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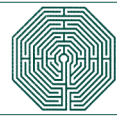
Manual Movement in Sign Languages: One Hand Versus Two in Communicating Shapes

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Abstract

In sign languages, the task of communicating a shape involves drawing in the air with one moving hand (Method One) or two (Method Two). Since the movement path is iconic, method choice might be based on the shape. In the present studies we aimed to determine whether geometric properties motivate method choice. In a study of 17 deaf signers from six countries, the strongest predictors of method choice were whether the shape has any curved edges (Method One), and whether the shape is symmetrical across the *Y*-axis (Method Two), where the default was Method One. In a second study of ASL dictionary entries for which the movement path of the sign is iconic of an entity's shape, the same predictors surfaced. These tendencies are captured in the Lexical Drawing Principle, which is coherent with biological constraints on movement in general. Drawing in the air with two hands, however, is costly, both cognitively and biomechanically. Furthermore, it distinguishes signers from non-signers, who draw shapes with only one hand. Signers assume this extra cost in the lexicon because of the enhanced iconicity the possibility of two hands offers; they assume it in drawing shapes in the air because they apply the same linguistic principle they use in the lexicon. Additionally, having a choice of methods allows the signer to benefit from over-specification in providing redundant information about the shape, enhancing comprehensibility and resolving ambiguity.

Keywords: Sign languages; Manual movement; Iconicity; Symmetry; Shapes

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1. Introduction

Iconicity effects in sign languages are apparent across the grammar (Meir, Padden, Aronoff, & Sandler, 2013; for overview, Napoli, 2017), and recent evidence suggests that iconicity is relevant to sign acquisition (Perniss, Lu, Morgan, & Vigliocco, 2018). This paper is an examination of one situation in which iconicity plays a fundamental role: communicating a shape (circle, triangle, wiggly line, whatever) via drawing its outline in the air.

Signs are analyzed as comprised of non-manuals plus three manual parameters: handshape, movement, and location (Stokoe, 1960; orientation is a fourth in Battison, 1978). We explore constraints on iconic movement; in particular, we ask which properties of a shape influence whether one uses only one moving hand (what we dub Method One) or two moving hands (what we dub Method Two) when communicating that shape via drawing in the air.

To do this, we carried out a survey of shapes for participants to communicate with their hands. We ran the survey with two groups: hearing participants who had no experience with signing, and deaf signers.[1] Our results indicate that for deaf signers two shape properties influence method choice: whether or not there are any curved edges and whether or not the shape is reflexively symmetrical across the *Y*-axis.

We did a follow-up survey of all entries in an online dictionary of American Sign Language (ASL), supplemented by random samplings from three other dictionaries. We examined signs with a concrete sense whose primary movement path draws the outline of the relevant concrete object in order to see if the properties relevant to method choice in drawing shapes were relevant to drawing in lexical items. We found that they were. Thus, we propose a principle for determination of method choice in these signs, the Lexical Drawing Principle. And we propose that when signers draw random shapes in the air, they apply the Lexical Drawing Principle just as they would if they were signing a lexical item.

2. How drawing shapes in the air is relevant to sign language grammar

Introductory sign language courses teach students how to sign shapes (not the names of shapes, but the shapes themselves, where the two might be different in a given sign language). The teacher will, for example, draw the outline of a shape in the air, and students then mimic and/or draw the shape on paper. This exercise lays the foundation for several critical tasks in signing. Being able to sign shapes properly is relevant in describing objects and individuals ("the guy in the tee-shirt with zig-zag lines," see Fig. 1 from Smith, Lentz, & Mikos, 1998, p. 103, reprinted with the kind permission of Dawn Sign Press).

Knowing how to sign shapes is essential for proper use of topographical space (MacSweeney et al., 2002; and see remarks in Murgiano, 2018). For example, in ASL the convention is that signers use their own perspective, and addressees map onto themselves. So if two people are facing each other and the signer draws an arrow in the air facing her right, the addressee is to understand that as an arrow facing her own right, not an arrow facing left. In Fig. 2 we see a typical exercise in an introductory text to ASL that teaches

Fig. 1. Example of visual description.
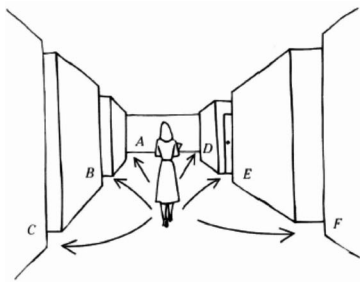
Fig. 2. Example task involving relative distance and drawing routes.

how to convey perspective (Smith et al., 1998, p. 20, reprinted with the kind permission of Dawn Sign Press).

Issues of perspective are critical to properly using and understanding classifier predicates. Classifier predicates are entire propositions (action or state plus participants in the event) in which the action or state is a movement or location and in which (a) the handshape is selected based on a variety of factors, some of which have to do with physical and behavioral properties of the referent of the moving/locating entity (Slobin et al., 2003), and (b) the path of movement and use of space are meaningful (Schick, 1990). In ordinary conversation in ASL, for example, to convey that something moved from location A to location B, then stopped halfway on the path to location C, the hand would move from A to B and then halfway to C, where the particular handshape (called the classifier) would indicate what type of something did the movement (the 3-handshape for certain vehicles; the bent-V-handshape for certain animals).

Classifier predicates are common in narratives (comprising 17% of the narrative ASL corpora studied in Morford & MacFarlane, 2003), and their phonological parameters can be played with in creative language (Sutton-Spence & Napoli, 2013); thus, correctly using space and path of movement in a meaningful way is part of signing.

Shape-based descriptions are also the basis for many lexical items and may form the foundation for coining new lexical items (Wilcox, 2000, particularly p. 38), although such items may soon get conventionalized and acquire a relatively non-iconic form (see suggestive findings in Petrich, Nicodemus, & O'Grady, 2013).

And, finally, signing shapes often involves using one hand to establish a fixed (immobile) reference point on the shape, called a point buoy. In these instances, the signer typically uses the tip of the index finger of the non-dominant hand to establish a point in the air (the buoy). Then, while the non-dominant hand maintains that buoy, the tip of the index finger of the dominant hand draws a shape starting at the buoy.[2] Consider the instance of the dominant hand drawing a curve with a constant slope. If the hand ends up back at the buoy, we know this is a complete circle. If the hand stops just a little bit before touching the buoy, we know there is a small gap, an incomplete circle. And so on. So the buoy can help convey essential shape information.

Point buoys are among the mechanisms used in signing common reference points, and they can be key to conveying spatial and temporal relationships (Vogt-Svendsen & Bergman, 2007). In Fig. 3 (from Smith et al., 1998, p. 79, reprinted with the kind permission of Dawn Sign Press) we see an exercise in an introductory ASL course that teaches how to establish a common reference point from which other locations can be identified.

For example, Person-A might ask where the men's room is. Person-B might respond by asking if Person-A knows the women's room on the first floor. If Person-A says yes, then Person-B might sign WOMAN TOILET[3] and put a point buoy in the air to indicate the location of the women's room. The tip of the index finger of the dominant hand would start at that point buoy and move in an arc to a point directly above the point buoy, indicating that the men's room is one floor up, right above the women's room.

3. Instructions in textbooks and online resources

Instructional texts and online resources on sign languages give directions for signing shapes. For example, some texts distinguish three types of shapes: "symmetrical,"
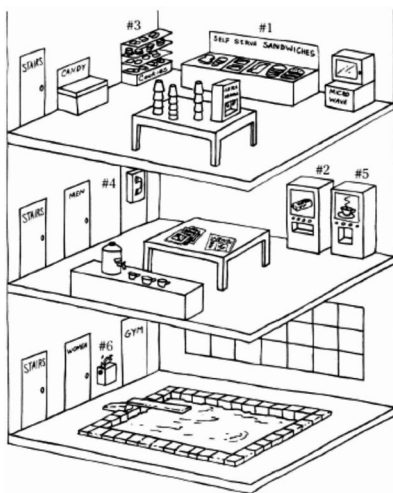
GRAMMAR PRACTICE

Giving Directions

Ben will ask Mary where he can find various things in the building illustrated below. Find #1 on the illustration, then watch Mary give directions to that location. Then do the same for #2 and #3.

Giving Directions Using a Common Reference

Again, Ben will ask Mary where he can find various things in the building. Watch how she signs directions to locations marked #4, #5 and #6 in the illustration. Notice how she establishes a common reference point.

Rewind the tape to the beginning of this activity. After Ben signs each question, stop the tape and give directions. Then compare your directions with Mary's.

Fig. 3. Example task on giving directions using a common reference.

"asymmetrical," and "linear," as in Fig. 4a (Smith, Lentz, & Mikos, 2008a, p. 75, reprinted with the kind permission of Dawn Sign Press). The directions are to use Method One with "asymmetrical" and "linear" shapes but Method Two with "symmetric shapes." The teacher guide for this textbook indicates that circles are exceptional in that they use Method One, like linear shapes do; see the note "circles too" in Fig. 4b (Smith, Lentz, & Mikos, 2008b, p. 147, reprinted with the kind permission of Dawn Sign Press).

No definitions of the terms *symmetrical*, *asymmetrical*, and *linear* are given, and we can see why: The terms are not used in ways coherent with their use in mathematics. All the shapes in Fig. 4a are, in fact, symmetrical, as are eight out of the 12 shapes in Fig. 4b.

Despite misuse of mathematical terminology, instructional materials seem to be grouping shapes based on mathematical concepts, as we will now show.

4. Relevant formal concepts

Here we briefly discuss mathematical concepts that help us extract generalizations from the proposals in instructional resources that pertain to the choice of using Method One or Method Two. We gather those generalizations in §4.4.

4.1. Symmetry

In mathematics, two shapes are said to be reflexively symmetrical to one another if there is at least one straight line that can be drawn between them so that they are identical reflections of each other across that line—the axis of symmetry. In all six cells of Fig. 5a the two shapes are placed reflexively symmetrical to one another, where the axes of symmetry vary (vertical, horizontal, or diagonal). In contrast, in Fig. 5b the two
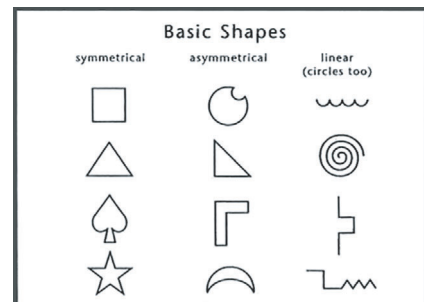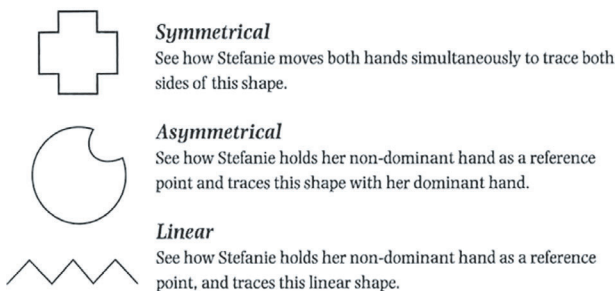
(a) shapes from instructional text   (b) shapes from teacher guide

Fig. 4. Three types of shapes with examples.
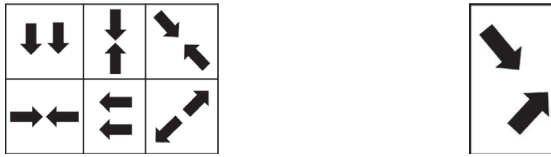
(a) arrows placed symmetrically   (b) arrows not placed symmetrically

Fig. 5. Shapes placed symmetrically or not with respect to each other.

shapes, while identical, are not placed reflexively symmetrical to one another; there is no straight line you could draw across which they would be mirror images.

We can also talk about reflexive symmetry with respect to a single shape. If a straight line can be drawn through the shape, cutting it in half, such that the two halves are mirror images of each other, the shape is reflexively symmetrical, known as bilaterally symmetrical. In Fig. 6a we see shapes that are bilaterally symmetrical, where the dashed lines show an axis of symmetry. In contrast, the shapes in Fig. 6b are asymmetric.

In fact, a shape can be bilaterally symmetrical across multiple axes. The pentagon in the upper left of Fig. 6a, for example, could have straight lines drawn from each vertex (here, each angle) to the middle of the opposite edge (or side); each of those lines would be an axis of symmetry. Likewise, the square has four axes of symmetry, and the circle has an infinite number of axes of symmetry.

For ease of exposition, we will talk simply about symmetry, meaning reflexive symmetry, whether of one shape to another (as in Fig. 5a) or one half of a shape to the other half (as in Fig. 6a). From here on the terms *symmetric* and *asymmetric* are used as in mathematics.

Looking back at Fig. 4, we see that every example of an asymmetric shape uses Method One (though the converse is not true; some symmetrical shapes also use Method One).

4.2. Geometric vertices

We here introduce terms and concepts important to later discussion. In geometry, any angular point where two rays (straight lines) meet is a vertex (Fig. 7a). The geometry of
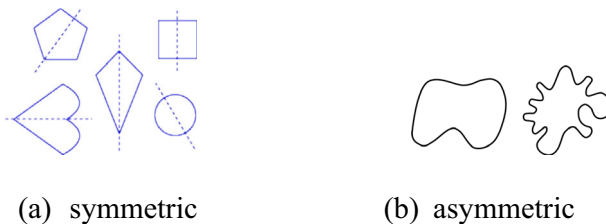
(a) symmetric   (b) asymmetric

Fig. 6. Symmetric and asymmetric shapes.

a. Angular vertices   b. Curve vertices   c. Cusps
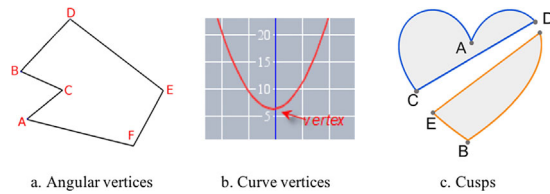
Fig. 7. Vertices. (a) Angular vertices.

planar curves also allows for the notion of vertex of a curve: Points of extreme curvature are vertices (Fig. 7b). Finally, the point where a straight line meets a curve or the pointed tip where two curves meet is called a cusp (Fig. 7c).

Angular vertices that point outward (A, B, D, E, F in Fig. 7a) are called ears. Vertices that point inward (C in Fig. 7a) are called mouths. We adopt the terms *peak* and *valley* for the curve and cusp counterparts to *ear* and *mouth*, respectively. Looking back at the two asymmetric shapes in Fig. 6b, we see the shape on the right has nine peaks and nine valleys, while the shape on the left has four peaks but only two valleys.

Ears, mouths, peaks, valleys, cusps, and contours in general are visually salient in ways relevant to what we first notice in detecting and recognizing a shape (Mundhenk & Itti, 2005; Wolfe, 1998; among many) and to how we feel about a shape (Larson, Aronoff, & Steuer, 2012).

4.3. Graph theory

Graphs consist of edges and vertices, where the appearance of those vertices and edges (straight or curvy, etc.) is not part of the graph itself but only part of the pictorial representation of the graph. That is, in graph theory neither vertices nor edges need have particular geometric properties. In Fig. 8 we have two pictorial representations of the same graph, consisting of two vertices (A, B) and an edge connecting them.

In contrast, in the drawings people make in the air, the geometric properties of vertices and edges matter because those define the shape. So in Fig. 8 the upper graph constitutes a different shape from the lower graph. The upper shape has many geometric vertices salient to the eye (as discussed in §4.3). The lower shape has only two vertices—the starting and ending points. Despite that difference, it is useful for us to talk about the movement of the manual articulators in the terminology that mathematicians talk about graphs, as we now show.
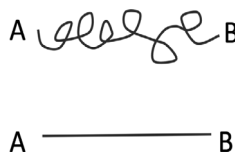
Fig. 8. Two pictorial representations of the same graph.

Mathematicians talk about walks, a sequence of alternating vertices and edges, as a way to analyze the properties of graphs. If any given vertex on a graph can be reached via a walk from any other vertex, the graph is connected. The graph in Fig. 8 (in both its representations) is connected; you can walk from A to B via an edge (in either direction). Likewise, the graph in Fig. 9a is connected; you can walk from any vertex (here labeled A, B, C, D) to any other vertex via a sequence of edges and vertices. However, the graph in Fig. 9b is not connected; if you were to draw it on paper, you'd have to lift the pen off the page during drawing.

A walk that starts at one vertex and ends at a different vertex is said to be open, while a walk that begins and ends at the same vertex is said to be closed.

Looking back at Fig. 4, we see that every example of a "linear" shape is an open walk except circles. We return to circles in §4.4.

A walk that has only distinct edges is called a trail (i.e., we never walk the same edge twice, so there's no doubling-back along a given edge). The graph in Fig. 8 is an open trail, and the graph in Fig. 9a is a closed trail. Closed trails are called circuits. Circuits in which no vertex appears more than once except the first/last are called cycles. In other words, cycles are walks along distinct vertices and edges that end up at the starting point. Any cycle in which you travel along every edge of the graph only once is called a Hamiltonian cycle (also called a Hamiltonian circuit). If one were to imagine vertices along the edges of the shapes in Fig. 6 and then start at one of those vertices and draw the finger along alternating vertices and edges back to the starting point, the finger would have walked a Hamiltonian cycle. In obvious visual terms, a shape that is closed with a hollow center is walkable as a Hamiltonian cycle.

Looking back at Fig. 4 one more time, we see that every example of a "symmetrical" shape is walkable as a Hamiltonian cycle. (However, the "asymmetrical" shapes are as well.)

4.4. Generalizations extracted from instructional resources

Since drawing is done with one manual articulator on paper, the null hypothesis says Method One should be the default for drawing in the air (the elsewhere condition in the sense of Kiparsky, 1973). So conditions should be stated on the use of Method Two, with Method One used elsewhere.

(a) a continuous graph   (b) a discontinuous graph
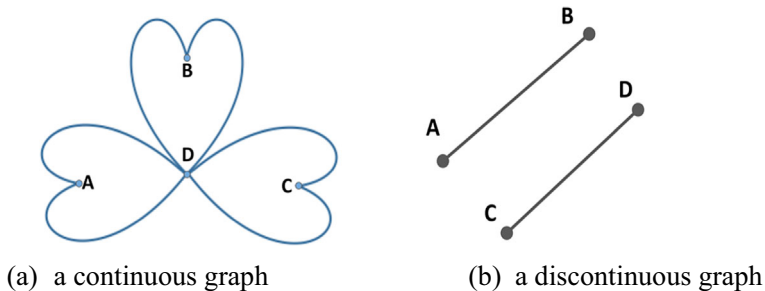
Fig. 9. continuous and discontinuous graphs.

First, asymmetric shapes are rendered with Method One. We therefore propose:

1. A shape must be symmetrical to use Method Two.

We refine this proposal in §5.

Second, shapes walkable as open graphs are rendered with Method One. This, added to the fact that all examples of "symmetric" shapes in Fig. 4 are Hamiltonian cycles, suggests:

2. A shape must be walkable as a Hamiltonian cycle to use Method Two.

We raise possible challenges to this expectation in §6, where we bring up composite shapes.

Finally, instructional resources point out that circles are drawn in the air with Method One. But circles are symmetrical and walkable as Hamiltonian cycles. If our two proposals are on the right track, circles are exceptional or some other factor is interfering. It turns out that circles are not the only problem: Instructional resources often point out that crescents and ovals use Method One. These three shapes consist entirely of curves. However, instructional resources also often claim that a heart shape uses Method Two. For now, then, we label circles, crescents, and ovals "Puzzling," in that they have an immediately obvious common geometric characteristic, but it is not immediately obvious whether that characteristic is responsible for method choice when drawing them. We now offer a third ad hoc proposal:

3. A shape must not be Puzzling to use Method Two.

So we have three tentative necessary (but not sufficient) conditions on a shape in order for it to be drawn with Method Two.

5. Expectations of method choice based on the lexicon

Drawing shapes in the air often requires creating a sign, in that the signer may never have signed nor seen anyone else sign that very shape before. In creating a sign, signers typically adhere to principles evident in established lexical items, as many have noticed, if only in passing (Bellugi & Newkirk, 1981; Mirus, Fisher, & Napoli, 2012; Supalla, 1986, 1992; Taub, 2001). That is, a signer manipulates the phonological parameters (handshape, movement, and location) in ways already licensed by the language. We see the same behavior in spoken language; new words generally adhere to principles evident in established words (Munat, 2007; Štekauer, 2002; among many).

Established lexical signs generally fall into three types with respect to manual movement (Battison, 1978; Napoli & Wu, 2003). In the first type, both hands move independently (rather than being joined and moving as a unit). In the vast majority of these, the movement is reflexive across the midsagittal plane that splits the body into a right and left half (as in DIVORCE) or across that midsagittal plane rotated up to 45 degrees to the left or right (as in HONOR). Movements are simultaneous or, sometimes, alternating (as in

BICYCLE). This tendency is strong; signs that start out with other movement characteristics often conform to reflexivity over time (Frishberg, 1975). In the second type, one hand is immobile while the other moves, usually in contact with or close proximity to a location on the immobile hand (Battison, 1978). In the third type of established lexical sign only one hand is involved.

Since drawing shapes in the air is like coining a sign, we expect the movement to adhere to the principles operative in these three types. Note that the *Y*-axis with respect to a shape drawn on paper corresponds to the midsagittal plane of the human body with respect to a shape drawn in the air. So, on the basis of manual movement in the three types of established lexical signs, we expect that if a shape is drawn in the air with Method Two, that shape is symmetrical across the *Y*-axis or an axis of symmetry rotated up to 45 degrees off the *Y*-axis.

From here on, when we talk about the property of symmetry across the *Y*-axis, we include symmetry across an axis rotated up to 45 degrees. We use YSym to refer to this property.

The proposal here can be stated as a refinement of the first proposal in §4.4:

1. (Revised) A shape must be +YSym to use Method Two.

This revision is probably what instructional resources intended, given that they label as "asymmetrical" those shapes that are symmetric across axes other than the *Y*-axis.

6. Composite shapes

Some shapes can be viewed as having multiple parts (Fig. 10).

Instructional resources say the signer will first draw the circle with Method One, and then the square with Method Two. But one might imagine that a signer could see this shape as a unit to be drawn fluidly with a single method. Which method?

What happens with shapes not analyzable as a connected graph? Our proposals would say that if the various parts of it were, in fact, symmetrical across the Y-axis (as in Fig. 11a), we have the possibility of using Method Two. Otherwise, we should use Method One.

Instructional resources we have consulted do not include discussion of such shapes, which may be the reason why we, unfortunately, included only one such shape in our participant survey.

Fig. 10. Shape made of circle plus square.
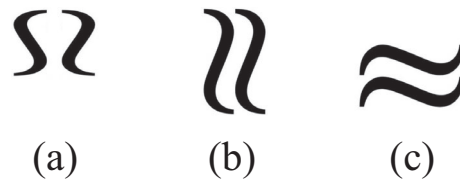
Fig. 11. Shapes analyzable as disconnected graphs.

7. Our surveys

To find out what shape properties influenced method choice, we carried out two surveys. Survey 1 gathered data from participants. Survey 2 gathered data from dictionaries to check whether the findings from the first study might be pertinent to the lexicon.

7.1. Survey 1 (Participants)

7.1.1. The stimuli
7.1.1.1. Number and selection of shapes: We designed the survey for completion in under 5 minutes, as participants were not compensated. For this reason we kept our list of shapes under 50 (i.e., 49), which is how many a test-run by each of us determined could be done comfortably in 5 minutes. Each subject saw all 49 shapes.

To choose shapes, we made drawings of dozens of shapes that tested our proposals and we each grouped them into piles by familiarity. We then asked a third person (hearing) to group them. The rationale for three piles was based on the fact that natural language production is guided by rules as well as by (seemingly arbitrary) conventions. For example, in English we pluralize *cat* to *cats*, by a rule that applies generally across nouns and that, if we are native speakers, no one ever explicitly taught us (i.e., much of our linguistic knowledge is unconscious). But we pluralize *foot* to *feet* by (what seems today) an arbitrary convention. That *cats* is rule-produced is shown by the fact that if we make up a neologism such as *gagoot*, we'll pluralize it as *gagoots*, not *gageet* or anything else. If drawing shapes in the air is part of natural language production (see §5), then it should, likewise, be guided by rules (the ones we are trying to uncover in our study) as well as conventions. We speculated that the more familiar a shape was to a signer, the more chance the signer would rely on experience in drawing it in the air—and experience could be rule-guided or convention-guided, whereas the more unfamiliar a shape was, the more chance the signer would rely on unconscious rules.

Eight shapes that appeared in the highly familiar pile for all three people seemed to us to be canonical. They are shown in Fig. 12a.

Twenty additional shapes that appeared in the familiar pile for all three seemed to be shapes that one might have seen in special contexts (like a math class) or that deviated slightly from the canonical (perhaps unfinished, or tilted, or with one edge curved instead of straight). They are shown in Fig. 12b. We were curious to know, for example, if
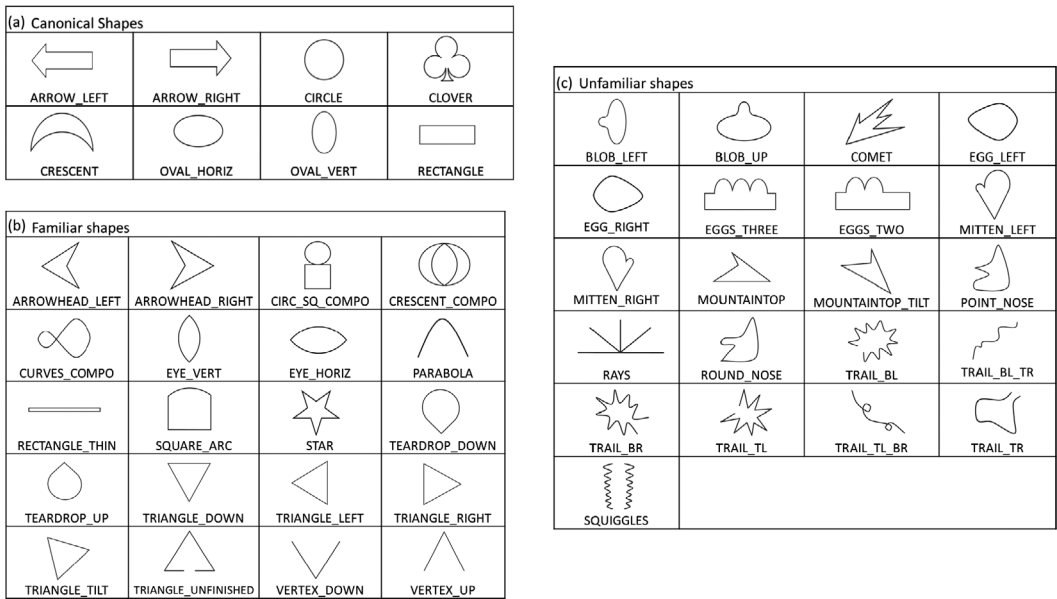
Fig. 12. Three groups of shapes.

rectangles would be signed the same way whether they were ordinary in dimensions (RECTANGLE in Fig. 12a) or extraordinary (RECTANGLE_THIN in Fig. 12b).

At that point we chose 21 shapes deemed unfamiliar by all three of us, shown in Fig. 12c, in order to have as nearly equal as possible numbers of the familiar and unfamiliar types.

7.1.1.2. Coding the stimuli: We included in our model the properties foundational to our proposed three necessary conditions for using Method Two, gathered here for convenience:

1. (Revised) A shape must be +Ysym to use Method Two.
2. A shape must be walkable as a Hamiltonian cycle to use Method Two.
3. A shape must not be Puzzling to use Method Two.

In evaluating the properties of a shape, we relied on the geometric concept of vertex (see §4.3) and line, where straight lines and curves are distinct. The properties coded-for were:

- *YSym*—Shapes that are +YSym are symmetrical across the Y-axis or across an axis rotated up to 45 degrees off that axis. 25 shapes are +YSym; 24 are −YSym.
- *HamC*—Shapes that are +HamC are walkable as Hamiltonian cycles—that is, they are closed shapes in which the only vertex that is walked through twice is the first/last. 35 shapes are +HamC; 14 and −HamC.

- *AllCurve*—Shapes that are +AllCurve consist only of curves. +AllCurve is a property of the Puzzling shapes. 24 shapes are +AllCurve; 25 are −AllCurve.

Additionally, we included:

- *XSym*. Signs which are +XSym are reflexively symmetrical across the X axis. Although unlikely, this is a potentially relevant property since that there exist a few two-handed lexical items in which both hands move in reflexive symmetry across the horizontal plane (Napoli & Wu, 2003). 18 shapes are +XSym; 31 are −XSym.
- *Circuit*. Signs which are +Circuit are walkable as circuits—that is, closed trails. Shapes that are +Circuit include all shapes that are +HamC, but also some that are −HamC (such as the composite shape in Fig. 10). So it seemed worthwhile to test for relevance of this more inclusive property. 36 shapes are +Circuit; 13 are −Circuit.
- *Curve*. Signs which are +Curve have at least one curved edge. Since some of our signs are +Curve but −AllCurve, it seemed worthwhile to test for relevance of this more inclusive property. 31 shapes are +Curve; 18 are −Curve.
- *Novel*. Signs which are +Novel are the unfamiliar shapes in Fig. 12c. This property is the only non-mathematical one, chosen based on experience in linguistics; +Novel shapes might offer the best examples of what signers do when they access unconscious knowledge of how to draw shapes in the air. 21 shapes are +Novel; 28 are −Novel.

We also coded for handshape and use of a point buoy. We chose not to include the graph properties of being analyzable as (1) connected or (2) a trail, since we had only one example of a disconnected shape (SQUIGGLES) and only two examples of shapes not analyzable as trails (SQUIGGLES and RAYS). We include both in our analysis, but we place discussion of details about them in Appendix S1. Issues in coding particular shapes are found in Appendix S2.

7.1.2. Participants

We ran our survey with two sets of participants.

One set consisted of 11 hearing participants without experience in signing. They all used only one hand in communicating the shape manually; they drew in the air in a similar way to how they would have drawn on paper or with a finger on a fogged over window. Since the results are uniform, we do not consider them further until §7.2 (and again in §8).

The second set consisted of deaf participants and is the source of the data we analyze in this paper.[4] Our dataset consists of video recordings from 17 deaf signers (8 men, 9 women). Of them, 12 were signers of ASL (5 men, 7 women). Ten of these were from different areas of the United States. The other two (women) were from Canada (which uses ASL), but nothing about their signing distinguished them from the American signers, so for our analyses we lump all 12 together. The remaining five use

other sign languages: the sign languages of Brazil (one woman), Italy (one man), the Netherlands (one woman, one man), and Turkey (one man). Participants ranged in age from their 20s to 60s. All but one reported their own sign language as the language (or one of the languages) they were most comfortable using. The remaining participant reported ASL as her second most comfortable language after English, as she was late-deafened. Since nothing about her signing distinguished her from the other ASL signers, we integrated her data into the whole. None uses only sign language; all have attained a university-level education and interact with hearing people on a regular basis. Seven were or had been teachers of their sign language (three ASL, and one from each of the other four languages).

We did not collect further information on the language backgrounds of our participants, either with respect to signing or with respect to their ambient spoken language. Collecting such data is not the accepted protocol in many deaf communities (Napoli, Sutton-Spence, & Quadros, 2017) and, therefore, might have unnecessarily limited who was willing to participate. Furthermore, collecting such data may have "a negative effect on deaf communities by exalting the language of those who were privileged enough to acquire a firm foundation in signing during the sensitive period for language development and discounting the language of others" (Fisher et al., 2019). Thus, their self-identification as being deaf (including hard-of-hearing) and comfortable with signing is taken to be enough for them to be participants in our study.

Signers were recruited through friends and acquaintances, who were instructed to pass along the survey to others who primarily used a sign language to communicate. We instructed participants to video record themselves via webcam or any other means of recording available (but all used webcam) while viewing the list of shapes, some of which would be common and some uncommon. Self-recording of this sort is standard practice among the people we asked to help us recruit. Given our method of recruitment, we expected participants to be familiar with it, which, in fact, they were. People recorded themselves from about the lower chest area to about the top of their heads, showing the full range of movement of the manual articulators. We asked them to show how they would sign each shape, and allowed them to offer as many responses as they wanted, but put the method they felt was "best" first. Appendix S3 gives full instructions. Appendix S4 gives the number of responses elicited by each shape.

7.1.3. Design

Each participant was given a link to a survey hosted through Qualtrics. After reading the directions, the participant was taken to a randomized list of the 49 shapes that they could scroll through at their own pace while signing. Each shape was large enough to fill the screen, so, while they had the ability to scroll ahead if they chose, the participants would otherwise see only their current shape. None of the shape "names" used in this paper was seen by participants. Participants were not given a time limit. All signers completed the task in one sitting, with a sufficiently lit setting (although we had not instructed them on these two points; their familiarity with the protocol guided them here).

7.1.4. Coding the data

We determined a coding guideline prior to data collection. One author did an initial coding of the whole dataset, consulting with the other as needed. The second author then did an independent coding of randomly selected videos that contained only one response for a shape, and of all videos that contained multiple responses.

Our participants also used what we call Method Mix, making adjustments during drawing, the most common by far being switching between the two methods. Another adjustment was changing which hand is moving in Method One. Method adjustments were often accompanied by handshape change.

7.1.5. Results of survey 1 (Participants)

Although we coded for handshape, it showed no statistically significant correlation with method choice (being the first or second to be eliminated in a logistic regression using a model comparisons approach). We also coded for the use of a point buoy, but that use offered no relevant insights. Thus, we do not discuss these factors further in the results here.

Subjects took an average of 5.7 min to record their videos (5.4 for ASL signers, 6.4 for non-ASL signers). One signer skipped a shape inadvertently; we have data for 48 shapes for her. Another signer's video froze on seven shapes; we have data for 42 shapes for her.

Six signers gave one response per shape (producing a total of 49 video clips each). All others produced multiple responses for at least one shape and some produced multiple responses for most shapes. Multiple responses were different from each other (as instructed). The maximum number of clips any signer produced was 95. The total of number of clips was 1,009.

Responses were characterized by several strategies, where those that were not pure drawing and, therefore, not relevant to the choice between Method One and Method Two, are discussed in Appendix S5. There were a total of 225 video clips using such strategies. Fully 784 video clips (1,009-225), instead, used pure drawing.

7.1.5.1. Testing our predictions: Our three proposals predicted only when it was possible to use Method Two—since they are necessary but not sufficient conditions. So only 13 of our 49 shapes (the 17 that are +YSym and +HamC, minus the four puzzling shapes : CIRCLE, OVAL_HORIZ, OVAL_VERT, and CRESCENT) had the possibility of using Method Two, and the remaining 36 should have used Method One. Instead, 44 of our 49 shapes used Method Two at least once. The five shapes that never used Method Two (using only Method One or Method Mix) are given in Fig. 13a, all of which would have correctly been precluded from using Method Two by our proposals. However, 31 shapes predicted not to use Method Two did use it at least once.

Forty-five of our 49 shapes used Method One at least twice (none used Method One only once). The four shapes that never used Method One (using only Method Two or Method Mix) are given in Fig. 13b. All were incorrectly predicted to be rendered with
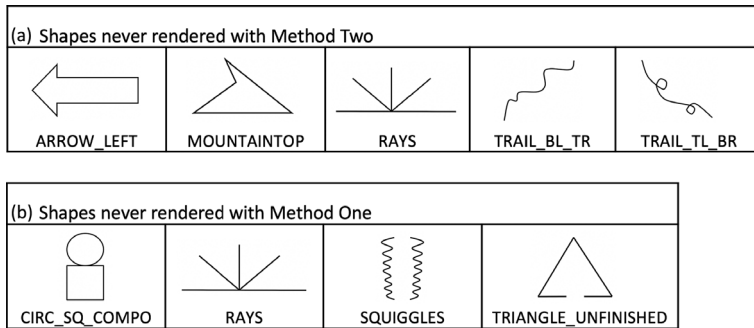
Fig. 13. Shapes that were precluded from Method Two or Method One.

Method One. Furthermore, all 13 shapes that met the conditions for using Method Two used Method One at least twice.

In Fig. 14 we give the segmented bar charts for three groups of shapes: the 13 predicted to have the possibility of using Method Two; the four puzzling shapes, predicted to use Method One; and the 32 remaining shapes predicted to use Method One. Of the 784 clips, 436 (55.6%) used exclusively Method One, 273 (34.8%) used exclusively Method Two, and 75 (9.6%) used Method Mix.

The charts in Fig. 14 look impressive, in that the set of 13 shapes allowed to use Method Two and the set of 32 shapes predicted to use Method One are near inverse partitions; together they (nearly) make up a partition. However, we cannot simply run a χ^2 test here to confirm that these sets are significantly distinct, since the individual data points in our corpus are not independent from each other. Instead, many of our data points come from the same participant and many are in response to the same stimulus.

7.1.5.2. Testing our properties with logistic regression: In order to account for possible interactions in the various properties in our data, we used a multinomial mixed effects model (Gelman & Hill, 2006, Ch. 12) on our data from Method One and Method Two,[5]
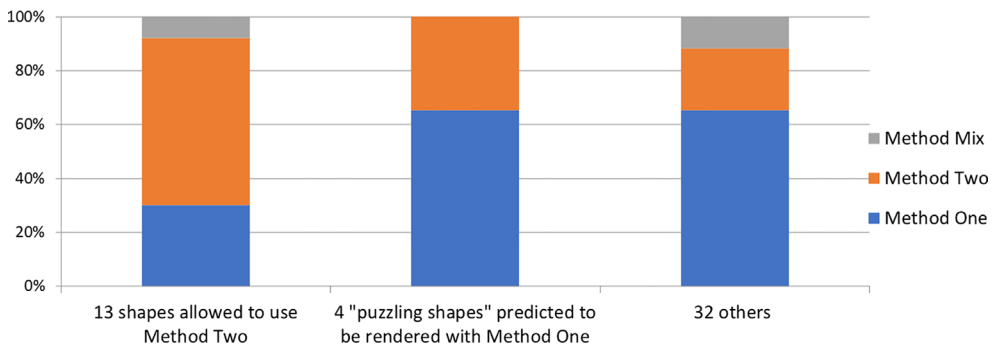
Fig. 14. Charts for method choice for three types of shapes.

allowing us to optimize for our two random effects (participants and shapes) and our various fixed-effects (properties of the shapes). Responses were analyzed using logistic mixed effects regression models (Baayen, Davidson, & Bates, 2008) carried out in R version 3.4.2 using the nnet package (Venables & Ripley, 2002). Our response variable was binomial: whether a subject used Method Two (here considered "1") or Method One ("0"). Data analyses were conducted via model comparison: after fitting a model of method choice with the seven pre-identified fixed effects (YSym, XSym, HamC, Circuit, Curve, AllCurve, Novel), fixed effects were removed one at a time using the drop1 function based on the AIC, as shown in Fig. 15, until the removal of the next fixed effect worsened model fit (witness column 7 of Fig. 15) (Hayes, Wilson, & Shisko, 2012). Improvements in model fit were evaluated using the change in the deviance statistic (2 times the log-likelihood), which is distributed as χ^2 with degrees of freedom equal to the number of parameters added. Parameter estimates are reported with their standard errors and P-values estimated using the normal approximation for the t-values with $\alpha = .05$. The predictors were tested for intercorrelations (multicollinearity), where any correlation coefficient that is less than 0.90 indicates sufficient independence to include them in a logistic regression (Tabachnick & Fidell, 2012). The highest intercorrelation coefficient was between the predictors HamC and Circuit (at 0.857) and AllCurve and Curve (at

	Dependent variable:						
	Method2vsMethod1						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
YSym	3.028***	3.013***	2.964***	2.953***	2.768***	2.585***	2.483***
	(0.296)	(0.295)	(0.293)	(0.295)	(0.270)	(0.206)	(0.199)
XSym	0.457*	0.371	0.438*	0.357			
	(0.256)	(0.240)	(0.233)	(0.223)			
HamC	-0.840	-0.850	-0.282				
	(0.523)	(0.519)	(0.227)				
Circuit	0.619	0.704					
	(0.588)	(0.578)					
Curve	-0.661	-1.004***	-0.943***	-0.941***	-0.863***	-0.782***	
	(0.405)	(0.223)	(0.219)	(0.219)	(0.212)	(0.198)	
Allcurve	-0.392						
	(0.389)						
Novel	0.631**	0.615*	0.537*	0.551*	0.293		
	(0.322)	(0.320)	(0.315)	(0.315)	(0.271)		
Constant	-1.894***	-1.905***	-1.787***	-1.960***	-1.666***	-1.507***	-1.932***
	(0.348)	(0.348)	(0.334)	(0.305)	(0.246)	(0.191)	(0.165)
Akaike Inf. Crit.	703.871	702.886	702.385	701.941	702.499	701.692	715.759
Note:					*p<0.1; **p<0.05; ***p<0.01		

Fig. 15. Fixed effects model comparison.

0.749), both falling under 0.90 and both unsurprising, given that the second of each pair of properties includes the first.

Including only YSym and Curve as the fixed effects yielded the best fit model at this point (AIC of Fig. 15 column 6 = 701.692). So the combination of +YSym and −Curve correlates positively with, and is the best predictor of, use of Method Two.

Bagozzi (2010) points out that the methods employed here reliably indicate statistically significant results. That is, multicollinearity cannot create artificially statistically significant results. But at the same time multicollinearity does not reveal other possible predictive factors not yet considered in the model. We therefore searched for other possible predictive factors.

7.1.5.3. Participant as a predictive factor: We re-ran the model comparison adding in Participant as a random effect. Again, including only YSym and Curve as the fixed effects yielded the best fit model (in Fig. 16 AIC of column 6 = 666.642), with the order of elimination of fixed effects differing somewhat from that seen in Fig. 15. In fact, with

	Dependent variable:						
	Method2vsMethod1						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
YSym	3.382***	3.342***	3.320***	3.297***	3.129***	2.892***	2.758***
	(0.329)	(0.327)	(0.329)	(0.327)	(0.301)	(0.233)	(0.224)
XSym	0.439	0.510*	0.385	0.326			
	(0.272)	(0.263)	(0.246)	(0.237)			
HamC	-0.822	-0.315					
	(0.564)	(0.249)					
Circuit	0.632						
	(0.631)						
Curve	-0.688	-0.590	-0.729*	-1.080***	-1.009***	-0.903***	
	(0.431)	(0.419)	(0.409)	(0.233)	(0.226)	(0.211)	
Allcurve	-0.523	-0.577	-0.425				
	(0.417)	(0.411)	(0.397)				
Novel	0.701**	0.637*	0.637*	0.609*	0.373		
	(0.342)	(0.337)	(0.337)	(0.335)	(0.288)		
ASL			-1.001**				
			(0.419)				
Constant	-2.080***	-1.981***	-1.453***	-2.112***	-1.845***	-1.641***	-2.119***
	(0.421)	(0.409)	(0.463)	(0.383)	(0.331)	(0.285)	(0.260)
Observations	682	682	682	682	682	682	682
Log Likelihood	-325.581	-326.084	-324.380	-327.516	-328.465	-329.321	-338.906
Akaike Inf. Crit.	669.162	668.168	664.761	667.032	666.929	666.642	683.813
Bayesian Inf. Crit.	709.888	704.368	700.961	694.183	689.554	684.742	697.388

Note: $^*p<0.1;\ ^{**}p<0.05;\ ^{***}p<0.01$

Fig. 16. Mixed effects model comparison.

the inclusion of Participant as a random effect, the predictive value of the combination of the two shape properties increased.

We then asked whether another fact we knew about individual participants might affect the model: whether a participant is or has been a sign language teacher ("Teacher"). The addition of Teacher worsened model fit: with Teacher as a random effect added to the model in Fig. 15, AIC goes from 701.692 to 703.542; with Teacher as a second random effect added to the model in Fig. 16, AIC goes from 666.642 to 668.642.

7.1.5.4. Difficulty as a predictive factor: We next asked whether shapes which signers found difficult to render via drawing might favor one method over another. Appropriately, then, we consider all clips here, including those using Method Mix.

In assessing difficulty, we worked with two hypotheses. First, shapes which elicited multiple responses might be more difficult to draw. Consistent with that hypothesis is the fact that the number of responses each shape elicited varied with shape, not participant. (The SD of average number of responses by participant was 0.5, and, by shape, was 2.9.)

Second, shapes which elicited strategies other than pure drawing (reported on in Appendix S5) might be more difficult. In Fig. 17 we show the segmented bar charts for shapes organized by the number of responses they elicited. So, for example, the leftmost bar represents the fact that shapes that elicited 17 responses each had the choices of renderings given there. In Appendix S4 we list the shapes grouped by number of responses.

There are 11 sets of shapes here. The two sets of 17 and 18 responses each do not significantly differ (Pearson's χ^2 test: $p = 0.463335$). Likewise, the five sets of 19, 20, 21, 22, and 23 responses do not significantly differ (Pearson's χ^2 test: $p = 0.069883$), although they come close. And, finally, the sets of 25 and 26 responses do not significantly differ (Pearson's χ^2 test: $p = 0.750594$). We therefore merge our data into five more inclusive sets: 17&18, 19–23, 24, 25&26, and 31 in the segmented bar chart in Fig. 18.

These five sets of shapes are highly significantly different (Pearson's χ^2 test: $p < 0.00001$). The percentage of other strategies rises nearly monotonically as the number of responses rises. The only blip is that the shapes that elicited 19–23 responses have a greater percentage of use of other strategies than the shapes that elicited 24 responses. While these two sets are highly significantly different (Pearson's χ^2 test: $p < 0.00001$),
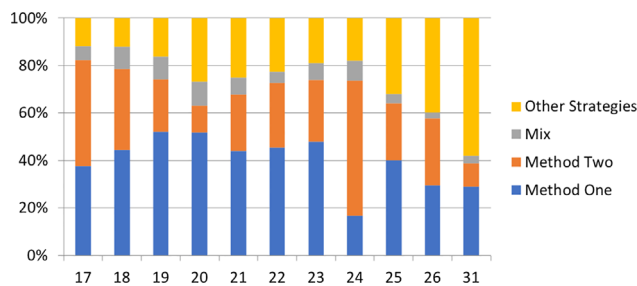
Fig. 17. Graph comparing the proportion each method was used by number of responses.
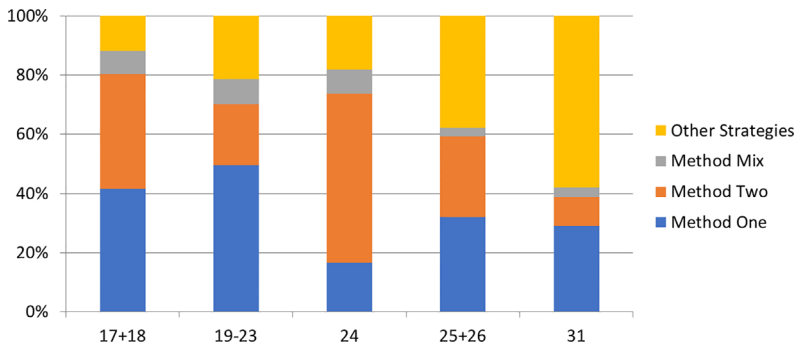
Fig. 18. Graph for method choice for merged sets by number of responses. (a) All data. (b) ASL data. (c) Non-ASL data.

one is so much larger than the other that the difference in percentage of usages of other strategies can be seen as minimal.

However, the percentage of pure drawings using Method Mix stays close to the same until there are at least 25 responses. After that, pure drawing responses of all sorts fall away as other strategies take over.

The variations in percentage of usages of Methods One and Two do not correlate with increasing numbers of responses. Shapes that elicited more responses also elicited more use of other strategies; it would seem it was not immediately obvious to the signers how to draw them.

7.1.5.5. Particular language as a predictive factor: Given that we have data from only a single signer for four languages, and only two signers for a fifth, analyses of individual languages in contrast to the others are precluded. However, we have two findings worth mentioning.

Heat maps offer a visually perspicuous way to see the variable strength of YSym as a factor in method choice based on participant's language. Full heat maps for the entire dataset, the ASL dataset, and the non-ASL dataset are found in Appendix S6, with the names of the shapes given there. In Fig. 19 we give condensed versions. The shortened column headings stand for the familiar properties (Y_S = YSym; A_C = AllCurve; X_S = XSym; H_C = HamC; Ci = Circuit; Cu = Curve; N = novel). The shapes are ordered from top to bottom according to how frequently they were rendered with Method Two, going from least frequent down to most frequent. The YSym column stands apart from the others in all three datasets in that there is a point at which all the cells below it are green. That means that the shapes at that point and below are much more likely to use Method Two than Method One. In contrast, all other columns have clusters of green here and there without a discernible pattern.

In Fig.19a, 20 shapes fall in the continuously green portion of the YSym column, leaving only five green cells scattered above. In Fig. 19b,c, only l6 shapes fall in the all-green portion, with nine green-cell stragglers above. Interestingly, the stragglers for the ASL

Y_S	A_C	X_S	H_C	Ci	Cu	S_C	N
0	1	0	0	0	1	0	1
0	1	0	0	0	1	0	1
0	0	1	1	1	0	1	0
0	0	0	1	1	0	0	1
1	0	0	0	0	0	0	1
0	1	0	0	0	1	0	1
0	1	1	0	1	1	0	0
0	0	0	1	1	1	0	1
0	1	0	1	1	1	0	1
0	0	1	1	1	0	0	0
0	0	0	0	0	0	0	1
0	1	0	1	1	1	0	1
0	0	0	1	1	1	0	1
0	1	0	0	0	1	0	1
1	1	0	0	0	1	0	0
0	1	0	0	0	1	0	1
0	0	0	1	1	0	0	1
0	1	1	1	1	1	0	1
0	1	0	1	1	1	0	1
0	1	1	1	1	1	0	1
0	1	1	1	1	1	0	1
0	0	0	1	1	0	0	1
1	1	1	1	1	1	1	0
1	0	0	0	1	1	0	0
0	0	1	1	1	0	0	0
0	0	1	1	1	0	1	0
0	0	1	1	1	0	0	0
1	0	0	1	1	1	0	1
0	0	1	1	1	0	0	0
1	1	1	1	1	1	1	0
1	0	0	1	1	0	0	0
1	0	0	1	1	0	0	0
1	1	0	1	1	1	1	0
1	1	1	1	1	1	1	0
1	1	1	1	1	1	0	0
1	0	0	1	1	1	1	0
1	1	1	0	1	1	0	0
1	1	0	1	1	1	0	1
1	1	0	1	1	1	0	0
1	1	0	1	1	1	0	0
1	0	0	0	0	0	0	0
1	1	1	1	1	1	0	0
1	0	0	0	0	0	0	0
1	0	1	1	1	0	1	0
1	0	0	1	1	0	0	0
1	0	1	1	1	0	0	0
1	1	0	0	0	1	0	1
1	0	0	0	0	0	0	0

Y_S	A_C	X_S	H_C	Ci	Cu	S_C	N
0	1	0	1	0	1	0	0
1	1	0	0	0	1	0	0
0	1	0	0	0	1	0	1
0	1	0	0	0	1	0	1
0	0	1	1	1	0	0	0
0	1	0	1	1	1	0	1
0	0	1	1	1	0	1	0
0	0	0	1	1	0	0	1
1	0	0	0	1	1	0	0
1	0	0	0	0	0	0	1
0	1	0	0	0	1	0	1
0	1	0	0	0	1	0	1
0	0	1	1	1	0	0	0
0	0	0	1	1	1	0	1
0	1	1	1	1	1	0	1
0	0	0	1	1	0	0	1
1	1	1	1	1	1	1	0
0	1	0	1	1	1	0	1
0	1	0	0	0	1	0	1
0	0	0	0	0	0	0	1
0	0	0	1	1	0	0	1
0	1	1	1	1	1	0	1
0	1	1	1	1	1	0	1
0	0	1	1	1	0	0	0
1	0	0	1	1	1	0	1
1	1	1	1	1	1	1	0
0	1	0	1	1	1	0	1
0	0	1	1	1	0	0	0
1	0	0	1	1	1	0	0
0	0	0	1	1	0	0	1
1	0	0	1	1	1	0	0
1	1	1	1	1	1	1	0
0	0	1	1	1	0	1	0
1	1	0	1	1	1	1	0
1	1	0	1	0	1	0	0
1	0	0	1	1	0	0	0
1	1	0	1	1	1	0	1
1	0	0	1	1	1	0	0
1	1	1	1	1	1	0	0
1	1	0	1	1	1	0	0
1	0	0	0	0	0	0	0
1	1	0	1	1	1	0	0
1	1	1	1	1	1	0	0
1	0	0	1	1	0	0	0
1	0	1	1	1	0	1	0
1	0	1	1	1	0	0	0
1	0	0	0	0	0	0	0
1	1	0	0	0	1	0	1
1	0	0	0	0	0	0	0

Y_S	A_C	X_S	H_C	Ci	Cu	S_C	N
0	0	0	1	1	1	0	1
0	1	0	0	0	1	0	1
0	1	0	0	0	1	0	1
0	0	0	0	0	0	0	1
0	1	0	0	0	1	0	1
0	0	1	1	1	0	1	0
0	0	1	1	1	0	1	0
0	1	0	1	1	1	0	1
0	1	0	1	1	1	0	1
0	0	0	1	1	0	0	1
0	0	0	1	1	0	0	1
0	0	0	1	1	0	0	1
1	0	0	0	0	0	0	1
0	1	1	1	1	1	0	1
0	1	0	0	0	1	0	1
0	1	0	1	1	1	0	1
0	1	1	0	1	1	0	0
0	1	0	0	0	1	0	1
1	0	0	1	1	0	0	0
0	1	1	1	1	1	0	1
0	0	0	1	1	0	0	1
0	0	1	1	1	0	0	0
0	1	1	1	1	1	0	1
1	1	1	1	1	1	1	0
1	1	0	0	0	1	0	0
1	1	0	1	1	1	1	0
1	1	1	1	1	1	0	0
1	0	0	0	0	0	0	0
1	1	1	1	1	1	1	0
0	0	1	1	1	0	0	0
0	0	1	1	1	0	0	0
1	0	0	1	1	1	0	1
1	0	0	1	1	0	0	0
1	0	0	0	0	0	0	0
1	0	1	1	1	1	1	0
1	1	1	1	1	1	1	0
1	0	1	1	1	0	1	0
1	1	1	1	1	1	0	0
1	1	0	1	1	1	0	0
1	0	1	1	1	0	0	0
1	1	0	0	0	1	0	1
1	1	0	1	1	1	0	0
1	0	0	1	1	0	0	0
1	0	0	0	0	0	0	0

(a) all data   (b) ASL data   (c) non-ASL data

Fig. 19. Heat maps showing strength of influence of +YSym on method choice.

users and the non-ASL users are both not identical and ordered differently with respect to how likely they are to employ Method Two (see Appendix S6 for details).

Noting these differences, we did box plots of our results (using the full corpus of drawing data; i.e., 784 videos), showing participants' use of Methods One and Two, one for YSym (shown in Fig. 20) and one for Curve (shown in Fig. 21). In those box plots we numbered the non-ASL participants as 1 through 5.
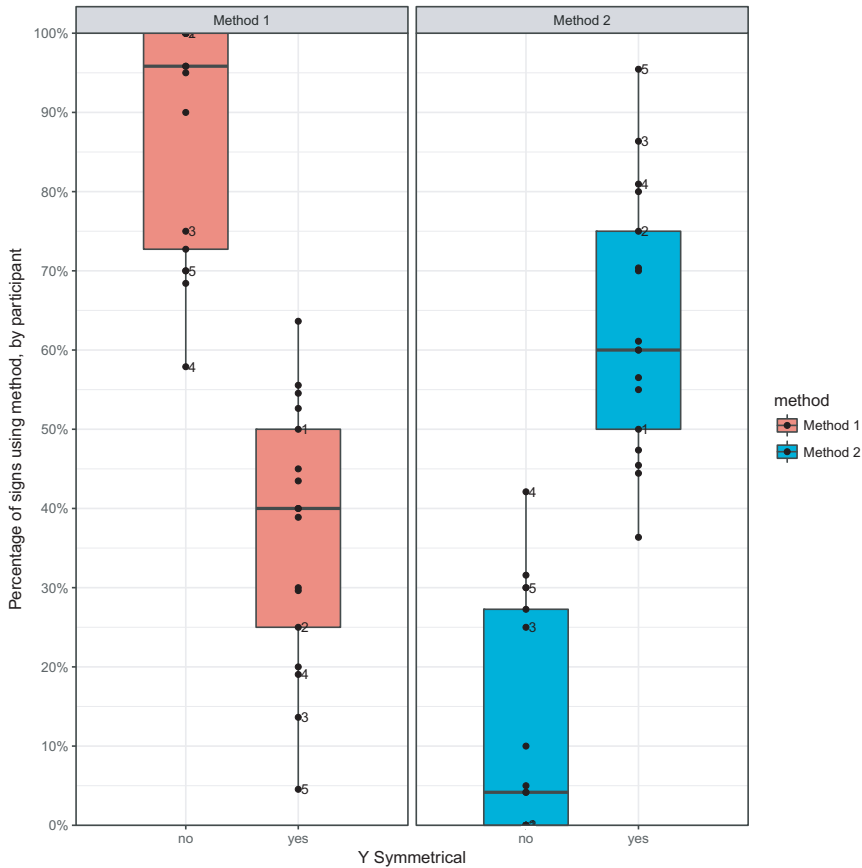
Fig. 20. Participant use of Methods One and Two based on YSym.

With respect to YSym, Participants 4 and 5 are consistently outside the Interquartile Range (IQR), while Participant 3 is sometimes outside the IQR and sometimes not. With respect to Curve, Participants 3, 4, and 5 are consistently outside the IQR, whereas Participants 1 and 2 sometimes are. Importantly, ASL participants also fall outside the IQR in all box plots.

Participant 5 uses the sign language of Turkey. Participants 3 and 4 use the sign language of the Netherlands. Neither of these languages is genetically related to ASL. Participant 1 uses the sign language of Brazil and Participant 2 uses the sign language of Italy, both of which are genetically related to ASL. Thus, with respect to both fixed properties, it would appear that the ASL family behaves cohesively.

Importantly, no participant is an outlier in Fig. 20 or Fig. 21 (defined as being at a distance of more than 1.5 times the length of the IQR; Iacono, Mignone, & Pesole, 2005). The combination of +YSym and −Curve remains the best model of predicting the use of Method Two in our dataset, whether in its entirety or separated into ASL and non-ASL users.
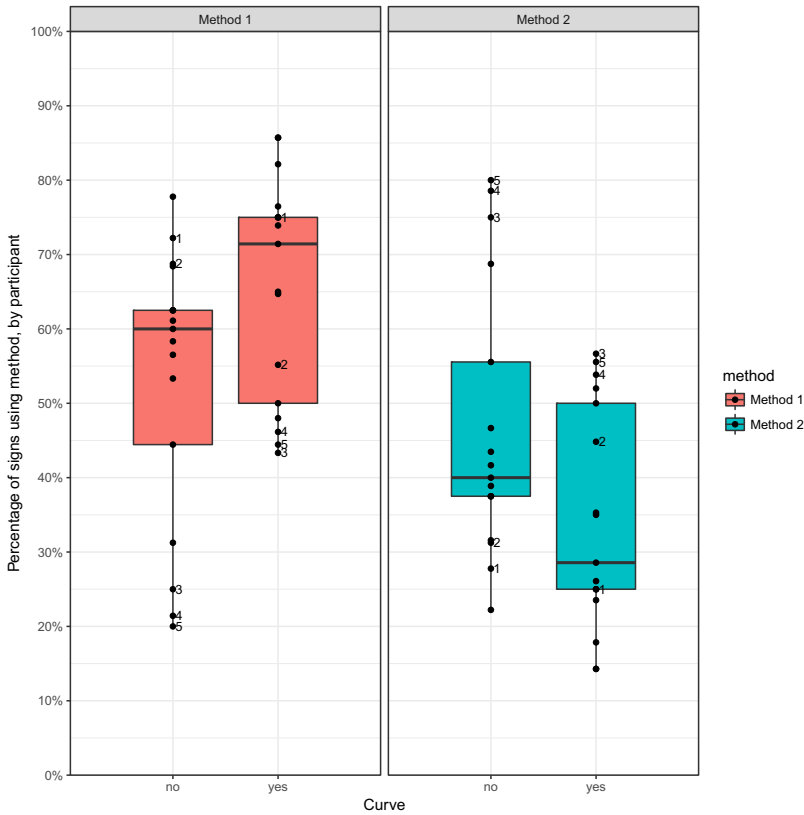
Fig. 21. Participant use of Methods One and Two based on Curve.

7.1.6. Summary of results of Survey 1 (Participants)

We found correlations between two mathematical properties of shapes and the method with which they are drawn in the air. We phrase these correlations in the form of a principle:

Shape Drawing Principle (Version 1): If a shape is +YSym and −Curve, it is more likely that it will be rendered with Method Two. All other shapes are more likely to be rendered with Method One.

7.2. Survey 2 (Dictionaries)

With respect to our Survey 1 (Participants), hearing people without experience in signing uniformly used only Method One. It was the behavior of our deaf signer participants that led us to the Shape Drawing Principle. In other words, Method Two is an option that correlates 100% with experience with signing. Furthermore, as we noted in §5, if both

hands move in articulating an established lexical sign, most often they move in a reflexively symmetrical way across the midsagittal plane. We suspect, then, that the Shape Drawing Principle follows from a principle operative in the grammar of sign languages.

We therefore did a preliminary study of ASL dictionary entries to test whether the following hypothesized principle is at play in the lexicon.

> **Lexical Drawing Principle**: If the primary movement path of a lexical item is iconic of an entity's shape, and if that path is +YSym and −Curve, the lexical item is more likely to involve two moving hands; otherwise it is more likely that only one hand will move.

For ease of exposition in assessing the likelihood of the Lexical Drawing Principle, we use the shorthand of calling a lexical sign by its primary movement path properties. For example, if the primary movement path is +YSym −Curve, we call that a +YSym −Curve sign. For the same reason, we say that a sign with only one moving hand uses Method One, whereas a sign with two moving hands uses Method Two.

7.2.1. Selection of dictionaries

We examined all entries in the online dictionary of ASL called aslpro (aslpro.com), the entries for which are rendered by a team of deaf adults and certified interpreters. We supplemented the resulting dataset with random samplings of entries in three other dictionaries. Two of these dictionaries are of ASL only: handspeak (handspeak.com) and signingsavvy (signingsavvy.com). The third is of multiple sign languages, with ASL among them: spreadthesign (spreadthesign.com). All three ASL dictionaries are recommended by Gallaudet University (http://www3.gallaudet.edu/clerc-center/info-to-go/asl/learning-asl-books_media_classes.html). Spreadthesign is maintained by the European Sign Language Centre in Örebro, Sweden, with local partners in each participating country, and deaf signers in all dictionary entries. Recent large-scale cross-linguistic studies rely on it (such as Sanders & Napoli, 2016; Östling, Börstell, & Courtaux, 2018; Yu, Geraci, & Abner, 2018).

7.2.2. Selection of corpus within the dictionaries

We included dictionary entries with a concrete sense whose movement parameter draws the outline of (part of) the concrete object. This guideline eliminates signs such as those:

- with a concrete sense that are iconic of the shape of an object, but the manual articulators are immobile. Example: CLOCK; the hands assume the shape of the object.
- with a concrete sense that use movement plus another strategy to convey the shape of an object. Example: CAT combines drawing with "hand-as-shape" (Appendix S5).

- with an abstract sense based on shape metaphor, such as CATEGORY. Metaphors do not aim to convey visually perceptible properties of an abstract object since there are none.
- based on mimicry of activities that bring to mind their sense, particularly verbs, where the movement seems to draw a shape but not the shape of an object, such as GATHER[6]

Furthermore, some entries were repetitive with respect to information about choice of method because they belong to the same lexical family (Fernald & Napoli, 2000), such as HOUSE/MUSEUM (we indicate families with a slash). We count only one example from a family.

Our final tally of signs was 137, where many we list are the representative of a family.

7.2.3. Findings

We separated our corpus into three types of signs. The first is +YSym −Curve signs that use Method Two (HOUSE in Fig. 22). The second is +Curve signs that use Method One (ELEPHANT in 22b—iconic of the upward curving trunk). The third is −YSym −Curve signs that use Method One (GIRAFFE in 22c—iconic of the tall straight neck). We list other lexical items of each type in Table 1.[7]

There are 37 +YSym −Curve signs; 41 +Curve signs; and 29 −YSym −Curve signs. These signs' behavior is consistent with the Lexical Drawing Principle. So out of 137 total lexical items, these 107 (78%) appear supportive of this principle.

The 30 remaining lexical items did not immediately fit into Table 1. They fall into three sets with two stragglers.

First, five lexical signs are precluded from fitting into just one type in Table 1, but they do, in fact, behave as expected with the Lexical Drawing Principle. One is FUNNEL. The movement in this sign is analogous to drawing a composite shape (see §6), where method changes between the two parts. The first part draws the narrow part of the funnel as a line oriented vertically (so is −YSym −Curve), and uses Method One. The second element draws the flared part of the funnel and is +YSym −Curve and uses Method Two.

The other four lexical signs have variants in the dictionaries we consulted,[8] where different variants would fall into different types in Table 1. Note that lexical signs that involve drawing outlines in the air are similar to canonical drawings on paper, the latter of which vary, biased by a range of factors, including the drawer's knowledge of and experience with the object (Matthews & Adams, 2008). Thus, we expect variation influenced by such factors—and that's what we see in the detailed discussion in Appendix S7. The variation examined there is consistent with the Lexical Drawing Principle. Our tally then changes to 112 signs out of 137 (82%) that appear to support the Lexical Drawing Principle.

Second, 10 signs in our corpus have a primary movement path whose shape corresponds to a disconnected graph (we call them disconnected signs). Even though the Shape Drawing Principle is not stated as limited to connected shapes, there was only one disconnected shape in Survey1 (Participants) (SQUIGGLES) and it was not consistent with

a. ASL HOUSE: hands move symmetrically across the Y-axis

b. ASL ELEPHANT: hand moves from nose in a curve down and then up

c. ASL GIRAFFE: hand moves straight up

Fig. 22. Examples of ASL signs of three types. (a) ASL HOUSE: hands move symmetrically across the *Y*-axis. (b) ASL ELEPHANT: hand moves from nose in a curve down and then up. ASL GIRAFFE: hand moves straight up. Note: Image recreated by deaf signers of the dictionary entry found on signingsavvy.com

the Shape Drawing Principle (it was +YSym +Curve, but it used exclusively Method Two). For this reason, we set aside all disconnected signs (including ones that would have fit into Table 1), reporting on their behavior in Appendix S8. Just as the Shape Drawing Principle does not predict the behavior of SQUIGGLES, the Lexical Drawing Principle does not predict the behavior of disconnected signs as a group.

Table 1
Lists of ASL signs of three types

+YSym −Curve (HOUSE)	ALTAR, ANTELOPE, APRON, ARROW (road sign), BAKING-PAN, BIKINI, BILLBOARD, BRA, BRICK, CASTLE, CHIMNEY, COUCH, DIAMOND (SHAPE), DIPLOMA, EASEL, FLOOR, (PICTURE) FRAME, GRANDFATHER CLOCK, LICENSE-PLATE, PEAK, ROOF, RULER, SALAMI, SHELF, SMILE, SQUARE, TENT, SWEATER, TELEVISION, TEEPEE, TRAY, TRIANGLE, TRUNK (for storage), TUSK, WALL, WATER-SKIS
+Curve (ELEPHANT)	ACROBAT, ARTERY, BANDAGE, (BEER) BELLY, BEND (as in a road), BLOOD-PRESSURE-CUFF, BRACES, CAMEL, CANDY-CANE, CIRCLE, CLOVER, COLORADO, COMMA, CURVE, DEVIATE, DOWNSPOUT, FAUCET, FERRIS WHEEL, FOUNTAIN, GLOBE, HAMMOCK, HILL, HOOK, HORSESHOE, IGLOO, ITALY, LIPS, LOOP, MOUND, PILE, QUESTION MARK, RAINBOW, SEMI-COLON, SKUNK, SLOPE, SPIRAL (BINDER), TAPE, TUBE, TWISTER (weather), U-TURN
−YSym −Curve (GIRAFFE)	ANGLE, ANVIL, BORDER, CHECKMARK, CYLINDER, CLIFF, CROSS (religious), EMPEROR/LORD/KING/QUEEN/PRINCE/PRINCESS (the royal sash), GRAPH, JAPAN, LINE, LIST, MOHAWK (hairstyle), NECKTIE, PERCENT, PLAID, PLATEAU, PLUMB-LINE, RADIUS, RAIL, RHINOCEROS, RIBBON (as in award), SCEPTER, STRIPE, TELESCOPE, THROAT, VEIN, ZIGZAG

Third, some signs in our corpus use a handshape other than the 1-handshape. In Survey 1 (Participants), handshape turned out not to be a statistically significant factor in method choice, so much so that we did not include it as a factor in our model. However, the 1-handshape was the most used (651 out of 784 clips; 83%). In Survey 2 (Dictionaries), a handful of signs using a handshape other than the 1-handshape appear in Table 1, but 13 others, instead, are described in Appendix S9. The findings there suggest that handshape might well be a factor in method choice in lexical signs that draw an outline of an object due to the fact that the hand is used not just to convey information about outline (in contrast to its use in Survey 1 (Participants)) but additional information about the object. The two remaining lexical items are +YSym +Curve, but they use method Two: FLAMING-HOOP (in aslpro), where the second element uses Method Two for drawing a circle, and OVAL (in aslpro; contrast to signingsavvy, where we find Method One).

7.2.4. Summary of results of Survey 2 (Dictionaries)

The Lexical Drawing Principle is well supported. That is, with respect to lexical items which draw the outline of (part of) an object, if their primary movement path is +YSym −Curve, both hands are more likely to move; otherwise, it is more likely that only one hand will move (82% of our corpus). Lexical items that did not behave as expected included two intransigent exceptions, plus disconnected signs and signs in which the handshape itself carries meaning.

8. Discussion

We arrived at two principles, one from each survey. Since both principles are observed only by signers and are highly repetitive, we revise one of them accordingly now, so that we have:

Lexical drawing principle: If the primary movement path of a lexical item is iconic of an entity's shape, and if that path is +YSym and −Curve, the lexical item is more likely to involve two moving hands; otherwise it is more likely that only one hand will move.

Shape drawing principle (Final version): When drawing a shape in the air, signers apply the Lexical Drawing Principle.

The behavior of the only disconnected shape in Survey 1 (Participants), SQUIGGLES, did not conform to the Shape Drawing Principle, nor did the behavior of disconnected signs as a group in Survey 2 (Dictionaries) conform to the Lexical Drawing Principle. From these two facts, we suspect the Lexical Drawing Principle is restricted to connected shapes. Furthermore, while handshape played no role in our shape survey, it did in our lexicon survey. We attribute this to the fact that the only relevant information in conveying shapes is the geometric properties of the shape, which are rendered by drawing the outline. Instead, there are other bits of information that enter into conveying the sense of a lexical item (i.e., MERRY-GO-ROUND means more than just the round shape of the path one travels when riding it). Handshapes can contribute to those other bits of information. Thus, the Lexical Drawing Principle is compromised by handshape (in ways we are investigating in ongoing research).

Keeping these restrictions in mind, we offer a flowchart in Fig. 23 as a summary of the trends in our findings, with the caveat that we do not claim psychological reality; rather, we leave open the question of how best to model the cognitive processes preceding production.

There are biological reasons (biomechanical and perceptual) for why, if one is to draw a shape that involves curves, we expect only one hand to move (i.e., Method One is to be used; see Appendix S10). There are also biological explanations (motoric and perceptual) for why, if both hands are to move in drawing a shape (i.e., if Method Two is to be used), we expect the hands to move in mirror symmetry (see Appendix S11). However,
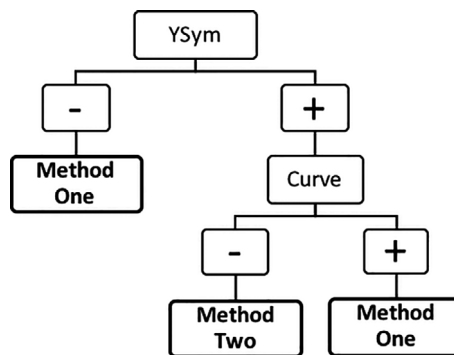

Fig. 23. Hierarchy structure tree for method determination.

nothing in these biological accounts tells us when it should be more likely to use two hands versus one.

The fundamental question, then, is why anyone would ever employ two hands in drawing a shape in the air. There are multiple reasons why we might expect people to use only one hand. Certainly, people draw on paper with one hand and even purportedly ambidextrous artists, such as Adolph Menzel, use only one hand at a time (Singer, 1910, reported on in Gurney, 2011). Furthermore, moving two hands rather than one poses a cognitive burden (as shown in studies of brain injuries, disorders and pathologies; see citations in de Oliveira, 2002). Plus, there are computational costs of coordinating the movement of multiple muscles around multiple joints on different limbs, costs that critically involve the cerebellum and the dorsal premotor cortex (Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2004). And, finally, bimanual mirror movement might take double the biomechanical effort of moving one articulator, where sign languages show a tendency toward wanting to avoid that double effort (as in conversational variants and in diachronic change; Frishberg, 1975; Napoli, Sanders, & Wright, 2014; Padden & Perlmutter, 1987).[9] So one might have expected all shapes to be rendered with just one articulator.

The connection between the Shape Drawing Principle and the Lexical Drawing Principle is fundamental to understanding why signers do not limit themselves to Method One in drawing shapes in the air: When signers draw shapes in the air, they are not simply drawing; they are signing. Hearing people will not take on the costs associated with using two hands in drawing in the air, but deaf signers do, because deaf signers are accustomed to assuming this burden in their ordinary communication tasks all the time. The expressive capacity—the iconic range across the grammar (Napoli, 2017)—of articulating two hands over one makes the burden worth it. Signers can indicate size relationships (GETTING-BIGGER), action of one character on an object (as in READ) or on another character (as in FLATTER), reciprocal action (as in LOOK-AT-EACH-OTHER) and many other relationships using two hands (Lepic & Occhino, 2018). These sorts of benefits of articulating two hands are not exploited when people draw isolated shapes; thus, they may not immediately come to mind in a study on drawing shapes. But since signers already have the Lexical Drawing Principle in their grammar, they apply it even when the use of two hands may appear to add no information about the shape being drawn in the air.

In fact, though, having the option of using two hands does yield an important benefit for communicating shape information, in particular: Each method itself is a kind of over-specification (Ladefoged & Vennemann, 1973; McWhorter, 2012; Szmrecsanyi & Kortmann, 2012) in that it is redundant of information supplied by the movement path. That is, Method Two itself signals both −Curve and +YSym with regard to the shape being signed, whereas Method One itself signals −YSym and the possibility of any kind of edge with regard to the shape being signed. This redundancy adds a small but perhaps extremely useful bit of predictability, particularly with respect to conveying information about unusual shapes (Campbell, 1982, p. 68). The use of Method One might well alert the addressee to pay extra attention precisely because this could be an asymmetric and

highly irregular shape. So redundancy could reduce error in the reception of complexity (Campbell, 1982, p. 73; and see Hunnicutt, 1985, p. 53).

The redundancy offered by having two methods for drawing shapes enhances comprehensibility and resolves ambiguity just as grammatical redundancy in spoken languages does (Wit & Gillette, 1999). For example, if one were to rapidly sign a rectangle, it would be entirely ordinary to round the corners (as some of our participants did). In fact, it could well look like one was signing an oval or even a circle, but for the use of Method Two—which clearly disambiguates and tells us this is a rectangle.

The existence of two methods, then, is an example of the principle of Contrast Preservation (Łubowicz, 2003); and it is critical that we find it in sign languages, since it should appear in all natural languages (Chiari, 2002).

Additionally, that the Lexical Drawing Principle states a tendency rather than an absolutely uniform choice is typical of language behavior. Phonological variation in spoken languages can be the result of gradient phonotactics (Alderete & Finley, 2016; Coetzee & Pater, 2005; Frisch, Pierrehumbert, & Broe, 2004; Gallagher, 2016; Pater, 2007), and cumulative constraint interaction can lead to a form being disfavored and even not surfacing. That is, constraints gang up, sometimes in a weighted way, both in spoken languages (Albright, Magri, & Michaels, 2008; Pater, 2009, 2016; Shih, 2017) and in sign languages (see Appendix S12).

Finally, our results may help to explain findings of others. Some shapes are difficult to describe in spoken language, but turn out easier to draw and sign. When tested on visual memory for such shapes and objects, "signing individuals (both deaf and hearing) were more accurate than non-signing individuals (deaf and hearing) at memorizing shapes" (Cattani, Clibbens, & Perfect, 2007, p. 114). The authors of the study conclude that signing (for both deaf and hearing) leads to visual skills that enhance memory performance for shapes. Perhaps the "visual skills" advantage that signers display here is really, or at least bootstraps on, language principles; that is, the Lexical Drawing Principle.

9. Conclusion and future directions

For the deaf signer, the task of communicating a shape is just as much a linguistic task as communicating a sign. Therefore, the benefits that enhanced meaning (via iconicity and/or redundancy) offers outweigh the costs (cognitive and biomechanical) of using two hands in drawing shapes in the air, whether those drawings are part of lexical signs or created on-the-spot to indicate a particular shape.

A range of possible consequences of our findings arises and calls for investigation. First, our Survey 2 (Dictionaries) was limited to ASL. It remains to be seen whether examination of the lexicons of other sign languages will, as predicted, yield similar results.

Second, the behavior of signers when drawing disconnected shapes (like SQUIGGLES) and shapes not walkable as trails (like SQUIGGLES and RAYS) needs to be examined.

Third, we mentioned in §8 that sometimes with Method Two our signers rounded corners. Given that redundancy in spoken language often correlates with reduced articulation, particularly of vowels (Oshika, 1975; and many others), we might wonder if Method Two is more prone to reduced articulation and, since reduced articulation often correlates with speed of articulation in spoken languages, if the rate of movement of the manual articulators is faster in Method Two than in Method One. Furthermore, the use of Method Two is more informative about a shape in that it indicates that it is +YSym and –Curve, while the use of Method One indicates only that the shape is not both +YSym and – Curve. Given that greater predictability of phonological form correlates with faster articulation in spoken languages (Blevins, 2005), we have a third reason to suspect that the rate of movement in rendering shapes with Method Two should be faster than in rendering shapes with Method One. These questions can easily be answered with well-designed experiments.

Additionally, many questions remain regarding signing shapes, including what factors render a point buoy obligatory, what factors determine starting point of manual movement (and see Appendix S10 for some initial observations), and what factors influence the direction the moving hand travels in Method One. We address them in ongoing work. And, as noted earlier, we also are working on handshape choice and its relationship to shape of path and to method choice.

Notes

1. We use the term *deaf* with a small d throughout, since the d/D distinction raises issues irrelevant here (Fisher, Mirus, & Napoli, 2019).
2. We adopt the common convention of calling the immobile hand "non-dominant" and the moving hand "dominant," which is to be thought of as distinct from the handedness of the signer (although in most cases they are the same).
3. We adopt the common convention of using small capitals to indicate signs.

4. Additionally, we gathered data from a hearing participant in a deaf family, who grew up using sign (a Child of Deaf Adults, CODA). If her data had been distinguishable from those of our deaf participants, we intended to run the survey with additional CODAs. However, they were not. We did not include her in our statistics, but had we plotted her in Figures 20-21, she would have been within the IQR in all four boxplots.

5. We do not include responses using Method Mix in our logistic regression analysis. Given the complexities raised by composite shapes (of which we have three in our study, the −HamC +Circuit shapes), we might have expected Method Mix to arise often with them. Instead, it never arose with CURVES_COMPO, it arose in 29% of clips of CRESCENT_COMPO, and it arose in 80% of clips of CIRC_SQ_COMPO. Furthermore, Method Mix was used at least once in pure drawing renderings of 27 of our 49 shapes (see the heat maps in Appendix S6). Method Mix is by far the least used (witness Figures 14 and 19) and we have been unable to relate it to any identifiable factor. We conclude that, in our study, Method Mix is not a coherent method; it is the garbage heap of drawing methods that were not uniformly Method One or Method Two. As such, it cannot shed light on the choice between drawing a shape with one hand versus two.

6. We put CANCEL in this group, since the movement mimics drawing an X, where it is the act of drawing itself that is iconic. That is, the sense is not the shape drawn but the act of drawing the shape.

7. With respect to compound signs, usually only one of the elements is relevant.

8. Others might, as well. Perhaps many. Remember, we looked at all entries of aslpro, but did only random samplings of other dictionaries.

9. We say "might" take double the effort because relevant factors could vary. Perhaps with regard to drawing shapes in the air, the duration of the movement is cut in half using two hands (since each is drawing half of the shape). Furthermore, moving two hands has the biomechanical advantage of reducing lift (the effort involved in moving against the resistance of gravity). For example, if we sign a rectangle with two moving hands, both hands move ipsilaterally, then down, then contralaterally—lift of the articulators is not called for. But if we sign a rectangle with only one moving hand, that hand will have to move upward for one edge of the shape, no matter which corner one might use as a starting point. Likewise, the number of times the articulator will have to change directions (where that may be a cognitive cost) is reduced by moving two hands rather than one, where consideration of signing a rectangle makes the point again.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article:

Appendix S1. SQUIGGLES and RAYS.
Appendix S2. Issues in coding particular stimuli.
Appendix S3. Instructions given to survey takers.
Appendix S4. Shapes by number of responses.
Appendix S5. Strategies other than pure drawing in the air.
Appendix S6. Heat maps.
Appendix S7. Variation.
Appendix S8. Disconnected signs.
Appendix S9. Signs with a handshape other than 1 or B.
Appendix S10. The biological foundation for sensitivity to Curve.
Appendix S11. The biological foundation for sensitivity to YSym.
Appendix S12. Gradient phonotactics in sign languages.