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# A human-editable Sign Language representation inspired by spontaneous productions... and a writing system?

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## Abstract

To equip SL with software properly, we need an input system to represent and manipulate signed contents in the same way that every day software allows to process written text. Refuting the claim that video is good enough a medium to serve the purpose, we propose to build a representation that is: editable, queryable, synthesisable and user-friendly—we define those terms upfront. The issue being functionally and conceptually linked to that of writing, we study existing writing systems, namely those in use for vocal languages, those designed and proposed for SLs, and more spontaneous ways in which SL users put their language in writing. Observing each paradigm in turn, we move on to propose a new approach to satisfy our goals of integration in software. We finally open the prospect of our proposition being used outside of this restricted scope, as a writing system in itself, and compare its properties to the other writing systems presented.

## 1 Motivation and goals

The main motivation here is to equip Sign Language (SL) with software and foster implementation as available tools for SL are paradoxically limited in such digital times. For example, translation assisting software would help respond to the high demand for accessible content and information. But equivalent text-to-text software relies on source and target written forms to work, whereas similar SL support seems impossible without major revision of the typical user interface.

Video integration seems natural for any kind of SL-related application, and many SL users make it a preferred storage format, including for personal notes. Some go as far as to say it serves enough not to need a written form altogether. The claim is that video provides an acceptable substitute for textual input, and that technology and its availability today compensates what might have been a

problem up to recently—virtually everybody now has a camera in their pocket at all times. But when producing a small mistake in a film take, correcting it requires repeating it entirely. One might pull up video editing software to cut and stitch pieces together if lucky enough that the mistake can be resolved in this way, but this requires more than language skills and leads to discontinuous signing (cuts, fade-in/out effects, etc.). For better use and integration in software, we are looking for a way of processing content comparable to word processors, in other words allowing to draft and organise discourse by editing pieces of their contents and to move them around. We call this an **editable** representation.

Also, when searching through video contents, finding data requires *both* scanning it and playing parts of it repeatedly, the search iterations being based on some memory of the contents. It is analogous to tape recordings when looking for, say, a forgotten rime in a song. It requires an alternation of winding the tape forward or backward, and listening from the new position on for at least enough time to make a decision on the direction of the next search iteration. The later replacing CDs partially reduced this problem as they used to (assuming that they are past technology) have direct access to song (“track”)—and more rarely sub-track “index”—beginnings. But nothing outside of the indexed entries could be found without falling back on some form of manual scan-play process.

Similarly, video indexing with time-tagged labels can help access key features of a video, but only tagged content can then be found. There is no possibility of arbitrarily precise data oversight allowing to target and focus any detail. Indexing contents therefore only partially solves the general search problem, and moreover requires to be built beforehand. We are looking for a representation with which data sets can be directly scanned and searched through, both to remove the need for separate indexing, and not to restrict searches to what has been indexed. We call this a **queryable** representation.

Besides, we have been modelling SL for about a decade, mostly pursuing the goal of Sign synthesis. Our progress led to AZee, which has produced increasingly promising results and is now being used to animate avatars [12, 11, 23]. We come back to it in a later section, but it is enough for now to say that it is a form of editable and queryable representation of SL. It also allows rendering anonymous SL animation, which is a significant advantage over users filming themselves if contents is to be made public. We call this a **synthesisable** representation, and would like to retain this property as much as possible.

However, AZee is a formal model, only readable if the system is learnt, and its abstraction layers understood. It is not readable in the sense that it would be shaped to match human intuition and recognition of patterns. Given the goal of implementation for human users of the language, we are aiming at a representation that is also **user/human-oriented**, facilitating content manipulation through software GUIs.

That said, we also take the three following statements to be true:

1. storing language content for one’s personal use or sharing it between people is one of the functions of writing (encoding), and implies reading (decod-

ing);

2. technology and software now have an essential role in manipulating and disseminating language content, if not indispensable, even for some social interactions today;
3. *if* there was a writing system used by the community of language users (shareable, inter-person readable, etc.), *then* they would rather have their language-related software implement it than be required to learn a bespoke system for a specific program use.

This naturally brings us close to the question of a writing system for SL. In this paper, we study writing systems in general, and the existing or possible parallels for SL.

We do though acknowledge that the purposes of a writing system encompass a lot more than use in software: note taking, thus ability to handwrite, institutional/legal archiving... We therefore wish to keep clear of any claim regarding what SL writing should be shaping into or how it should socially be developing, as much as to feed the scientific discussion on SL writing and digitalisation.

## 2 Writing systems

First, not all human languages have a standard written form known and put in practice by its users. Second, the languages that do (or did) are all vocal languages. No SL has such system, known and adopted, but some forms have been proposed. This section presents the scripts for vocal languages; we talk about those for signed languages in the following section.

### 2.1 Categories

It is common to distinguish language writing systems in two groups, depending on whether its basic symbols encode meaning, or things to pronounce. This section presents the useful dichotomy, and a gradient of sub-categories in existing scripts.

On the side of those encoding meaning, we find **ideographic** systems. Their symbols encode full/fixed meanings like that in fig. 1, whose interpretation is “do not smoke in this area”. But while they are drawn and interpretable in meaning once learnt, they do not determine a specific way to *read out* the captured meaning, and are indeed not the written form of any specific oral language.



Figure 1: “No smoking” pictogram

A language-specific writing system whose symbols are mapped to meaning is called **logographic**. Chinese is the best known example of such system: the

character “明” means “bright”, “雨” means “rain”. They *happen* to be pronounced<sup>1</sup> “míng” and “yǔ” respectively, but this is not conveyed by the symbols in a systematic way. The reader must know it to read them out.

On the opposite side, a **phonographic** system is made of symbols that encode what to pronounce. In this case, a combination of several is normally required before meaning can emerge. A good example is Spanish, where the Latin alphabet is used to encode the sequence of phonemes to be pronounced. For example “p” encodes the phoneme /p/, and the character string “pelo” the phonemic sequence /pelo/. It *happens* to mean “hair”, but it is not what is captured by the written symbols. The reader needs to know it to understand the sequence.

Zooming closer on this rather coarse dichotomy, we see a finer continuum in the level of linguistic abstraction applied. A logographic system composes linguistic elements on a level that we have seen is at least morphemic, e.g. equivalent to words like “rain”. Syllabaries have minimal phonographic units that stand for a full syllable weight in time (mora) each<sup>2</sup>. Abugidas also encode syllabic rhythm but each syllable character reveals the combined phonemes<sup>3</sup>. Alphabets encode sequences of phonemes with no syllabic marking. Full alphabets give equal status to vowels and consonants, e.g. most European languages, whereas abjads mark only the consonantal base on top of which vowel marking is mainly optional or partial (usually because imposed by the grammatical role or context), e.g. Arabic. Finally, some featural systems even reveal the phonetic (articulatory) features to combine to produce the sounds<sup>4</sup>.

## 2.2 Implications

In a purely phonographic system, one:

- must learn the mapping between sounds (or sound features) and written symbols;
- is able to read out (pronounce) any written input and write down anything heard without understanding;
- has to know more of the language to make sense of text;
- uses a relatively small number of symbols all together.

Spanish is an almost perfectly phonographic system in this sense. For example, once you have learnt the following bidirectional mappings: “m” is pronounced /m/, “a” /a/, “n” /n/ and “o” /o/, you can read “mano” to pronounce /mano/

<sup>1</sup>The Chinese phonological transcription system used here is Hanyu Pinyin.

<sup>2</sup>E.g. in hiragana: “か” = consonant–vowel combination /ka/; in katakana: “ミ” = /mi/.

<sup>3</sup>E.g. in the Devanagari script used to write Hindi: “कु” /ku/ = base glyph “क” /k(a)/ + the diacritic for vowel /u/.

<sup>4</sup>E.g. in the Korean Hangul script: “ㅋ” combines velar consonant /k/ (base glyph “ㄱ” = tongue against palate) + aspiration (–).

and write the former when hearing the latter. But the fact that the sequence means “hand” is still out of reach until you learn the language.

Note that in such system, nothing precludes ambiguities in the meaning of the text, as similar sounds can still bear multiple and distinct meanings, a phenomenon called *homophony*. For example in English<sup>5</sup>, the sequence “just” is composed of 4 ordered graphemes standing for the respective phonemes /dʒ/, /ʌ/, /s/ and /t/, together pronounced in sequence as /dʒʌst/ and meaning both “equitable” and “only/merely”. The same written–pronounced form is interpretable either way, and the ambiguity will remain as long as context allows.

In a purely logographic system, one observes symmetric properties:

- the direct mappings are between written symbols and their meaning;
- sense can be made of input text and concepts be written down without speaking the language;
- knowing the language is required to read text out loud or write down oral input;
- a large number of symbols constitute the script.

In the Chinese writing system, usually classified as logographic at first, “雨” is an example of a non ambiguous logographic character meaning “rain”. It is not necessary to know how to pronounce it to interpret it, and indeed dialects may not all agree on an identical pronunciation for it. But any capable reader will interpret it correctly.

## 2.3 Neither complete nor fully-exclusive systems

In general, no system in use possesses all properties of a given class, in writing and reading directions.

In English, many homophones have different spellings. For instance “night” and “knight” are both possible written forms of /naɪt/, a phenomenon called *heterography*. Conversely, different possible pronunciations are sometimes written with identical forms, e.g. the letter sequence “minute” in “this will take a minute of your time” (meaning: 60 seconds) vs. “only a minute fraction of the total will be lost” (meaning: very little), respectively pronounced /mɪnɪt/ and /mɪn.jʊt/. They are called *heteronyms*. In other primarily phonographic writing systems:

- French “a” vs. “à”, both pronounced /a/, mark the difference between a conjugated auxiliary verb and a preposition;
- Japanese “は”, normally standing for /ha/, is actually /wa/ when it is the topic marker (grammatical function for a particle);

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<sup>5</sup>This is a working example of homophony in English for the sake of reader’s understanding, but the properties of this section very poorly apply to written English, which on the whole is far from a purely phonographic system. We address this in the next section.

- German “du hast” vs. “du hasst”, both read /duhast/, are formed from inflections of the different verbs “haben” (to have) and “hassen” (to hate) respectively;
- etc.

In all examples above, it is the *meaning* or function that justifies a distinction in writing or pronunciation, which is not a natural property of the phonographic approach. Some languages are known to have a very high grapheme-to-phoneme and phoneme-to-grapheme correspondence like Finnish or Croatian, but this still often has to exclude things like loan words. Also, punctuation marks and number digits, part of the script as much as the letters, encode lots of meaning and very little or no pronunciation cues. What is more, these scripts consistently separate words with a space, which we argue is alone a highly functional (non-phonographic) feature of the script, as nothing allows to know where the spaces must go on a purely phonemic basis.

The system best classified as logographic, Chinese, also has comparable irregularities. For example, a character typically has several reading–meaning pairs. Also, it allows to write pronunciations, which enables transcription of foreign place names for example. On a lower level, characters are often themselves composed of pieces including a phonological clue. For example “瘋”, meaning “crazy, insane” and pronounced<sup>6</sup> “fēng”, combines the key “疒” (denoting illness) and the character “風” (pronounced “fēng”). The latter is a pronunciation hint (here identical to the target) for the whole character; its meaning (“wind”) is irrelevant. These are not natural features of a logographic system.

Japanese even famously mixes systems right from the start: it involves the two distinct syllabaries *hiragana* and *katakana*, plus *kanji* characters borrowed from the Chinese script. Used conventionally, hiragana marks grammatical particles and verb or adjective endings, katakana loan words and sometimes emphasis, kanji normally capturing the remaining lexical units. All three systems read out with the same set of syllables. The first two are phonographic and encode them directly with a one-to-one mapping; whereas kanji is as logographic as can be said about written Chinese.

So a mix seems always to be present. The two extreme categories, phonographic and logographic, are mostly fantasised, all systems instead showing features of both sides, in variable proportions.

Finally, it must also be noted that a lot is *not* written, and left to be compensated, even in the most featural phonographic system. Features like stress can be essential to pronunciation (i.e. mandatory articulations), but never written. This is true for English. Most short vowels in Arabic, though one could write them, are left for the reader to infer from semantic context, recognise from the written context (surrounding letters and spaces).

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<sup>6</sup>See footnote 1.

### 3 SL writing

As we stated in our introduction, some SL users question the need or benefit of a writing system for Sign Language. They sometimes argue that video captures the subtle articulations of the speaker, whereas any transcription would come with a decrease in precision. Sometimes, writing is even seen as an intrusive feature of vocal language culture, if not a threat. We have explained why video should not be considered sufficient for software processing, and reported that it is usual for a script not to convey every aspect of what must be read. For several reasons we therefore argue that it is simply wrong to equate cameras and pencils. A very good and articulate multi-fold discussion is provided by Grushkin on this topic [14], in the first half of his article.

#### 3.1 Designed systems

There have been various attempts to devise SL writing systems, from personal propositions with local use to others reaching enough popularity to see some discussion on their potential future as actual writing systems.

**SignWriting** [30] is by a significant margin the most visible one. It takes the form of a string of pictures, each representing a sign and encoding its basic *parameters* as attributed to Stokoe [28]. That is, a hand shape is written for each active hand, by means of a base symbol filled according to its orientation in space (facing forward, towards the signer, etc.). Hand location is given through relative positions of the symbols in the drawing, movement and contact are shown with arrows and other diacritics. Facial expression can be specified in a circle representing the head, as well as shoulder line. Figure 2a gives an example of a single sign involving one hand with an extended index configuration, a contact with the temple, a facial expression and a repeated manual rotation. An interesting feature of this system, also a voucher of its relative popularity, is that it has been subject to experiments in deaf classes in several places, in particular to assess how it could be learnt by early language users. It is also the only one to have been granted a Unicode block.

Other systems have been proposed more or less following the same underlying principles, e.g. **Si5s** and its **ASLwrite** fork (fig. 2b), which have been subject to strong promotional efforts. We have also encountered a system developed by a teacher at INJS<sup>7</sup>, a Parisian institution for deaf education in Sign Language. She wished to give students a way to write signs even if they did not know (or have) a written French equivalent. She called it “**signographie**” (fig. 2c). It is interesting to mention because it is also taught and used in class by both teachers and students to support educational communication, though in a different fashion to the SignWriting experiments. We will be referring to this again in the next section.

The choice and style of the graphics differ in the systems listed above, which is relevant when implementing some of the functions of writing. For example,

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<sup>7</sup>*Institut National des Jeunes Sourds* = National Institute for Deaf Youth.



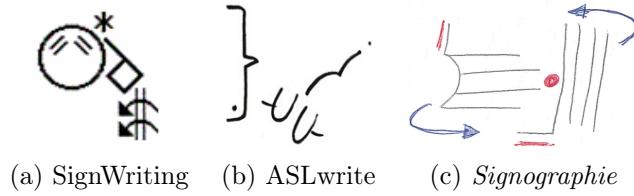


Figure 2: SignWriting and similar systems

standard SignWriting requires colouring zones to show hand orientations, which can be uneasy with a pencil. But they all otherwise share the same features, capabilities and composition rules. So in terms of system features and classification, there is no essential difference between them.

Alternatively, and actually before SignWriting was born, a more linear approach had been used, which still has representatives. **Bébian** [4], **Stokoe** [28] and **Friedman** [13] all separated the manual parameters and linearised them in script, resulting in character sequences, each looking more like words made of letters and covering what would form a single picture in a system of the previous group. With the advent of technology, computers and data processing, more scripts came out falling in this same category of linearised scripts, given how easier it was to design fonts, rely on common input devices like keyboards and display TrueType sequences in word processors. Various such scripts have been proposed since (see figure 3), intended with more or less international coverage: the generic **HamNoSys**<sup>8</sup> [25, 16], **SignFont** [21] and its follow-up **ASL-phabet** [29] for ASL<sup>9</sup>, **ELIS** [2] and **SEL** [18] for LIBRAS<sup>10</sup>.

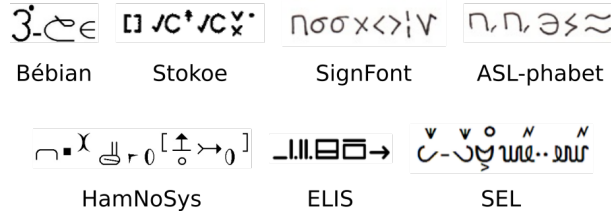


Figure 3: Linearised SL writing systems

HamNoSys is certainly the most popular fontified script for SL. It has been used as the main means of representing signs in academic papers by several scholars, even doing away with drawings or pictures at times. More impressively yet, it was implemented, through its XML adaptation SiGML, as the primary input format to an avatar animation software after the turn of the millennium [5, 6]. This is a unique property that was never successfully reached by any other, and which is relevant to one of our goals here (synthesisable).

<sup>8</sup>Hamburg notation system.

<sup>9</sup>American Sign Language.

<sup>10</sup>*Língua brasileira de sinais* = Brazilian Sign Language.

## Observations

All of the systems mentioned above encode minimal forms to articulate and combine, though the granularity of the minimal forms are variable. They show features such as hand shapes (coarse grain), finger bending (finer grain), hand locations, mouth gestures, and may include more abstract features like symmetry or repetition instead of duplicated symbols. In every case it is a description of what must be articulated, i.e. *form* features. None of them write anything directly mapped to meaning without an indication of the form. To learn the system is to learn to articulate the symbols, and it is then possible to do so without understanding what is read. In this sense they are all phonographic systems.

Also, they all assume a segmentation on the same level as the one that linguists use to *gloss* signed input. It is the level usually called “lexical”, i.e. of dictionary entries (“signs”) and other non-lexicalised productions such as classifier placements or movements. The latter use the signing space in a way that is more semantically relevant, but they are nonetheless written following the same composition rules in the scripts. In every system, these units are stringed one after the other in a linear sequence, as illustrated in fig. 4.

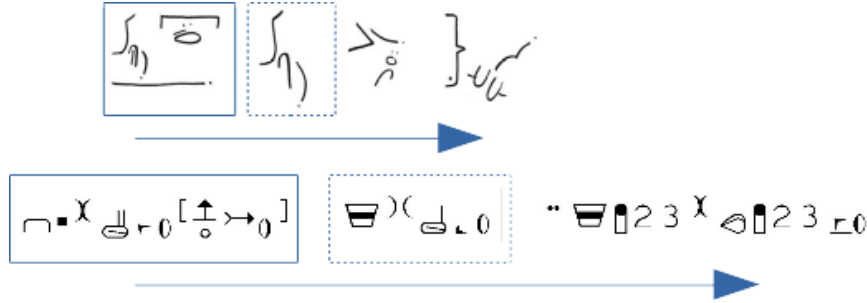


Figure 4: Unit sequences in ASLwrite (top) and HamNoSys (bottom)

We point out that no explicit justification is put forward for these design features. They seem consistently taken as self-evident starting points, but we submit that they can be questioned. For example in the light of the wide panel of other known written scripts: why not a single logographic property? Most of the scholarly work we found discussing SL writing systems either take a phonographic goal for granted without even mentioning the distinction [20, 17], or do talk about the duality only to evacuate logography and favour phonography with no compelling reason to do so [19, 15].

It is probable that this is largely due to a double cultural influence. Firstly, the systems above originate from Western cultures with dominant Indo-European languages all written via phonemic systems juxtaposing whitespace-separated lexical units in linear text. Secondly, the dominant SL theories in the last five decades have been inspired by parametric description of signs in Stokoe’s sense, which is rooted in phonology, phoneme inventories and minimal pairs. Every

system presented so far assumes such parametric composition, and chooses to represent it in some way. However, without implying that things should be different in all respects, we argue that they could in many, while thorough exploration of the alternate paths has not taken place.

Grushkin [14] is one of the rare authors we found to present Chinese logography seriously and discuss some of its benefits. He even reports on findings telling that deaf Chinese readers have less difficulty reading logographs than the English do strings of alphabetical letters [31], which is a door wide open on logography for SL writing. Yet somehow he too ends up closing it, advocating what he calls an “alphabetical” (in our terms here, phonographic) paradigm<sup>11</sup>, ultimately to facilitate literacy in English. After such an admirable plea to equip SL with writing and so eloquently explaining the need to empower SL and the Deaf culture with an autonomous system, rejecting glossing and rebutting what he labelled “objection 3” (the fear that it would put deaf people off reading and writing English), we find this last call rather surprising.

At least two major differences with the dominant scripts stand out though, which we analyse as coming more or less directly from the difference in the physical channel, because they have to do with simultaneity and iconicity. The first one comes from the fact that *within* a lexical sign, phonemic composition is simultaneous and not reducible to a sequence, like “just” is the concatenation of /dʒ/+/ʌ/+/s/+/t/. This has forced to choose between two strategies, each breaking something of the alphabetical idea of continuous phonemic sequence. The symbols to be articulated simultaneously are either:

- packed in a planar arrangement to form one complex unit, as shown boxed in the top line of figure 4—the equivalence between the sequence of symbols and that of the production is retained, but the units of the sequence are no more each a minimal phonographic unit;
- or linearised, and some form of spacing takes place to separate the flattened units (bottom line in the figure)—the sequence of symbols is then to be segmented on two different levels, one of which is no more an account of the production sequence.

Incidentally and likely for the same cultural reasons as above, scripts generally follow the left-to-right writing direction (arrows in fig. 4). An exception is SignWriting, which now prefers a vertical top-down direction.

The second major difference with common writing systems is about the symbols themselves. Most of the systems (and all the major ones) have embedded some iconicity in the graphics, i.e. a resemblance between the symbols and the way to articulate them. For example, the flat hand shape with spread fingers is

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<sup>11</sup>As we understand Grushkin’s final position in the paper, his support of an “alphabetical” system is in fact one that both favours phonography over logography and wishes to minimise iconicity in the script. Indeed he opposes the term “alphabetical” to “iconographic”, which he uses to mean “whose phonemic symbols are iconic”. We come back to this property of iconic symbols further down.

drawn 𐄎 in HamNoSys, 𐄏 in SignWriting, 𐄐 in ASLwrite... They are iconic of the form to produce, involving five countable fingers.

From what we can tell, most writing systems of vocal languages have actually started this way. Some Chinese logographic characters are even still reminiscent of that fact, e.g. 雨 (rain). But they have gradually been abstracted, simplified and conventionalised over time, often giving rise to new or altered meanings, and it is fair to say that writing systems today are not iconic. Whether it is natural for a system to lose iconicity over time, and whether or not there is a different case to be made for Sign Language, we at least call out this difference for now as the notion always has special relevance in Sign Language studies.

## 3.2 Spontaneous productions

All the scripts presented in the previous section were designed *systems*, i.e. sets of rules intended to be complete (covering everything deemed necessary) and consistent (identical events captured with identical representations). Aside from those developments, in the few years leading to our present questions, we encountered other uses of pen and paper aimed at SL representation without relying entirely on dominant (“foreign”) language support.

First, many SL users taking notes of signed input or preparing signed speeches resort to graphics to represent the original or intended signed production. Whether to capture a sign, path, movement, space location or meaningful relationship between elements of the discourse, graphical schemes found sufficient to express the production are for these users naturally preferred as the added cognitive search for words or phrases in a second language becomes unnecessary.

A second example is in teaching deaf students in signing environments. Teachers and deaf education experts encourage the use of visual material for deaf education, even if SL is not the only language used in the programme. At INJS, we met teachers who have pushed this idea further than, say, explanatory diagrams to teach new concepts. According to them, students should be able to turn in work in a written form, the official written language is a foreign one, and Sign Language is best captured with drawings. So in addition to *signographie* (see §3.1), they allow the students to draw SL the way they feel it should, provided they understand the signing that motivated the drawing. The school has kindly agreed to share a few of those productions with us. Figure 5 shows one of the pages of a piece of homework.

The third use case is that of text-to-Sign translation. Professionals are taught to draw “deverbalising diagrams” as a first step from input texts to capture all of what must be delivered in SL (the meaning) while enabling to work without the texts (the source form) afterwards, so as to produce a semantically equivalent discourse in SL (the target form) in a way that is detached from the original foreign input. We have begun to work with LSF<sup>12</sup> professionals on possible software assistance to this deverbalising task. Both figures 6 and 7 are examples of diagrams produced in translation tasks.

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<sup>12</sup>*Langue des signes française* = French Sign Language.

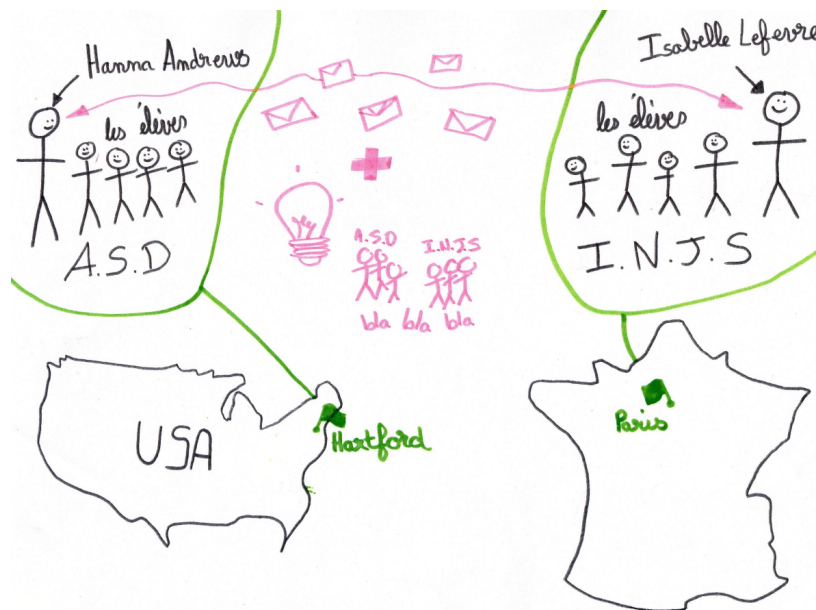


Figure 5: Diagram produced by an INJS pupil

All of these diagrams lie somewhere on a continuum, already observed by Athané [1], between:

- semantic representations, which capture meaning regardless of any language in which it could be expressed;
- and what we shall call *verbalising diagrams* (VD) henceforth, i.e. drawings laid out in such way that they can be followed directly to produce well-formed SL discourse.

Figure 6 is primarily an example of the first kind. It looks more like an explanatory diagram than inspired by SL particularly. In the case of translation, such a representation will come from a pure deverbaling effort, and will often be annotated in a second step with numbers to order pieces in a Sign-logical way for SL production, though this step is not always easy. Figure 7 is closer to the second end of the continuum, as it produces its own SL-inspired information sequence (the number annotations only confirm the natural flow of its contents), and every piece seems to mirror the way to express its meaning in SL. Given our interest in writing SL specifically, this article will preferably work with the second kind (VD).

Unfortunately, these are all local or personal productions, usually intended for short-term use and discarded afterwards. No archive or data compilation exists of such diagrams whereas, after looking at the few shared with us, we came to observe much more expressiveness and regularities than what even their own

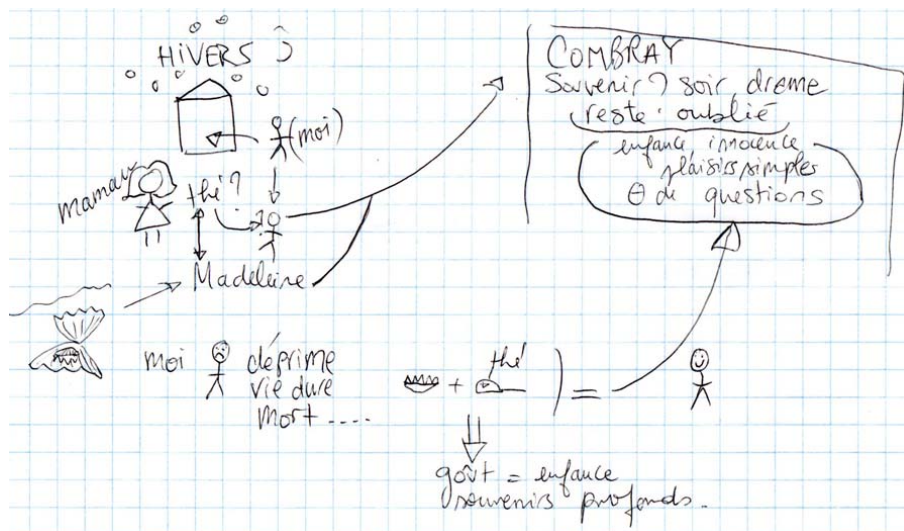


Figure 6: Semantic diagram, hardly SL-specific

authors seemed willing to grant them. We therefore believe science ought to take a better look at them. To this effect, we have begun building a corpus of such diagrams, aligned with their signed equivalents, whose elicitation protocol is described in detail elsewhere [7]. In summary, it involves various linguistic profiles (e.g. nativeness) and uses (e.g. translation, note taking, authoring), elicitation material (e.g. text, video) and genres (e.g. story, definition), etc. It enforces some time (in weeks) between the production of the diagrams and that of the signing so that short-term memory is not relied on. We are still harvesting data—and hope to be for while—but the amount collected so far already provides examples of recurrent observations, which we wish to expose.

## Observations

In this type of graphical representation, meaning plays a major part in what is written, and on first look a lot more so than articulated SL forms. Let us first look at the *atomic* level in more detail, i.e. the smallest, non-breakable symbols populating the diagrams.

What we observe is: all participants drew dogs to mean the pet animal; none drew what body articulators should do to sign “dog”. The same applies for most icons on the collected pages. Without knowing the language, one can be told—or in this case even guess—what these symbols mean and understand them regardless of how to sign them, and nothing from those symbols tells how to sign them for sure.

In this sense they make diagrams lean towards the logographic category of scripts, should they be recognised as such. Although, on this same atomic level, examples of graphical units representing the signed form (and not only its

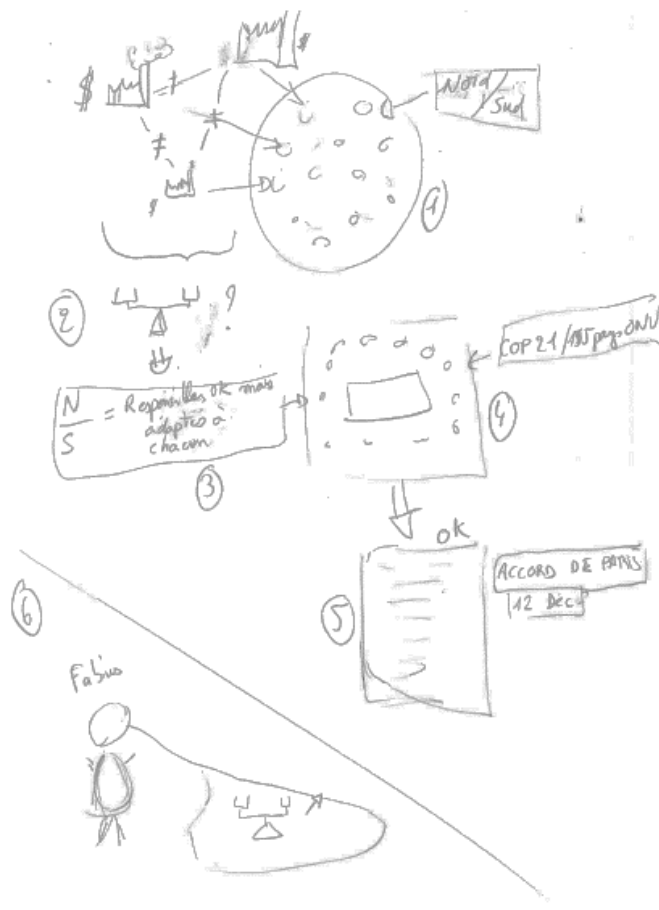


Figure 7: Verbalising diagram, laid out to fit the target SL discourse structure

meaning) are found in three circumstances:

1. illustrative/depicting units, e.g. fig. 8a, which represents a jaw drop meaning astonishment and to be reproduced as a form (a kind of short role shift), or fig. 8b, which represents the path followed by a mouse underground and whose geometry (wiggling forward then popping out straight up) must be redrawn in the signing space;
2. high salience of form over ease of representation ratio, e.g. fig. 8c representing the sign for the notion “the most important, dominant”, which involves a movement of hand shape “thumb-up” (LSF “1”) reaching the top of the other “flat hand”—it is clearly a drawing of the form to articulate, easier to capture in a drawing than the rather abstract notion it conveys;
3. the special case where authors knew a phonographic system, and that it

was shared with the potential/intended reader, like in the INJS environment where the teacher’s *signographie* was proposed to the students for use in their diagrams—for example fig. 8d, encoding the LSF sign for “result” in that system, was found used as a section title.

It is yet to note that all forms in case (1) and many of case (2) are iconic, hence represent their own meaning in some way, which undermines the proposition of an exclusively phonographic status for these units. Also, out of the 29 A4-sized pages full of drawings satisfying the premisses of case (3), we only count 11 instances of *signographie*, which tells us that even in the case of an available phonographic system, the preference for meaning is not overturned.

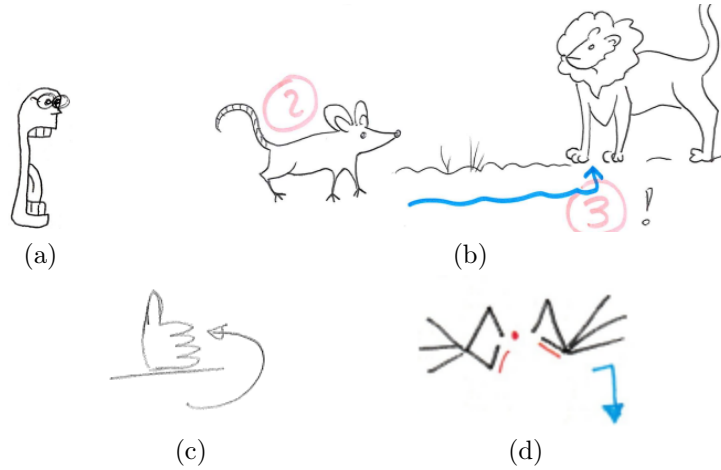


Figure 8: VD symbols representing form over meaning

We therefore observe that for atomic graphical elements there is spontaneous preference of users for encoding meaning, though articulated forms are not avoided at all costs<sup>13</sup>. This is a significant difference with the current offer in designed systems, whose atomic level always exclusively encodes forms.

There is yet a different, non-graphical type of atomic unit observed in the diagrams, namely written words or phrases borrowed from outside languages. The evident most frequent choice being a surrounding spoken/written language. Figure 9 gives an example featuring the French word “aide”, meaning “help”.

They appear in quite variable proportions, from zero occurrences on a full page to leaving only little graphical contents. This leads to consider a new continuum between “purely word-less” VDs and “fully written” productions. Contemplating autonomous scripts for SL, we wish to discard the latter (wordy, verbose) end of this continuum, like we discarded non-SL semantic graphs. On

<sup>13</sup>Admittedly, results would be different for borderline cases like writing poetry, since it is mostly a play on form. The small amount we have seen of written SL poetry does indeed encode articulated forms in a more significant proportion (focus on hand configurations, movement paths and rhythms, etc.)—see page 64 in [3] for an example.





Figure 9: Written word in VD. Directional binary relationship.

the other hand, the purist position would dismiss any written word as an unnecessary foreign intrusion. But very few of the collected VDs conform to this, most productions containing written atoms of some kind.

Figure 10 gives an account of the number of written atoms found per collected diagram, considering each page separately when a production comprises more than one. As a conservative limit to VD word verbosity, we excluded diagrams containing more than twice as many written atoms as others, resulting in a total of 86 pages considered, and 17 discarded. In the diagrams, lines and arrows were counted as graphical, and proper nouns (like the town name “Hartford” spelt in fig. 5) ignored from the count.

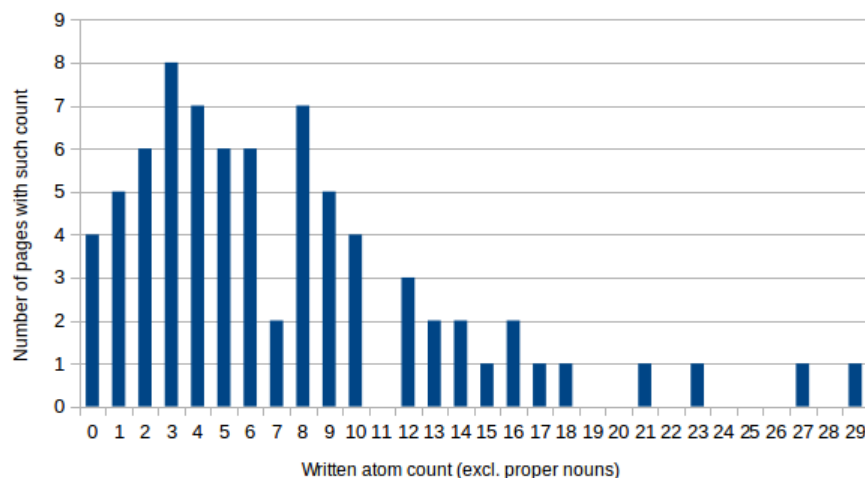


Figure 10: Frequency chart for the number of written atoms on VD pages

While the distribution does seem to favour limited use of words in VD, it does not exhibit their total absence as typical. This is to some extent explained by the frequent bilingual culture of the speakers and the dominant status of the language borrowed from. Further investigation on the reasons for those written atoms would eventually be welcome, for example by testing the correlation with drawing skills, deafness, or literacy in the invoked script—although interestingly, such conjectures do not seem to hold well in this first set. In any case, as far

as our form–meaning focus is concerned, such written units cannot be regarded as direct representations of the form. Invariably of course, the written word or phrase is chosen by virtue of it carrying the same meaning as the intended Sign production.

Outside of the atomic level, meaning also plays a strong role in the diagrams. Relationships with various arities<sup>14</sup> are shown by linking the participating diagram entities with relative positions, lines and arrows of different styles, sometimes tagged. They represent semantic relations, often in a way similar to semantic graphs [27]. Figure 9 is an example of a directional relation between two people, one helping the other, represented by a tagged arrow between them. It does not inform on how to sign a corresponding utterance, rather it clearly represents the semantic relationship between the two.

Thus it is tempting to extend the hypothesis of *inclination to meaning* to the whole process of diagram drawing. But a lot in the end has to do with form too, again for reasons rooted in iconicity. A high proportion of the diagrams’ layout choices not only serve legibility purposes or the needs of a 2d projection on the paper. They also perfectly reflect the spatial arrangements observable in the original signed discourse if any, and in the later productions when the diagram is “read”.

For example, figure 5 on page 12 was a student’s diagram representing a discourse signed by the INJS teacher who gave the assignment, about exchange trips between two schools including theirs. Figure 11 shows three relevant moments of the original video, in order of appearance: (a) anchoring the ASD institution<sup>15</sup>, class and teacher on her left; (b) anchoring the French counterpart on her right; (c) explaining that letters were sent both ways between the two schools, in the centre. It is clear that the student captured the exact same layout in the diagram. Similarly, the full page given in figure 12 identifies Alice Cogswell (though misspelt) as the 3rd child of a family of 4, who became deaf after an illness. A reader with just enough SL will easily see how this directly maps from the frontal vertical plane of the signing space, with the scene developing from top (parents) to bottom (the focused child).

The distinction between meaning and form as target of the representation is therefore often difficult to make, and we would argue even nonsensical in many cases. By definition, iconicity confounds the two. Thus when it is involved, form is likely identifiable as meaning, and representing one likely represents the other too.

Meanwhile, whether they capture form, meaning or both, the symbols used are overwhelmingly iconic, i.e. bear resemblance with what they represent. In this case there is a clear convergence of almost all approaches mentioned up to here: they favour iconic symbols in the script. We consider this an interesting finding: all SL major scripts, including the designed and the spontaneous ones,

<sup>14</sup>The arity of a relationship or operator is the number of arguments it expects. Binary operators have an arity of 2, ternary ones of 3, etc.

<sup>15</sup>American School for the Deaf.

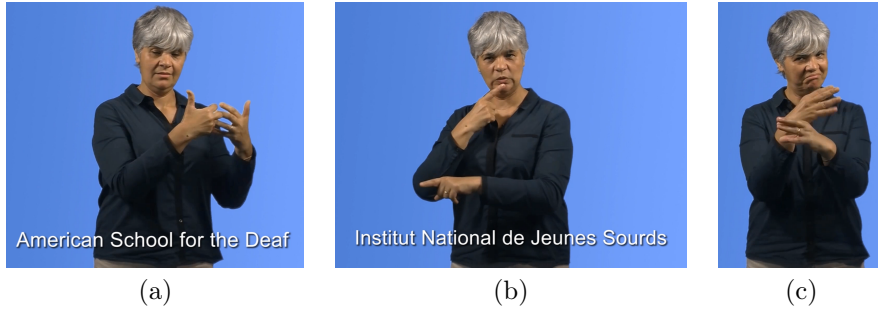


Figure 11: Snapshots of the SL source of fig. 5

use iconic symbols whereas none can be categorised as such in vocal language scripts.

Contrarily to the scripts presented earlier though, there is no systematic level of reading where a sequence is to be segmented in ordered units. Although parts of them happen to be ordered in some places, the diagrams are essentially two-dimensional. Consequently, it is difficult to raise the question of a direction of reading, or at least to produce any conjecture at this point.

## 4 Linking to a formal description

After observing a first set of verbalising diagrams produced by multiple people, and multiple diagrams for each person, we found recurrent graphical strategies to capture language components. And something struck us even more yet: the ease with which those systematic mappings between graphical forms and meaning could be expressed in AZee. This section explores these new waters a little deeper.

### 4.1 AZee

AZee is a framework to represent SL in a way that is both linguistically relevant and formal, in other words unambiguously interpretable by both humans, e.g. for linguistic accounts of phenomena, and computers, e.g. for synthesis. We have published about it enough to avoid too long a diversion here [10, 9, 12], but this section summarises the key elements and properties of the model, on which we build our next proposition.

AZee is an umbrella term for:

- the general approach to SL description, summarised below, based on *production rules* and free synchronisation of the whole body articulator set;
- a programming language to formalise those rules;

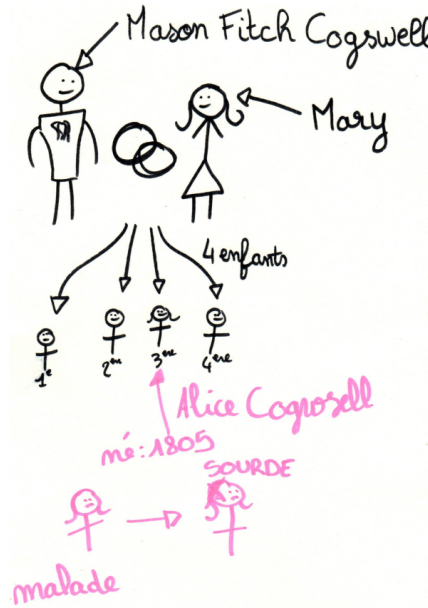


Figure 12: Diagram layout entirely reproduced in signing space

- the software tool able to compile correctly formed input and generate *sign scores*, then usable by external software to synthesise and render animations.

The entire approach is built around the duality between observable form and semantic function, and aimed at bridging them together. To do so for a given SL, *production rules* are formalised, each associating necessary forms to an identified semantic function. For example in LSF, the semantic function “dog” is associated the form shown in fig. 13a. This association allows to define a production rule which when applied generates a *signing score* specifying the gestures/movements (forms) to articulate to mean “dog”. Notably, all of this is done with no level distinction such as morphology vs. lexicon. The fact that the result of “dog” is often categorised as a lexical production is irrelevant as far as the model is concerned.

A rule can be parametrised if parts of its form depend on an interpretable piece of context. The meaning “surgical cut, scar between points  $P_1$  and  $P_2$  on the body” is associated a form which includes a movement between  $P_1$  and  $P_2$ . Fig. 13b gives an example with both points on the abdomen. The rule is parametrised with the two point arguments accordingly, and specifies a resulting score whose description depends on those arguments. Later applying the rule to two (meaningful and only given in context) points of the body will automatically generate the appropriate form, in accordance with those points.

Parameters can be of any type defined by AZee (geometric vector, numerical, left/right body side...). In particular, rules can be parametrised with signing

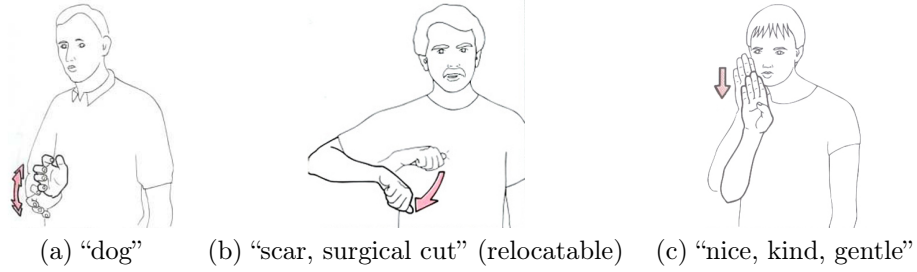


Figure 13: LSF sign dictionary pictures [22]

score arguments to allow recursive use of production rule applications as arguments for others. For example, the semantic function “it is generally agreed that  $X$ ” produces a signing score whose specification is a mouth gesture (lip pout) synchronised with  $X$  with a time offset (see fig. 14). We have elsewhere called this function “non-subjectivity” [12].

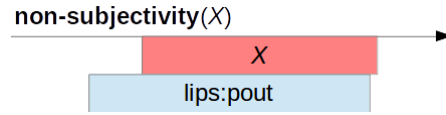
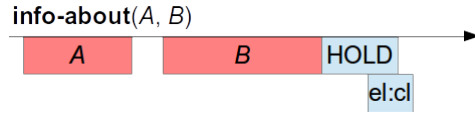


Figure 14: Signing score produced by the AZee expression “non-subjectivity( $X$ )”

This all together allows to generate functional expressions, which when evaluated produce complex utterances nesting scores in one another. For example, let us take the two more production rules below:

- “nice-kind”, whose name is self-explanatory and which produces the form shown in fig. 13c when applied;
- “info-about( $A$ ,  $B$ )”, which means “ $B$  is the (focused) information about  $A$ ” and produces the score in fig. 15.



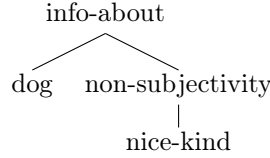
$A$  and  $B$  must be provided as parameters  
“el:cl” encodes an eye blink

Figure 15: Signing score produced by the AZee expression “info-about( $A$ ,  $B$ )”

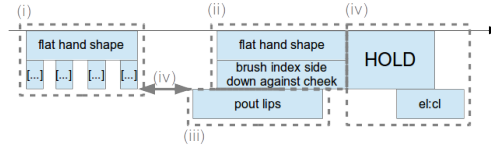
Combining 4 of the rules presented above, expression (E1) below recursively evaluates to the signing score given in fig. 16:

**E1** info-about(dog(), non-subjectivity(nice-kind()))

For legibility, AZee expressions are often represented as trees where child nodes are the nested expressions used as arguments of the parent in the right order. For (E1):



It was observed that recursively combined rules produce scores that can be interpreted as a whole as the combination of their respective interpretations. For example, the reader might already have interpreted (E1) as meaning “dogs are [generally thought to be] nice”, which is what one interprets from the production scored in fig. 16 (to the extent that such constructed examples allow out of context). Therefore while AZee trees look like syntactic trees, they are rather comparable to semantic representations because unlike syntactic trees, every rule node carries meaning (or would not exist at all), and they form interpretable utterances on the whole.



- (i) contains the form represented in fig. 13a
- (ii) contains the form represented in fig. 13c
- (iii) is the lip pout generated by “non-subjectivity”, as per fig. 14
- (iv) eye blink, hold and coarticulation time generated by “info-about”, as per fig. 15

Figure 16: Signing score resulting from (E1)

## 4.2 Bridging VD to AZee

The quest for AZee production rules in LSF has now been going on for a few years. And with no claim of it being complete yet, our current set usually allows to almost cover monologues of the informative type such as news reports. This makes us consider the approach as worth pursuing and the state of the rule set, if not definite, solid enough to entrust.

Now as we hinted while introducing the section, patterns in the collected diagrams were found, which could easily be expressed with identified AZee rules. Let us list a few. We do not give counts or statistics as they will not be meaningful at this stage, but we do give a few of the clear qualitative tendencies. We have already mentioned trivial examples while discussing the tendency for logography on what we called the atomic level. For example, the drawing of a dog corresponds to the rule “dog”. But other patterns arise on higher levels.

An example of a repeated pattern is the use of *context bars*: a piece of the drawing  $C$  (which can itself combine multiple pieces) is “followed” by<sup>16</sup> a straight line separating it from a second piece  $F$ . The already shown fig. 7 contains an example of this feature. The overall interpretation is that information  $F$  is focused, but given in the context of  $C$ . In the SL equivalent (source or result), the portion corresponding to  $C$  is always signed first, and followed by  $F$ .

We often make the same interpretation of the following *colour change* pattern: a scene  $C$  is drawn, on top of which a piece of drawing  $F$  is superimposed in a different colour, with  $F$  being signed after  $C$  in the SL production. Fig. 8b is an example of such colour change. The two animal entities set up a context scene (initial positions) in which the blue arrow (movement of the mouse) is the focused event. Fig. 5 exhibits the same pattern on a larger scale: the exchange of letters drawn in red is the focused information, and occurs between two sides set up as context by the rest of the drawing. And the same goes for fig. 12, where the deaf child is focused in the context of her family. Of course this is limited to cases where colour was available; some informants have indeed chosen to use a single colour. Also, we found other uses of colour change, but focusing/highlighting a piece  $F$  in a contextualising scene  $C$  is a frequent one. The noteworthy thing here is that both colour highlighting and context bars have a direct mapping to the one-rule AZee expression “context( $C$ ,  $F$ )”, which means “ $F$  in context  $C$ ”.

Another repeated pattern is when two pieces  $A$  and  $B$  are drawn side by side with more or less similar sizes and an equal sign (“=”) in between, as shown in fig. 17. These instances match the AZee expression “info-about( $A$ ,  $B$ )”, already introduced above. A graphical pattern using *bullet lists* (e.g. fig. 18) also emerged for exhaustive (closed) enumerations of simultaneously true/applicable items, with equal focus on each of them, which has its AZee rule “each-of”...

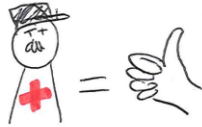


Figure 17: Equal sign in a VD for function “info-about” (in context: “Fidel Castro is well”)

Such regularities keep surfacing in the diagrams. We must investigate them further and try our observations statistically on the full corpus to come. It will exceed 300 drawings, and keep growing as more informants might still wish to contribute afterwards. But to summarise, at this point we make the two following observations:

<sup>16</sup>This locally assumes a direction of reading in the diagrams. In all cases observed, this was top-down and left-to-right, which corresponds to the culture of the informants’ environment (France).

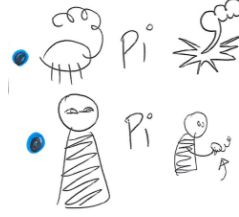


Figure 18: Bullet list in a VD for function “each-of” (in context: “it is the scorpion’s nature to sting, and it is mine to save it”)

- spontaneous verbalising diagrams and AZee trees are both in essence close to semantic representations shaped for production in the target SL;
- they share common structuring and composition elements to represent the meaning.

This apparent proximity made us want to explore the possibility of a bridge between the two types of representation. Let us first acknowledge an interesting symmetry between them.

First, even in the form of trees, AZee expressions are of a mathematical, formal nature, in other words friendly only to those familiar with the model, not human-oriented drawings easy to draw and decipher. On the contrary, VDs are graphical objects spontaneously used by many who wish to put SL in some form of writing. Thus they can only be viewed as accessible to humans, and considering our goal, as a way to ease the interface between users and software.

Conversely, VDs do not provide full access to the forms to produce to read them. Whereas, unlike formal semantic representations like conceptual dependency [26], semantic graphs [27] or more theoretical concepts like “interlingua” which are intended to be detached from any specific language, every AZee expression produces definite forms. That is to say that given any representation in AZee, a computer program can automatically generate the corresponding sign score. In the terms defined in our introduction, it is synthesisable, which is a desired property for our editable form.

This property comes from the fact that when building an AZee rule set, any abstraction of observed signed forms behind semantically relevant rules is done by embedding a link to the factorised forms inside the abstracted rule. So the forms are hidden in subsequent expressions invoking the rule, but retrievable to produce a result. We have elsewhere called this building “from the target and back” [8].

Looking to translate forward from VD to AZee would currently be an ill-defined task as we have seen that VD is still entirely non-standard. Instead, we propose to follow the idea above and build a graphical tool kit *back from* AZee, in other words to define graphics, icons, symbol layouts, etc. for AZee rules and structures we already know exist for sure. Then like no AZee rule exists without an associated form description, no graphics will be made available without an



associated AZee equivalent—which itself comes with forms to produce. So the Ariadne’s thread leading to the ultimate forms will always be preserved.

### 4.3 A new type of editable SL representation

The simplest plan to start building back from AZee without losing coverage is to assign a graphical form to every possible node of an AZee tree. Such node is of either kind below:

- a *rule node*, referring to a named production rule—this is the most expected case, and indeed that of all nodes in example (E1);
- a *native node*, containing an AZee expression combining native objects to build a specific value (numerical, geometric point or vector in space, on the body...)—for example, arguments of a parent rule node “scar, surgical cut” would likely specify body points directly, without applying a named rule.

We will mostly base our narrative on the first kind henceforth, though of course both should be addressed. On top of this, here are two additional recommendations we wish to follow:

- the first tentative graphics for an AZee target should be close to any spontaneous regularity already observed in the diagrams, as it should maximise intuitive reading and minimise the difference with VD;
- for atomic symbols or icons, prefer Unicode characters, as their code points are secured across future fonts and systems, and many are available, all the more so as emojis are entering the standard set.

For example, the rule “dog” can be assigned the atomic symbol in figure 19a, and “nice-kind” the one in fig. 19b. They are both standard characters, with respective code points U+1F415 and U+1F493. Furthermore, rule “non-subjectivity” can be graphically represented with the addition of, say, a tick mark (U+2713) over its argument  $X$  as shown in fig. 19c, and template “info-about( $A, B$ )” with the arrangement in fig. 19d, observed in our data. Accounting for the recursive nature of AZee expressions, diagrams for  $X$ ,  $A$  and  $B$  can themselves be diagrams of complex expressions, which creates the possibility of recursive diagrams. Combining these graphical operations, expression (E1) would then be encoded as shown in figure 20.

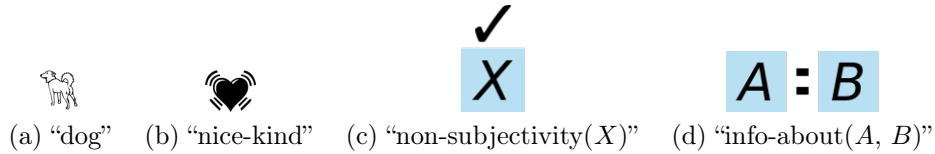
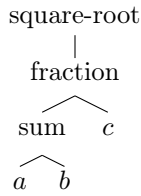


Figure 19: Building a graphical script back from AZee

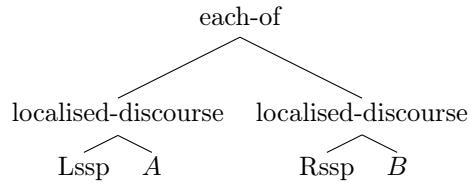


Figure 20: Proposed script for (E1)

This is very similar to the way arithmetic expressions are written in the standard math script, as their elements are operators and atomic elements nested in one another to form one recursive structure. That is, figure 20 is to expression (E1) as the written expression  $\sqrt{\frac{a+b}{c}}$  is to the following recursive structure, representing operator and argument nesting levels:



More graphics can later be defined for larger AZee templates, i.e. AZee sub-trees of more than a single node, for constructions that are frequent and semantically salient enough in spontaneous productions. For example, figures 11a and 11b anchor a discourse *A* on the left-hand side (*A* is signed with hands and shoulder line turned to the left), then another *B* on the right. This is a frequent form for comparison or opposition of some sort between *A* and *B*, for which a possible AZee tree is<sup>17</sup>:



This template could be abstracted as a whole into a binary graphic operator to further abstract the combination into something that directly makes sense to the users like “opposition of *A* and *B*”. For example, we could represent it as shown in figure 21.



Figure 21: Left-right comparison/opposition between *A* and *B*

<sup>17</sup>“Lssp” and “Rssp” are native AZee points in signing space in front of the signer, to the left and right of the centre respectively.

Following the same principle, we can provide more and more useful abstractions of AZee templates into compact graphical representations. At any rate, we see how this develops into a planar (2d) representation with a recursive structure, equivalent in content to an AZee expression but more helpful in appearance to human apprehension.

This completes the list of properties initially expressed as our goals for use in software. Namely, our proposition is:

- editable, as pieces can be copy-pasted and edited like formulae in many math editors;
- queryable, as the input structure can be parsed by a computer and its contents searched;
- human-readable, because it is graphical, and the graphics chosen to be iconic and resemble what humans already produce spontaneously;
- synthesisable, as they are equivalent to synthesisable AZee expressions, as explained in §4.2.

The prospect opened here is that of SL editing software that allows for saving, modifying and sharing anonymous content, enables quick search functionalities like the now ubiquitous “Ctrl+F” shortcut in applications, and is linkable to signing avatars for regular (oral) SL rendering.

## 5 Prospect for writing SL

As we said right at the beginning, we expect users of a Sign Language to want software input to match their own written practice if they have one some day. Thus we now want to consider our above proposition outside of its intended scope of software integration, and characterise its properties in the midst of the scripts mentioned so far.

For a better grasp of what such proposition would turn out like, we have written the full AZee expression (tree) for a signed version of the short story *La bise et le soleil*<sup>18</sup>, and encoded each node with a symbol as proposed, with only a few approximations or assumptions when AZee coverage was still limited (unexplored language phenomena). Figure 22 shows the result for the ten pieces of the overall 80-second performance.

The actual look of the writing shown here here is outside of our present consideration. The symbols and line styles put out are all only tentative, if not mere dummies to instantiate our proposition as it can develop. We even leave out explaining the encoded expression, since our interest at this point is only to characterise the type of script we are dealing with, and some of its properties.

The first question of logography vs. phonography proves tricky if we state the fact that for all rule nodes, the assigned glyph refers to a form–meaning

<sup>18</sup>In English: “The Bise [North/cold wind] and the Sun”. The version used here is viewable at <https://atlas.limsi.fr/?tab=LNT> (click on the “LSF” entry).

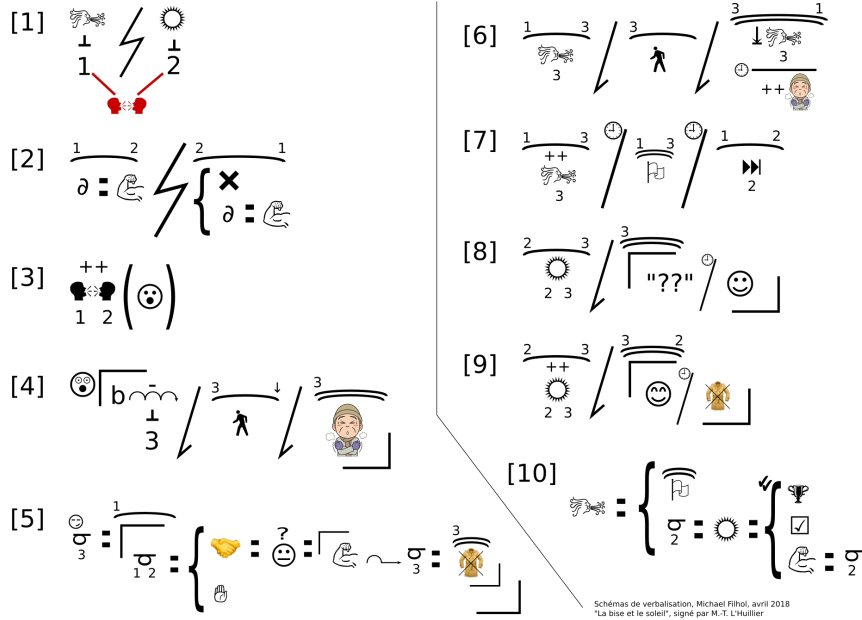


Figure 22: Pieces of a full story

association. In other words then, what is written is not *either* a form or a meaning, but necessarily both. For example, the tick mark suggested in fig. 19c maps to the “non-subjectivity” rule, in other words to *both* the “generally found true” interpretation *and* the lip pout form, jointly. From this angle, considering the symbols’ direct (linguistic) references, we would have to question the logo-phono dichotomy at its roots.

But while symbols could in theory be arbitrary, they never appear to be so in spontaneous VD, rather as we noticed, they mostly appear as iconic of something. So if we keep supporting the present submission with the use of observed VD features, we are led to prefer **iconic** symbols over abstract ones. As we have already mentioned for VD, this compares to many (though not all) proposed systems for SL, and similarly contrasts with the writing systems used in the vocal world.

Now embedding iconicity in the glyphs raises the question of what the glyphs should be iconic of. For example, the “non-subjectivity” tick mark proposed is iconic of its meaning (shape drawn when one marks approval), but could instead be written as lips to suggest the associated form (lip pout). This question reenables the logo-phono characterisation of the script, this time considering the symbols’ iconic references. We have already touched on this while trying to characterise VD in section 3.2, and seen that in most productions, glyphs were iconic of the meaning, while they would still occasionally refer to form. For instance it is possible that lips be favoured over the tick mark, especially as

the choice can fall under case 2 of the list on page 14. Whatever the ultimate choices, it seems unlikely that such system grow into the 100% phonographic state of the other designed propositions. By analogy with VD, we rather predict a mix with **logographic** references, and even a dominant number of them. As we have shown in §2.3, unbalanced mixes of phonography with logography are a typical feature of the world’s writing systems. This time the system would be no different.

The issue of directionality must also be revisited, because no linear layout is assumed to begin with. We do note some directional reading of operators<sup>19</sup> with arity greater than one and whose reversal would seem unnatural (depending on the subject’s culture and literacy) or ambiguous (an arrow can be reversed, but not an equal sign). But they are local issues related to specific operators used in the script, not a property of the script design itself which would organise, say, a whole page systematically. Instead, it is 2-dimensional, or **planar**. What is more, it gives an account of the embeddings of the written discourse pieces nested in one another, which allows to qualify the system as inherently **recursive**. This scripting layout is identical to that of the preferred mathematical script, which lays out a planar recursive structure, including local directionality for specific operations<sup>20</sup>. So these last two properties would be rather new if ported to a natural language script, but are not alien to scripting, handwriting or reading practice.

## 6 Conclusion

In this paper, we created an editable, queryable, human-readable and synthesisable representation to implement in SL-related software. It builds on two complementary grounds:

- the spontaneous handwriting of SL users in the form of verbalising diagrams, which we are building a corpus of and finding patterns in;
- the formal AZee framework, which we have been promoting for a few years, especially in the SL processing community.

The point of sourcing from VD is to tap into already existing practice, increase intuitive use and human apprehension of the system, and to inspire the graphical layout of the resulting diagrams. The point of AZee is to take advantage of the formal background, and cancel the subjectivity that is intrinsic to VD’s personal and non-standardised practice. By building backwards from the formal base, we also guarantee synthesisable input. We now wish to try out our proposition by implementing and demonstrating a simple software editor.

In a final section, we have opened the prospect of seeing our proposition used outside of the restricted scope of software interaction, in particular as a writing

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<sup>19</sup>See footnote 16.

<sup>20</sup>Interestingly, math script is also dependent on the surrounding culture and literacy. Arabic vs. European math scripts are often reversed where a direction of reading is required.

system. We have compared its properties to the other writing paradigms presented, existing for vocal languages or designed for SLs. We have shown that it fits key characteristics of writing systems (mixing phonography and logography), while exhibiting more or less new properties (iconic, planar, recursive). We hope that after a few developments, SL users will eventually be tempted to test it as it will at least help us shape up what is implemented in software, and maybe feed the important and difficult reflection on SL writing and literacy. Whether or not it actually proves robust or adaptable to all uses signers will require of a writing system in the future is of course not yet possible to tell.

## Acknowledgements

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