Fishing in a Speech Stream - Angling for a Lexicon

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Abstract

We present a learning device able to deduce a set of Danish color and shape terms. Only two data sources are available to the learner: A phonetic transcription of a human informant solving a description task, and a minimal formal model of the picture being described. The system thus contains no preconceived lexical, morphological, or semantic categories. The test data are from the phonetic corpus DanPASS, a standard Danish reference corpus. The learning device, called InShape-2, is an early result of an ambitious research programme at CMOL on data-driven language learning.

1 Introduction

Imagine a device able to learn the lexical units and linguistic structures occurring in a natural language discourse. The device would have access to data of only two sorts: a sound recording of a language user and a formal representation of the scene (physical or mental) being talked about. In particular, the device would have no built-in language model, no grammatical or lexical expectations, no phonological bias. Such a device would not only be of practical value, it could also play a role as evidence in the still unsettled debate about linguistic universals and innate language capacities. In addition, it would have obvious use as an instrument for first language (L1) acquisition studies.

In this paper we present a toy system called InShape-2, intended as a small step towards the general learning device. We begin with a short introduction of the speech data that we have used, followed by some methodological considerations, a presentation of our implementation, and some test results. The paper concludes with a discussion of the limitations of the current framework – and how to remove those limitations.

2 A learning experiment

We take our starting point in a simple-minded world of geometrical figures.

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1 This paper, and the associated line of research, is primarily aimed at the auditory part of the speech situation, not the related visual and tactile cues (gestures, gaze directions, body movements, etc).

2 InShape-2, here presented for the first time, is a complete rewrite of the earlier program InShape-1 (Henrichsen 2010, now deprecated). More details below.

3 The 13 objects are colored; consult the original graph at http://www.cphling.dk/~ng/danpass_webpage/figs/geometry.pdf. Symbols e1..e13 are not included in the original.
DanPASS consists of a monologue part and a dialogue part, each containing a number of lab recordings of Danish informants solving various language tasks. The design in fig. 1, call it G (for "geometrical network"), was used in a series of description tasks. Eighteen male and female informants were asked to give a complete description of G as if to a person who could not see it. The informants were instructed to begin with the object pointed to by the arrow, but otherwise no clues were given as to what specific terms should be used for e.g. colors and shapes, nor to the sequence in which the objects should be named. As a result, the sessions vary considerably with respect to term selection, description strategy, rhetorical and grammatical style, informational redundancy, and duration. The shortest session is only 45 seconds, the longest more than four times longer.

The goal of the InShape-2 project was to design a robust learning device able to determine for each G session its basic vocabulary (the shape and color terms being used) and its temporal composition (the sequence of naming events) based on two information sources only, (i) the phonetic transcription data available with DanPASS and (ii) a minimal formal representation of G.

At this point we are not making claims of cognitive isomorphism. We simply wanted to demonstrate that linearly ordered phonetic data can be sufficiently rich for extraction of structured lexical and semantic information in a process governed by a specific learning purpose.

2.1 Formal preliminaries

We refer to the geometrical objects of G as e1, e2, ..., e13, reading the branches of the network clockwise (see fig. 1). For reference to individual sessions, we use the DanPASS identifiers m_n_g (m='monologue', n=informant code, g='geometrical network').

For reasons of computational tractability, some basic constraints had to be hardwired into the implementation. Some of them concern the naming events of the sessions, i.e. those utterances by which informants refer to the particular objects. Examples of naming events are "en gul firkant" (a yellow square), "den lilla trekant" (the purple triangle), but also "en rund grøn" (a round green) using two adjectives instead of a standard noun phrase, and "en grøn tre- en blå trekant" (a green triangle including a self-correction. Since the informants were instructed to include all objects in their descriptions, the naming events are expected to occur in sequences of 13. Such a complete sequence referring to each object in turn, we call a path.

\[e1, e2, e3, e7, e8, e9, e4, e5, e6, e10, e11, e12, e13\]

The path above happens to be the one most frequently used by the informants, but by no means the only one. Perhaps surprisingly, no less than seven different paths are represented in the 18 sessions.

Formal requirements

- A session has (at least) one path consisting of 13 unambiguous naming events
- In any path, the first naming event denotes \(e1\)

In addition to the formal requirements, we also imposed some linguistic conditions for reasons to be discussed shortly.

Linguistic conditions

In any path, all color terms and shape terms must be used consistently in the following sense:

- no synonymy (i.e. no two distinct terms for one color or for one shape)
- no homonymy (no single term can denote a particular color and a shape)
- no material inclusion among the terms within a domain (no color term can be a part of another color term, excluding term pairs like "light green"+"green"; similarly for shapes)
- adjacency of terms for shape and color (e.g. not "a circle in a green color")

In G sessions there are often multiple naming events referring to one particular object, or several uses of the color and shape terms not referring to any object at all. Some naming events may even refer to non-existing objects, sometimes (but not always) followed by a self-correction. Most of this variation is not critical with respect to InShape learning (and shouldn't be!) as long as at least one well-formed path exists. It should be noticed, though, that the significant naming events may be very unevenly distributed; in session m_009_g, the initial naming event (e1) thus occurs after no less than 74 seconds.
Finally, to limit the search space an integrity constraint is adopted formalizing the observation that informants tend to move from object to adjacent object whenever possible rather than jumping arbitrarily around in the network. The constraint is defined in terms of path complexity (PC), defined informally as the minimal number of instructions in {‘up’, ‘down’, ‘left’, ‘right’, ‘reset’} needed in an explanation. For instance, the path mentioned above can be explained as:

"e1 UP e2 e3 e7 e8 RIGHT e9 RESET e3 LEFT e4 e5 e6 RESET e3 RIGHT e10 e11 DOWN e12 RIGHT e13", making PC=8 for this path. Only one other path has PC=8, while ten paths have PC=9. The PC<10 paths include all actually occurring DanPASS naming sequences with the sole exception of the quite entangled m_31 g (PC=10). Moreover, the PC=8 paths are generally preferred (7+3 cases) over the PC=9 (3+2+1+0+0+0+0+0+0+0), adding some psychological plausibility to the complexity measure.⁴

**Integrity constraint**

- Path complexities >9 are not considered

Following the requirements, conditions, and constraints, a number of sessions must be excluded from the InShape test material leaving a test corpus of 13 sessions. The excluded sessions (see table 1) do however play an important role as negative evidence in the testing of the implementation.

| Session | Disqualifying feature |
|---------|----------------------|
| m_003_g | e9 is wrongly described as "en gul cirkel" (a yellow circle) |
| m_005_g | e10 is wrongly described as "en rød cirkel" (a red circle) |
| m_008_g | e3 is wrongly described as "en flirktant lilla" (a square violet); the mistake is corrected, but too late to restore the path. |
| m_013_g | Homonymy: two terms for square ("flirkant", "kvadrat") |
| m_031_g | Integrity constraint violation: Path is too entangled |

Table 1. Discarded sessions.

It is worth mentioning that even the formally well-formed G sessions may be quite informal in style with lots of repetitions and quite verbose explanations. Several sessions contain one or more self-corrections, such as

"en violet en lilla trekant" [m_007_g] (a violet a purple triangle)

"en lilla nej en brun en brun firkant" [m_014_g] (a violet no a brown a brown square)

"til en blå eller til en grøn cirkel" [m_016_g] (to a blue or to a green circle)

Deducing the lexical paradigms and semantic relations in G thus calls for parsing strategies that are not usually taught in courses on formal grammar.

### 2.2 Color blindness

A curious property of G – probably unintended by its designers – is the similarity of the left branch [e4,e5,e6] and the upper branch [e7,e8,e9] concerning shapes and colors. Both branches share the shape sequence [square, triangle, circle] while the color sequences are [X, Y, green] and [Y, X, green], respectively. As colors X and Y do not occur elsewhere in G, an inference engine needs to learn some location terms in order to deduce the intended terms for red and yellow. Picking the wrong color terms for X for Y, for the reasons mentioned, we shall refer to as color blindness.

### 3 InShape-2 – the implementation

Skipping over irrelevant programming details, we present the implementation as a pipeline of functional modules. The chain is strictly feed-forward (no backtracking between modules).

```
Extract_phones > Find_siblings > Assign_shapes > Assign_colors > Build_lex
```

Figure 2. The InShape-1 functional modules.

Each of the stations in fig. 2 is introduced below, with special emphasis on those implementing the semantic inference system, viz. Assign_shapes and Assign_colors. Other papers expanding on the data preprocessor (Extract_phones) and the growth of lexical structure (Build_lex) are in preparation; Find_siblings is treated at length in Henrichsen (2004).

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⁴ In InShape-1 the set of well-formed paths were wired into the system whereas InShape-2 derives it directly from the G-geometry, preparing the system for experiments with varying geometries.
3.1 Extract_phones

The phonetic data are derived from the TextGrid files (Boersma 2001) included in the DanPASS corpus. Fig. 3 shows a sample from the orthographic tier of m_007_g:

```
du starter nederst på papiret med= en= + blå firkant + deraf= går du= + opad= + mod toppen af papiret + og lægger en grøn+ cirkel + og endelig= lægger du= en= + violet en lilla + trekant + fortsætter du opad+ og lægger en gul firkant + og en rød trekant + og til højre for den røde trekant men+ på= niveau+ med trekanten + lægger du en+ grøn= cirkel + så vender du tilbage til den= + lilla + trekant= der nu er i midten + til højre + men= på niveau+ med den lille trekant + lægger du en+ blå cirkel +
```

Figure 3. Orthographic transcription.

Extract_phones reads a TextGrid, returning the phonetic transcription in compact form excluding pauses, hesitation, stress pattern, stød, and syllabification, since these features tend to be less consistently annotated by transcribers than vowels and consonants. For m_007_g, the string returned thus begins with [dusdAd0neD0sp-cp0piCDmEDenblcfiRkant...].

3.2 Find_siblings

Which is the easier to learn, the shape domain or the color domain? Two observations on G suggest the answer. Firstly, there are six color types and only three shape types. Secondly, each shape type has a substantial amount of occurrences in the geometrical network (5+4+4), as opposed to the thinner spread of the colors (4+3+2+2+1+1). As data-driven learning typically relies on repetition and limited diversity, the shape domain should, arguably, be addressed first.

The phone stream from Extract_phones must be segmented into potentially meaningful units, interpreted as recurring substrings of phones. For the segmentation analysis we used the Siblings-and-Cousins algorithm of Henrichsen (2004). Due to space limitations, we have to introduce the S&C algorithm very briefly; a thorough presentation is in the paper mentioned. Originally, S&C was suggested as a way of clustering the lexical items (words) occurring in an unannotated text corpus based on their distributional similarity. A main ingredient in the S&C framework is the proximity measure comparing the similarity of two types based on the distribution of their adjacent tokens in the corpus.

Modifying the S&C framework to accommodate the current data type, the proximity of two n-grams X and Y occurring in a phonetic transcription T is given by the Prox formula.

$$\text{Prox}(X,Y,T) = \frac{\sum_{z \in \text{Voc}} c(z) \cdot \left(1 - \frac{L_1 - L_2}{L_1 + L_2}\right)}{c(X)} \cdot \frac{\sum_{z' \in \text{Voc}} c(z') \cdot \left(1 - \frac{R_1 - R_2}{R_1 + R_2}\right)}{c(Y)}$$

Figure 4. Proximity of two n-grams X and Y.

$Voc$ is the set of all tokens in T; $c(g)$ is the $T$ count function, i.e. the number of occurrences of n-gram $g$ in $T$, and

$$L_1 = c([z X]) / c([X]); \quad L_2 = c([z Y]) / c([Y]); \quad R_1 = c([X z']) / c([X]); \quad R_2 = c([Y z']) / c([Y]).$$

Intuitively, $\text{Prox}$ measures the similarity of two n-grams occurring in a transcription, based on their left and right context functions. $\text{Prox}$ values always range between 0 and 1 for valid input. Kindred n-grams (such as two color terms, or two shape terms) tend to score high, while less associated n-grams (such as one color term and one shape term) score lower. $\text{Prox}=1$ occurs for pairs of n-grams with identical distribution of tokens in their immediate surroundings, while a pair of n-grams not sharing a single left-side token or right-side token makes $\text{Prox}=0$.

Figure 5. Sample from the S&C log for m_019_g

| #62 | 'f_i_R_k_a_n' | 5 |
| 1.000000 | f_i_R_k_a_n | 5 |
| 0.321535 | t_r_z_k_a_n | 8 |
| 0.140000 | s_i_R_g_0 | 1 | 5 |
| 0.124675 | b_l_c | 4 |
| 0.098937 | z_R | 4 |
| 0.098209 | t_C | 4 |
| 0.080672 | g_r_Q_n_s_i_R_g_0 | 1 | 4 |

(...)

93
Sets of n-grams with mutually high Prox-values are informally called siblings. Consider the sample in fig. 5, quoted from the S&C analysis for \(X=f_i R k a n\). As reported, this particular n-gram has five occurrences in the transcription, and it was analysed as the 62th item. In the quoted list, the Ys (i.e. the siblings of \(X\)) are sorted by their associated Prox values. Speakers of Danish will notice the difference between this phonetic string and the standard pronunciation for "firkant" (square), especially concerning the final part of the word. Whereas the Danish standard phonetic dictionary prescribes a final stop [d], the pronunciations in \(m_{019\_g}\) show some variation, with [fiRkan] being the invariant part. Therefore (only) this part is suggested by the Find_siblings module as a potentially meaningful unit – and similarly for triangle, \(t_r z k a n\).

Observe that the 10-gram \(g r Q n s i R g 0 l\) (greencircle), even though it is not an acknowledged Danish lexeme, is also suggested as a potentially meaningful unit in the specific learning context of InShape. The prediction of \(g r Q n s i R g 0 l\) as a semantic atom is an effect of the \(G\) model where circles are generally green, with only one exception. As we will argue, predictions like this should be seen as signs of lexical flair rather than just errors.

As demonstrated in fig. 5, lexical types belonging to the same semantic category, e.g. shape terms, color terms, or direction terms, tend to appear near each other in S&C log tables. This property is used by Find_siblings for output generation. All sets of three siblings above a certain Prox threshold (typically >0.1) are thus extracted and exported as input for the Assign_shapes module.

\[
\begin{align*}
(f_i R k a n, t_r z k a n, s_i R g 0 l) \\
(f_i R k a n, t_r z k a n, b_l c) \\
(f_i R k a n, s_i R g 0 l, b_l c) \\
(t_r z k a n, s_i R g 0 l, b_l c) \\
(...)
\end{align*}
\]

Figure 6. Exported tri-sets for \(m_{019\_g}\).

Of course, algorithms other than S&C could be used for segmentation and grouping of the phonetic data. Most of those known to us would however force us to split up the n-gram formation and the paradigm-formation in two more or less independent steps, which is why we settled on the S&C framework with its simultaneous and inter-dependent chunking and clustering. More discussion on the segmentation methodology is to follow in the final section.

3.3 Assign_shapes

The Assign_shapes algorithm is implemented in the programming language Prolog (e.g. Bratko 2000). In this language, propositional knowledge is particularly easy to formalize and to reason about, as exemplified by the \(G\) model below.

\[
\begin{align*}
\text{prop(color,blue,[}e_1,e_{10},e_{12}\text{]).} \\
\text{prop(color,green,[}e_2,e_6,e_9,e_{13}\text{]).} \\
\text{prop(color,red,[}e_4,e_8\text{]).} \\
\text{prop(color,yellow,[}e_5,e_7\text{]).} \\
\text{prop(color,purple,[}e_3\text{]).} \\
\text{prop(color,brown,[}e_{11}\text{]).}
\end{align*}
\]

\[
\begin{align*}
\text{prop(shape,square,[}e_1,e_4,e_7,e_{11}\text{]).} \\
\text{prop(shape,circle,[}e_2,e_6,e_9,e_{10},e_{13}\text{]).} \\
\text{prop(shape,triangle,[}e_3,e_5,e_8,e_{12}\text{]).}
\end{align*}
\]

Figure 7. Formal model of \(G\).

The Assign_shape algorithm is perhaps best presented by an example. Consider a particular tri-set \(T3\) of shape term candidates as delivered by Find_siblings, and transformed to the shape lexicon \(T3'\).

\[
T3 = \{f_i R k a n, t_r z k a n, s_i R g 0 l\}
\]

\[
T3' = \{\text{square: } f_i R k a n, \text{circle: } s_i R g 0 l, \text{triangle: } t_r z k a n\}
\]

We trace the program execution at a point where \(T3'\) is to be evaluated with respect to the session transcription, \(m_{019\_g}\), and a particular path \(P'\).

\[
P' = \{e_1,e_2,e_3,e_7,e_8,e_9,e_4, e_5,e_6,e_{10},e_{11},e_{12},e_{13}\}
\]

Consulting prop/3 (fig. 7), the Prolog engine infers that \(P'\) has the related shape sequence [square, circle, triangle, square, triangle, circle, square, triangle, circle, circle, square, triangle, circle], so \(T3'\) is evaluated by searching for a 13-section of the transcription \(m_{019\_g}\) faithfully representing the shape sequence (that is, its \(T3'\) mapping). As it turns out, such a 13-section does exist, verifying \(T3'\) in this case.

In general, each tri-set delivered by Find_siblings is evaluated for each of its six permutations, and for each formally well-formed path (cf. 2.1). Each combination of path and tri-set for which a 13-section was found is then
passed on to Assign_colors for further evaluation.

### 3.4 Assign_colors

In this part of the Prolog script, a partly instantiated variable Table is declared.

\[
\text{Table} = [\text{green:}, \text{blue:}, \text{red:}, \text{yellow:}, \text{purple:}, \text{brown:}],
\]

Using Prolog backtracking, a solution is sought in the form of a fully instantiated Table structure. A slightly simplified version of the central Prolog predicates is shown below (excluding some performance improving modifications).

\[
\text{eval(Tran, [T1, T2, T3]):­} \\
\quad \text{path(Path),} \\
\quad \text{perm(Shapes, [T1, T2, T3]),} \\
\quad \text{Table} = [\text{green:}, \text{blue:}, \text{red:}, \text{yellow:}, \text{purple:}, \text{brown:}], \\
\quad \text{traverse(Tran, Path, Shapes, [], Con),} \\
\quad \text{deduce_colors(Con, Table),} \\
\quad \text{write_result(Table, Path).}
\]

\[
\text{traverse( Tran_in, [E|Path]​,} \\
\quad [\text{Tr, Sq, Ci}], \text{ ConIn, ConOut}):
\]

\[
\quad \text{prop(color, Col, Colset),} \\
\quad \text{member(E, Colset),} \\
\quad \text{prop(shape, Shp, Shpset),} \\
\quad \text{member(E, Shpset),} \\
\quad \text{member(Shp:Shpname, [triangle:Tr, square:Sq, circle:Ci])}, \\
\quad \text{occur(Shpname, Tran_in, Tran_out, Con),} \\
\quad \text{traverse( Tran_out, Path, [Tr, Sq, Ci],} \\
\quad [\text{Col|Con|ConIn}], \text{ ConOut})
\]

\[
\text{traverse(_,[], _, Con, Con).}
\]

\[
\text{deduce_colors([], _).} \\
\text{deduce_colors([Col:Txt|More], ColTable)­:} \\
\quad \text{append(ColName, Txt),} \\
\quad \text{member(Col:ColName, ColTable),} \\
\quad \text{deduce_colors(More, ColTable)}
\]

Figure 8. Central Prolog predicates of Assign_colors

Two sessions contain small variations of the pronunciation for a specific color term, viz. m_029_g (yellow: g_u l, g_u) and m_033_g (yellow: g_u l, g_u l_0). As these two are otherwise fit for InShape-2 analysis, we accommodate the phonetic variation replacing

\[
\text{Table} = [\text{green:}, \text{blue:}, \text{red:}, \text{yellow:}, \text{purple:}, \text{brown:}],
\]

by

\[
\text{Table} = [\text{green:}, \text{blue:}, \text{red:}, \text{yellow:}, \text{purple:}, \text{brown:}], \text{ Extra=none}
\]

in eval/2 (fig. 8). Notice the logical disjunction (the connective ;/2) ensuring that a proper one-to-one mapping (Extra=none), if any, is preferred over versions with an Extra color term. This way, a single unspecified lexical deviation can be accommodated in a controlled manner. Of course, more licenses could be issued by adding more Extras to the Table list, at a price of extra processing load.

### 4 Results

The inference engine delivers satisfactory results for all sessions, however with some interesting twists. Before we go into the details, we present an example of an output from the Assign_colors module.

\[
\text{m_017_g} \\
\text{triangle : } [\text{t}, \text{r}, \text{z}, \text{k}, \text{a}, \text{n}, \text{d}] \\
\text{square : } [\text{f}, \text{i}, \text{R}, \text{k}, \text{a}, \text{n}] \\
\text{circle : } [\text{s}, \text{i}, \text{R}, \text{g}, 0, \text{l}] \\
\text{blue : } [\text{b}, \text{l}, \text{c}] \\
\text{brown : } [\text{C}, \text{t}, 0, \text{h}, \text{Q}, \text{j}, \text{C}, \text{e}, \text{C}, \text{d}, \text{R}, \text{g}, \text{b}, \text{r}, \text{o}, \text{n}] \\
\text{green : } [\text{g}, \text{r}, 0, \text{n}] \\
\text{purple : } [\text{C}, \text{X}, 0, \text{n}, \text{i}, \text{g}, \text{E}, \text{n}, \text{h}, \text{A}, \text{d}, \text{u}, \text{e}, \text{n}, \text{b}, \text{r}, \text{o}, \text{n}] \\
\text{red : } [\text{n}, \text{r}, \text{x}, \text{D}] \\
\text{yellow : } [\text{g}, \text{u}, \text{l}] \\
\text{Extra = none}
\]

\[
\text{PATH : } [\text{e1}, \text{e2}, \text{e3}, \text{e7}, \text{e8}, \text{e9}, \text{e10}, \text{e11}, \text{e4}, \text{e5}, \text{e6}, \text{e12}, \text{e13}]
\]

Figure 9. Output from Assign_colors.

The PATH is correctly identified: informant 017 did name the thirteen objects in the order shown. Concerning the deduced vocabulary, several unusual phonetic forms are encountered. Perhaps most surprising are the very long terms for colors brown and purple. With a little bit of reflection, it is easy to see why the inference engine, with each of these colors occurring only once among the significant naming events, has too sparse data to determine their usual delimitation. As expected, the standard color names are identified by the right edge of the proposed strings (shown in
bold in fig. 9). Like English, Danish usually has adjectives in pre-nominal position.

Notice also that red translates to \([nrxD]\) rather than the expected form \([rxD]\) due to the fact that the latter on all its occurrences in \(m_{017}g\) is preceded by \([n]\). More examples in the same vein can be studied in table 2, showing the variety of color terms picked for yellow.

Such non-standard delimitations are the fingerprints of a truly data-driven learning autom. Of course, several cosmetic operations could be applied post festum, arriving at tokens much more like the dictionary forms — for example by relating the deduced color-terms to the frequency distribution of the \(n\)-grams in the S&C log. We have chosen not to do so. Actually, we find the deduced terms quite beautiful as they are.

The results of all \(G\) analyses are summarized in table 2. Paths are explained using the symbols \(A=[e1,e2,e3]\), \(B=[e4,e5,e6]\), \(C=[e7,e8,e9]\), \(D=[e10,e11]\), and \(E=[e12,e13]\).

| Session | Path   | Instantiation of yellow | Status   | Diagnosis |
|---------|--------|-------------------------|----------|-----------|
| 003     | ABDEC  | -                       | OKneq    | Anomaly   |
| 005     | ABCDE  | -                       | OKneq    | Anomaly   |
| 006     | ABDEC  | \([e,n,g,u,1]\)         | OK       | -         |
| 007     | ACDEB  | \([n,r,x,d]\)           | OK       | ColBlind  |
| 008     | ACDEB  | -                       | OKneq    | Anomaly   |
| 009     | ABDEC  | \([g,u,1]\)             | OK       | -         |
| 013     | ACBDE  | -                       | OKneq    | Violation |
| 014     | ACBDE  | \([g,u,1]\)             | OK       | -         |
| 016     | ACBDE  | \([n,g,u,1]\)           | OK       | -         |
| 017     | ACBDE  | \([g,u,1]\)             | OK       | -         |
| 018     | ACBDE  | \([d,c,e,n,g,u,1]\)     | OK       | -         |
| 019     | ACBDE  | \([e,n,r,x,d]\)         | OK       | ColBlind  |
| 021     | ACBDE  | \([n,g,u,1]\)           | OK       | -         |
| 027     | ACBDE  | \([e,n,g,u,1]\)         | OK       | -         |
| 029     | ADEBC  | \([g,u,1]\)             | OK       | -         |
| 031     | AC/D   | BC2E                    | OKneq    | I.con.viol. |
| 033     | ABCDE  | \([n,r,x,d]\)           | OK       | ColBlind  |

Table 2. Learning results for InShape-2

In table 2, 'ColBlind' stands for an instance of color blindness (cf. 2.2); 'Violation' for a violation of a linguistic constraint (2.1); 'I.con.viol.' for an integrity constraint violation; 'Anomaly' for a factual description error.

As seen, all sessions were successfully analysed, in the sense that the same paths were identified by the inference engine (IE) and by a human listener (HUM). The sessions are marked as OK if the vocabulary and the path deduced by IE is the same as those reported by HUM, modulo color blindness, i.e. possibly with confusion of the terms for red/yellow and the related confusion of branches B and C. Sessions for which no well-formed paths could be found either by IE or by HUM, are marked as OKneg. These anomalous cases either contain factual description errors with late or no self-correction, or are in conflict with the well-formedness criteria of 2.1.

4.1 Linguistic constraints revisited

From a general linguistic point of view, the conditions of 2.1 are not very attractive. Which language does not have instances of synonymy or homonymy? How, then, could an L1 acquisition model afford to reject it?

We did a few test runs with manufactured sessions copied from real ones, but with certain vital elements changed, e.g. replacing each occurrence of the term for blue by the term for triangle (creating homonymy), and replacing every second occurrence of the term for green by a fresh term (synonymy). As it turned out, the InShape-2 system is actually fully capable of learning homonymy in this sense, and even synonymy with one synonymous term allowed for each extra uninstantiated element in the Table structure of the Assign_colors module — however at the cost of a heavy overhead in processing loads, especially in the case of synonymy.

Concerning the adjacency condition and the material inclusion condition, these are perhaps even more weakly motivated than the synonymy and homonymy constraints from a linguistic point of view. Again it is easy to modify the program to make it accept non-contiguous naming events, but the processing cost is high.

5. Discussion

InShape-2 is a simple-minded learning device, but nevertheless quite successful on its own terms. Based on unbracketed strings of phones representing a great variety of speech styles, the
system robustly derives a set of lexemes and semantic categories in a combined process of low-level data clustering and high-level semantic inference. However, still some refinement is needed. Only property terms were learned (in Danish mostly associated with adjectives and nouns) while locations and spatial relations were not (prepositions and adverbials), causing symptoms of color blindness. We are currently working on an enhanced learner with improved color vision, to be presented in the near future.

Greater challenges are waiting further ahead. Shifting from pre-digested phonetic symbols to uninterpreted acoustic data will soon force us to reconsider the whole regime of speech sound segmentation. It is by no means given that the phonematic level, of all possible levels, will provide the optimal domain for information extraction. In contrast, we expect that the most fertile segmental level will vary dynamically with the purpose of the learning session. "Meaningful units" thus cannot be identified a priori with phonemic or syllabic or prosodic elements, or any other independently defined domain, since the very meaning of meaningful depends crucially on the purpose and the success criteria of the task at hand. Simple examples of situated meaningful units are the terms extracted from the G sessions which did not always coincide with Danish dictionary items, simply because they were generated as handles for deductive reasoning under very specific conditions, rather than as speaker and purpose independent abstractions. We hence need to develop methods for sound analysis able to lock in on a particular domain of segmentation in a semantically informed feedback-loop. This means that the current phonetic transcription data must be abandoned and replaced by data derived from the sound signal directly (e.g. Henrichsen et al 2009).\(^6\)

An acoustically based learning device would provide a number of interesting spin-offs, both of theoretical and practical nature. One of our immediate goals is to extend the InShape experiment to data from other languages. At CMOL, we have built a large collection of G session recordings for languages within the Indo-European family (German, Bulgarian, Hindi, ...), as well as typologically unrelated languages (Tamil, Xhosa, Khmer, ...). For most of these recordings by far, we have no phonetic transcription, so sound-driven learning is the natural approach towards genuine language-independency.

Even more difficult than the segmentation problem is however the model-theoretic challenge. The scene around the purple triangle must eventually be replaced by something of greater psychological relevance in order for us to approach a claim of cognitive realism. This does not mean, however, that the use of very simple models should be frowned upon. Even infants begin their linguistic career by developing primitive, highly personal sound units as names for a small number of concrete objects.

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\(^{6}\) An interesting investigation which we leave for others to explore, would be to compare the current S&C based chunking algorithm to alternative unsupervised, statistical methods using mutual information (e.g. Cover et al 1991), r-score (e.g. Church et al 1990), or newer frameworks as Ando (2003) and Belkin (2004).