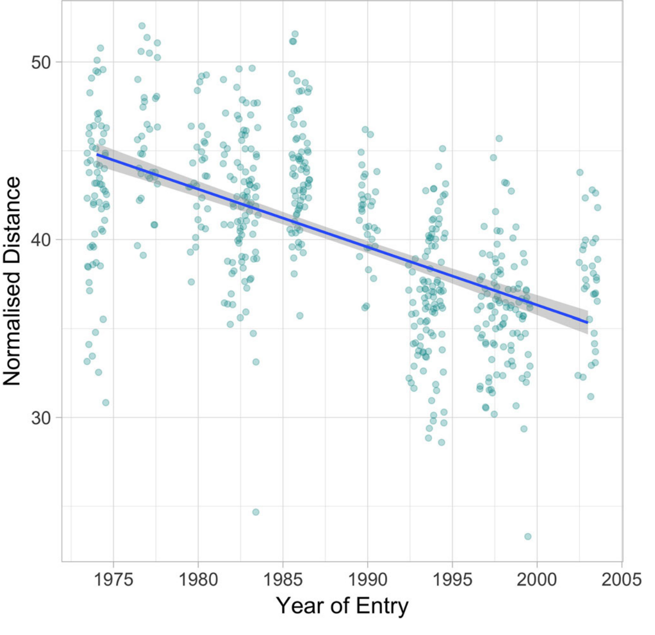

Fig. 6. The average distance between the origin of the body data (between the shoulders) and the wrists (averaged over both wrists) by year of entry into the community. The unit of measurement corresponds to *cm* after participants' measurements are rescaled to be the same size as the average participant. Each point represents an utterance.

the size of the signing space, decrease from the oldest signers, who learned the language when it was first being born 45 years ago, to the youngest signers, who learned the language 30 years later. This decrease in the size of signing space is occurring as a natural consequence of three decades of use and transmission of this new natural language.

It is all the more remarkable that we find this global decrease in signing space size given what our data look like. The reduction in signing space emerges despite the fact that individuals may be choosing different ways to describe the same event. Variation like this is typical of all languages, and Nicaraguan Sign is no exception. This variation is part of what we measure in this study. Additionally, as a young language, NSL is changing in many ways simultaneously, for example, lexical variation between older and younger signers (Pyers & Senghas, 2020). It is striking that the change in size of signing space is evident even amidst the variance and ongoing change in this young language.

Interestingly, although we find a reduction in the average size of signing space from older signers to younger signers on the two aforementioned measures, we do not find a difference in the overall limits of articulatory space (our bounding box measure). One of our reviewers made the suggestion that perhaps older signers might produce answers that were longer overall in duration and, therefore, have more opportunity to occupy a larger space. To explore this possibility, we looked to see if length of utterance differed from younger to older signers, and found that it did not: a mixed effects model predicting utterance length (in frames) with a fixed effect of year of entry into the community (centered so intercept corresponds to the earliest year in our data set) and random intercepts per signer performs no better than the null model with random effects only ($X^2(1) = 0.01, p = .9$) (comparison by likelihood ratio testing). The model intercept is 173.06 frames, with an estimated decrease of –0.13 frames per increase in year of entry, that is a very slight and nonsignificant decrease in number of frames in younger signers compared to older signers. The difference between the measures based on all frames and the measure based on the outer limits of the articulatory space may simply reflect the sensitivity of the latter to noise, though it is worth noting that other researchers using a similar measure do show a reduction in the size of the articulatory space of the improvised silent gestures of hearing nonsigners in a lab setting (Namboodiripad et al., 2016), although their experimental design did not include transmission. It may be the case that other language internal pressures push against this overall reduction in size of the potential signing space. For example, Börstell and Lepic (2020) document a pattern across antonym pairs in 27 sign languages in which negative valence signs are generally produced higher in the signing space (when considering just the frames within a sign) and positive valence signs are produced lower. They also find that despite the general tendency for signs to move downward through the signing space over the course of articulation, positive valence signs are more likely to move upward than are their negative valence antonyms. The drive to create this kind of spatial contrast might create a strong counter pressure to overall reduction in size of the signing space.

Nonetheless, despite the fact that the full range of possible articulatory space remains available to the younger signers in our data, the average size of their signing space decreases. Our principle goal in this paper is not to identify precisely why the size of the signing space is decreasing, and we can not say for certain why this is occurring, but efficiency of articulation is a likely factor.[9] Though we were not able to measure the smallest, most distal joints (finger joints), this line of reasoning is logically consistent with arguments made in other sign languages about distilization as a strategy for effort reduction (see, e.g., Mirus et al., 2001, Napoli et al., 2014 discussed above). All else being equal, smaller articulatory movements require less effort to produce than larger movements. Reduction in articulatory effort could then motivate the decrease in average size of signing space as the new language is used and transmitted.

It is important to note that while wrist movement is one measure of efficiency in articulation, it is far from the only one. We have evidence that the average body wrist distance decreases with use and repeated transmission, but this does not indicate that younger signers are necessarily more efficient overall in communicating. For example, it is entirely possible that a message might be communicated equally well in either fewer larger signs, thus more efficient in terms of number of lexical items but less efficient in terms of wrist movement, or more smaller signs, less efficient in terms of signs but more efficient in terms of total wrist movement. Neither of these can be simply characterized as overall more efficient, as efficiency always operates at multiple levels. The Kinect does also not allow us to measure a key articulator in producing signs: the fingers. Using other methods, a measure of total finger movement might yield quite different results from those we report here for wrist movement. Movement in other nonmanual articulators such as those on the face would also be important to quantify in order to have a more complete picture of articulatory effort and efficiency in NSL signers. Furthermore, it is certainly not the case that languages evolve to be increasingly efficient overall until they reach some point of maximal efficiency (see, e.g., Kinsella & Marcus, 2009). While we find it likely that the changes in this brand new natural language are more dramatic than those found in older language as they change over historical time, all languages continue to grow and change for as long as they exist, and over the lifetime of any language, it will grow more efficient in some areas, less efficient in others, and then back again.

The decrease in articulatory space that we document here occurs between the oldest signers in our study, those who began using the language soon after its birth, and the youngest signers in our study, who learned the language several decades later. If reduction in signing space were the result of sustained use of the language by one group of individuals, we would not have expected this result. The oldest signers have actually been signing for decades longer than the youngest signers, so if continued use by a single group were the force affecting articulatory space reduction, the oldest signers should sign smaller on average than the youngest signers. This is the opposite of what we document here. Reduction in signing space then may be a product of repeated transmission of the language to new learners, not continued use within a group.

Perhaps surprisingly, some lab studies of emergent gestural communication systems have seen an *increase* in gesture length over multiple rounds of transmission to new learners (e.g., Motamedi et al., 2019). However, in lab studies at least, this effect appears to be due to lack of interaction rather than transmission per se. Where participants must acquire from other participants, either through multiple rounds of interaction, or as new learners exposed to previous participants' productions, and then also go on to use that system in an interactive setting, gesture length decreases over time. The signing of the youngest signers of NSL, as opposed to the oldest signers, represents a version of the language that has been in use for several decades. Reduction in signing space could then certainly be the joint product of the language itself being used over years of interactions and also of its repeated transmission.

It is also important to note that we cannot rule out one potential alternate explanation for our results: it is possible that the larger signing space of older signers today is in fact a result of their age and its effects on articulation, rather than a reflection of an earlier state of the language. In our methodology, we follow the logic of Labov's Apparent Time Hypothesis (1963; 1966) which indicates that, all else being equal, differences between the language of older and younger individuals generally reflect differences in the state of the language at the time those individuals learned it. That is, we can observe changes in the language itself by comparing older and younger signers to one another today. This hypothesis finds significant support in Labov's work as well as that of others (i.e., Bailey, Wikle, Tillery, & Sand, 1991's work comparing apparent time data with longitudinal data from random surveys of U.S. Texan speech). However, not all differences between older and younger individuals may necessarily reflect historical language change (or emergence). Indeed, Börstell and colleagues (2016, 2019) find age-related differences in articulation speed Swedish Sign Language, British Sign Language, and the Sign Language of the Netherlands. Older signers of these three languages sign more slowly than do younger signers both in terms of the duration of individual signs as well as the number of signer per minute produced. Though this finding is for signing speed, not size of signing space, and our oldest signers are several decades younger than Börstell and colleagues' oldest signers,[10] it is possible that a similar phenomenon is occurring in our data. In order to rule out this possibility, we would need equivalent motion tracking data from signers of NSL collected several decades prior to the data we discuss here. Unfortunately, obtaining this historical data using our Kinect methodology is not possible. However, the first author is currently working on a collaborative effort with other researchers to extract similar motion tracking data from historical footage of NSL (see Caselli, Occhino, Artacho, Savakis, & Dye, 2022 for their work using these methods in ASL). With these data, we may be able to much more effectively weigh in on this alternative explanation.

In this paper, we have documented the overall reduction in size of signing space in NSL using portable motion capture: a promising tool that is not commonly employed in the study of sign languages. Though the full complexity of a dynamic language system can never be captured by one tool or one analysis, we believe that the use of motion tracking technology to partially automate work in the study of sign languages and language evolution has great potential. It is our hope that further research in this area will be the site of rich collaboration between many researchers using a diverse set of methods and tools. We believe that if we can bring together methods from a range of approaches, work in our field will richly benefit from the use of many complimentary tools used together to ask complex questions about the origins of language structure and the mechanisms of language emergence and change.

Notes

1 By using the term co-create, we highlight that language is a human cultural product. The earliest signers of NSL are its creators, though this creation is a spontaneous, emergent process.

2 Frishberg speculates that this type of change to prefer smaller, less peripheral signs is due to assimilation pressures.

3 Stamp (2022) reports on an earlier study in which they used a Kinect motion tracker to characterize Israeli Sign Language. They compared the signing of 12 gay and straight male signers of ISL. The authors find a statistically significant effect of sexuality: gay signers' signing space was larger in volume as well as longer in duration and faster in speed than that of straight signers, though no further quantitative details are provided. The authors also report the same pattern in the gestures of 12 gay and straight hearing speakers of Hebrew. The authors come to the conclusion that these features index gay identity in both signers and gesturers.

4 Ripperda, Drijvers, and Holler (2020) also report results for automated gesture detection without the use of a motion tracker via their SPUDNIG system.

5 It would also be informative to quantify change in the size of signing space at another level of analysis. For example, you might see similar changes in size of signing space, or average distance traveled by the hands in the signing space, at the sign-level. Different stimuli would be required to complete this analysis most fruitfully, however. A study containing a task in which the participant is given the target sign and then asked to produce that sign in an utterance would be a useful next step to investigate this phenomenon at the more micro sign-level.

6 We explored the possibility of using the nonutterance frames as a baseline against which to measure change in the utterance frames; however, the nonutterance frames turned out to be quite variable, containing linguistic movement that is not part of the experiment, nonlinguistic movements, such as stretching, and periods of relative stillness while participants view the vignettes. The nonutterance frames, therefore, vary unpredictably, making it unsuitable for use as a baseline.

7 We excluded one utterance produced by one participant due to technical failure of the device in the middle of the utterance.

8 We did not look at one-handed and two-handed verbs separately in this analysis because our analysis is conducted at the utterance level and there were no one-handed utterances in our data set. However, in response to a reviewer's question, we did perform an exploratory analysis in which we found a very slight decrease from the oldest to youngest signers in the number of one-handed signs produced. The effect size, however, is tiny: $\beta < 0.008$, meaning we would expect to see one more one-handed signs in a signer who entered the community 125 years after the oldest signer. As the difference between the oldest and youngest signers in our sample is only 30 years, an effect of this size is so tiny as to be functionally meaningless in our data.

9 One of our reviewers suggested that a decrease in the frequency of constructed action from the oldest signers to the youngest signers might partially underlie the overall decrease in signing space that we document. Though documenting the frequency of

constructed action in our data set is beyond the scope of this project, this remains an interesting possibility for future investigation into which factors underlie the decrease in signing space. As Lepic and Occhino (2018) point out, however, attempting to classify signs into discrete categories such as constructed action or classifiers may also introduce artificial boundaries into what would more fruitfully be described as a continuum of linguistic constructions, especially in such a young language. We plan significant further investigation into this complex issue in the future.

10 The signers in our study are between 20 and 51 years old. Börstell and colleagues' participants are 20–70 years old (Börstell et al., 2016) and 15–75 years old (Börstell et al., 2019).

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Supporting Information

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