Connectionist Language Processing

Lecture 10: **Situation Modeling using Microworlds**

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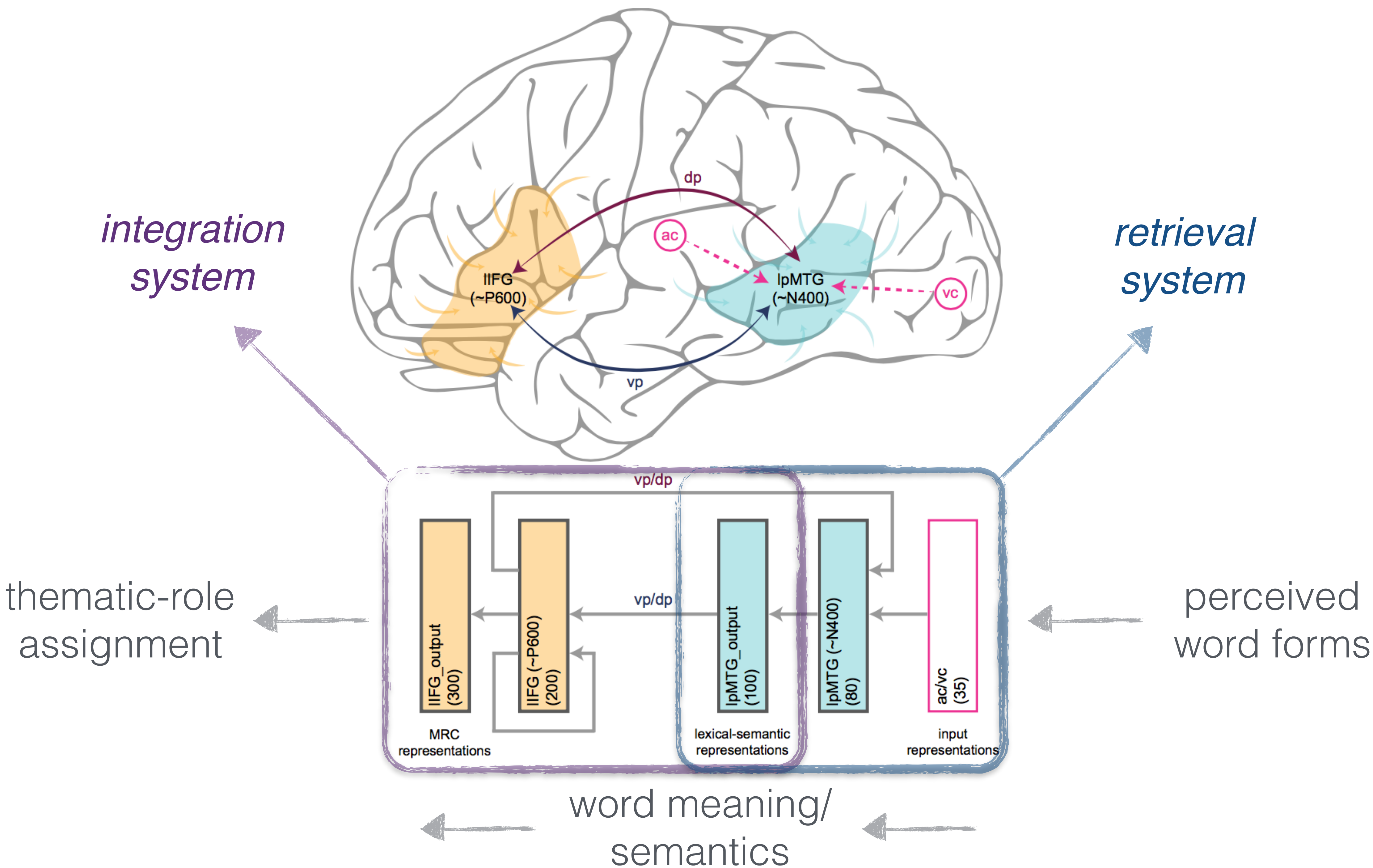
A Neurocomputational Model



Brouwer et al. (2017)
Cogn. Sci.

Sentence comprehension

"charlie plays soccer"

play(charlie,soccer)

Zwaan & Radvansky (1998). *Psychol. Bull.*

Two requirements

A richer representational scheme

We need to ***represent*** that Charlie is outside, on a field, playing with a ball, and with others, etc.

Knowledge about the world

We need to ***know*** that Charlie is outside on a field, because soccer is typically played on a field, with a ball, with others, etc.

> **Solution:** the Distributed Situation Space (DSS) model

Distributed Situation Space (DSS)

> A non-symbolic, distributed representational scheme for meaning

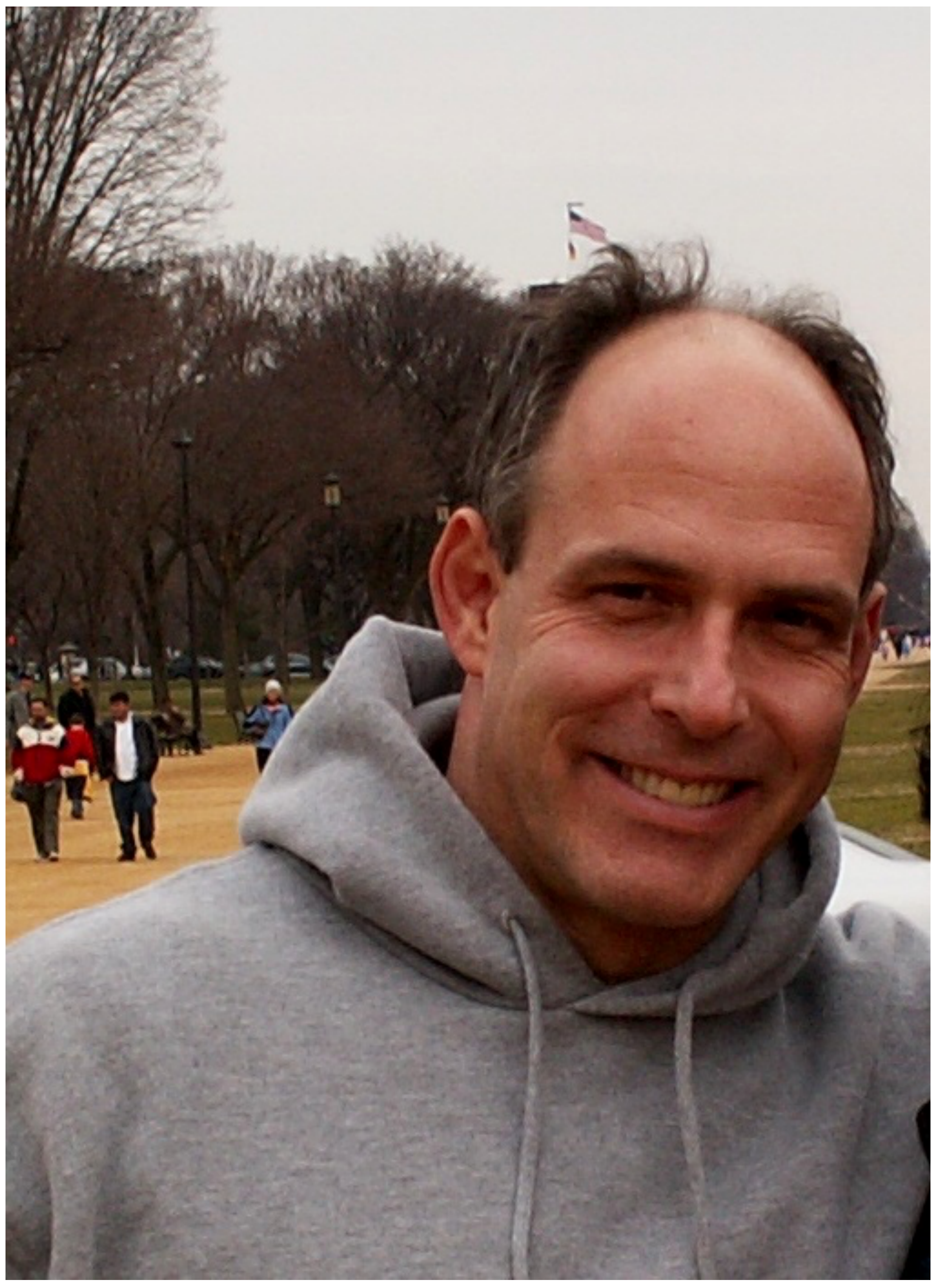
> Situations are represented as vectors in a high-dimensional space called "*situation-state space*"

> DSS vectors capture dependencies between situations, allowing for 'world knowledge'-driven *direct inference*

> To encode all world knowledge, DSS vectors are derived from observations of *states-of-affairs* (situations) in a *microworld*

Frank et al. (2003). *Cogn. Sci.;* Frank et al. (2009). *Cognition*

Introducing… Golden & Rumelhart



DSS—The main idea

Take a snapshot of the world ("a sample") at many different times, and for each snapshot write down the ***full state-of-affairs*** in the world

t=1

t=2

t=3

[…]

t=n

Next: extract regularities—***world knowledge***—from the full set of observations, and construct meaning representations (vectors) that encode this world knowledge

Problem: How to record full state-of-affairs in the world for each snapshot?

> use a confined ***microworld*** (which limits the scope of the world)

Defining a Microworld

A ***state-of-affairs*** (observation) in a microworld is defined in terms of ***atomic events*** that can be assigned a state (i.e., they can be *the case* or not *the case*)

Class	Variable	Class members (concepts)	#
People	p	charlie, heidi, sophia	3
Games	g	chess, hide&seek, soccer	3
Toys	t	puzzle, ball, doll	3
Places	x	bathroom, bedroom, playground, street	4
Manners of playing	m_{play}	well, badly	2
Manners of winning	m_{win}	easily, difficultly	2
Predicates	—	play, win, lose, place, manner	5

Event name		#
play(p, g)	$3 \times 3 =$	9
play(p, t)	$3 \times 3 =$	9
win(p)		3
lose(p)		3
place(p, x)	$3 \times 4 =$	12
manner(play(p), m_{play})	$3 \times 2 =$	6
manner(win,m_{win})		2
	Total	44

More specifically, states-of-affairs are combinations of these 44 atomic events

Example—“heidi loses at chess”: $play(heidi, chess) \wedge lose(heidi)$

> 2^44 (≈10^13) possible situations, but world knowledge precludes many

Frank et al. (2009). *Cognition*

*Micro*world knowledge

World knowledge enforces constraints on event co-occurrence. Some examples:

Personal characteristics—each person has a specialty, a preferred toy, and some persons frequent specific places

Games and toys—each game/toy can only be played (with) in specific places, and has a number of possible player configurations; soccer is played with a ball

Being there—everybody is exactly at one place; if hide&seek is played in the playground, all players are there; all chess players are in the same place

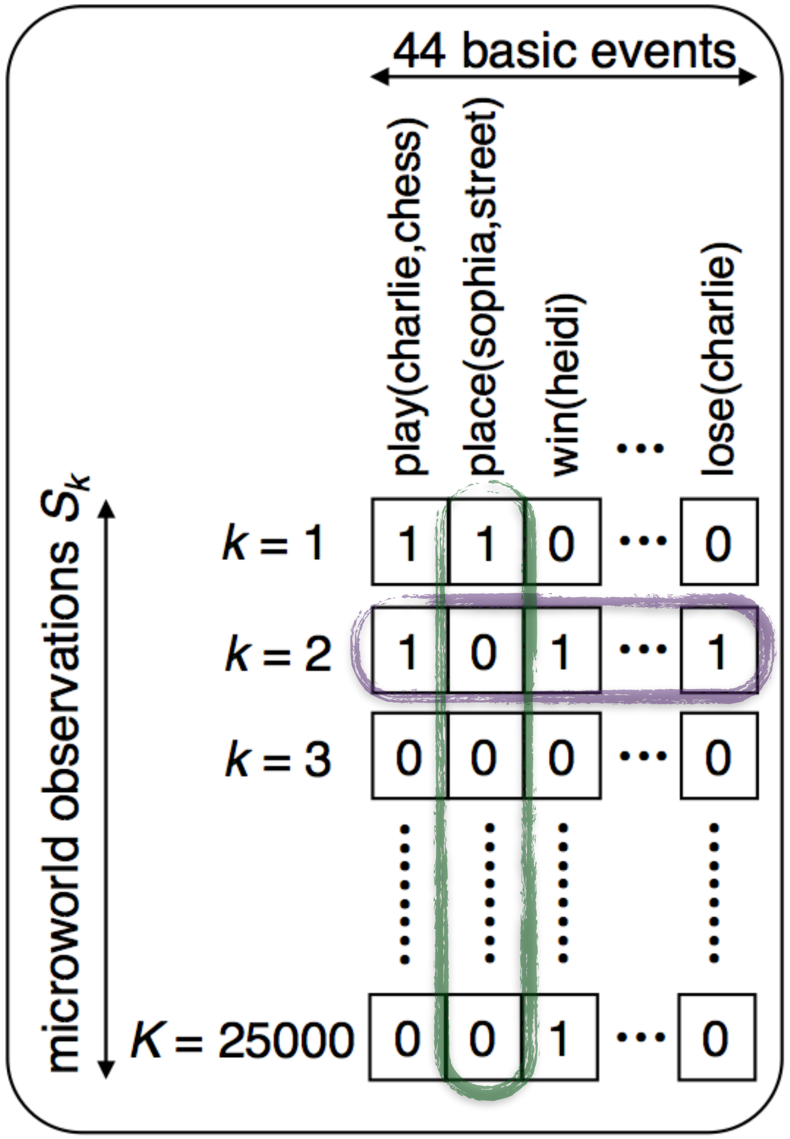
Winning and losing—only one can wine, and one cannot win and lose; if someone wins, all other players lose

Note: there are *hard* (being there) and *probabilistic* (preferences) constraints

Frank et al. (2009). *Cognition*

Situation-state space

Many samples of microworld observations constitute a "*situation-state space*"



Rows represent observations (states-of-affairs)

Columns represent situation vectors for atomic events:

$$\vec{v}(a) = (\vec{v}_1(a), \ldots, \vec{v}_n(a))$$ (a point in situation space)

Using (fuzzy) logic, ***complex event*** vectors can be derived:

$$\vec{v}(\neg a) = 1 - \vec{v}(a)$$

$$\vec{v}(a \wedge b) = \vec{v}(a)\vec{v}(b) \quad \text{where} \quad \vec{v}(a \wedge a) = \vec{v}(a)$$

which gives *functional completeness:*

$$\vec{v}(a \uparrow b) = \vec{v}(\neg \vec{v}(a \wedge b))$$

Frank et al. (2009). *Cognition*

Situation vectors

Situation vectors encode events by means of *co-occurrence probabilities*

Prior belief in atomic event ***a*** (= estimate of its probability):

$$B(a) = \frac{1}{k}\sum_i \vec{v}_i(a) \approx Pr(a)$$

Prior conjunction belief of atomic events ***a and b:***

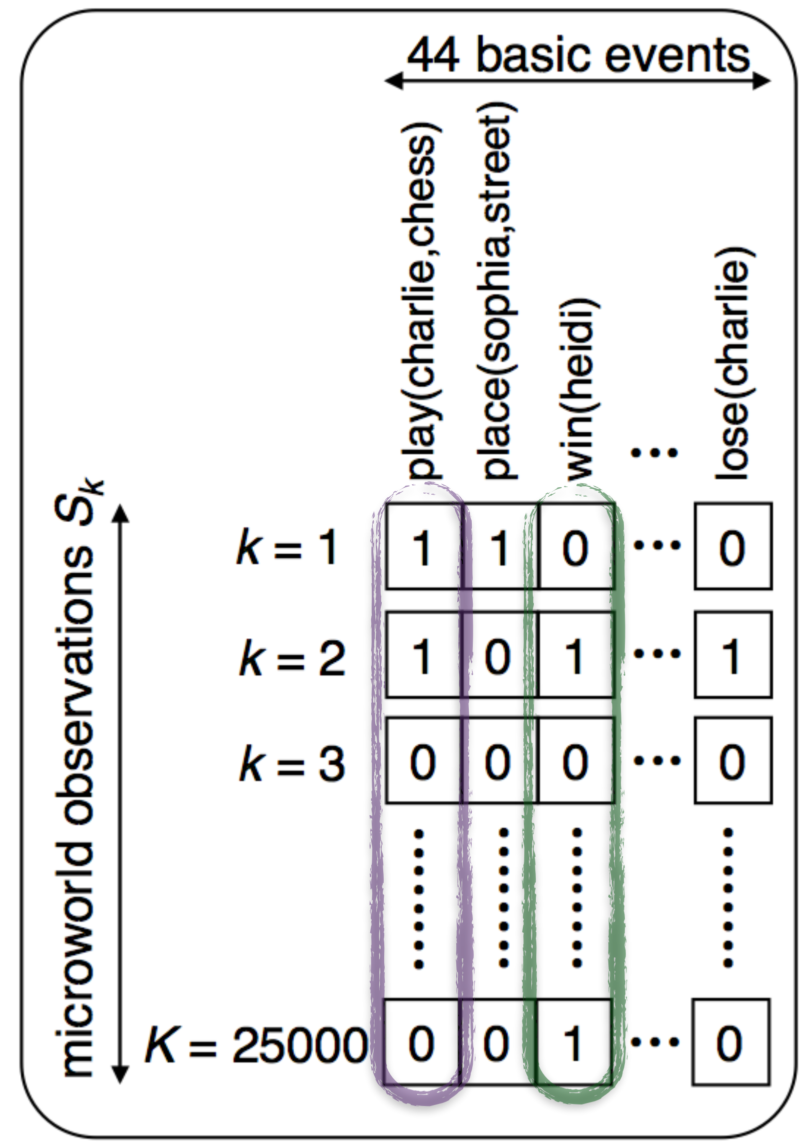
$$B(a \wedge b) = \frac{1}{k}\sum_i \vec{v}_i(a)\vec{v}_i(b) \approx Pr(a \wedge b) \quad \text{where} \quad B(a \wedge a) = B(a)$$

Prior conditional belief of atomic event ***a given b:***

$$B(a|b) = \frac{B(a \wedge b)}{B(b)} \approx Pr(a|b)$$

Critically, either ***a*** and/or ***b*** can be atomic or complex events

$B(a|b) \approx Pr(a|b)$ means $\vec{v}(b)$ encodes ***b*** and all that depends upon ***b***; this allows 'world knowledge'-driven inference



Frank et al. (2009). *Cognition*

Quantifying “comprehension”

Beyond conditional belief—how much is *a* ‘understood’ from *b*?

If *a* is **understood to be the case** from *b*, the conditional belief *B(a|b)* should be higher than the prior belief *B(a)*: knowing *b* increases belief in *a*

If *a* is ***understood not to be the case*** from *b*, the conditional belief *B(a|b)* should be lower than the prior belief *B(a)*: knowing *b* decreases belief in *a*

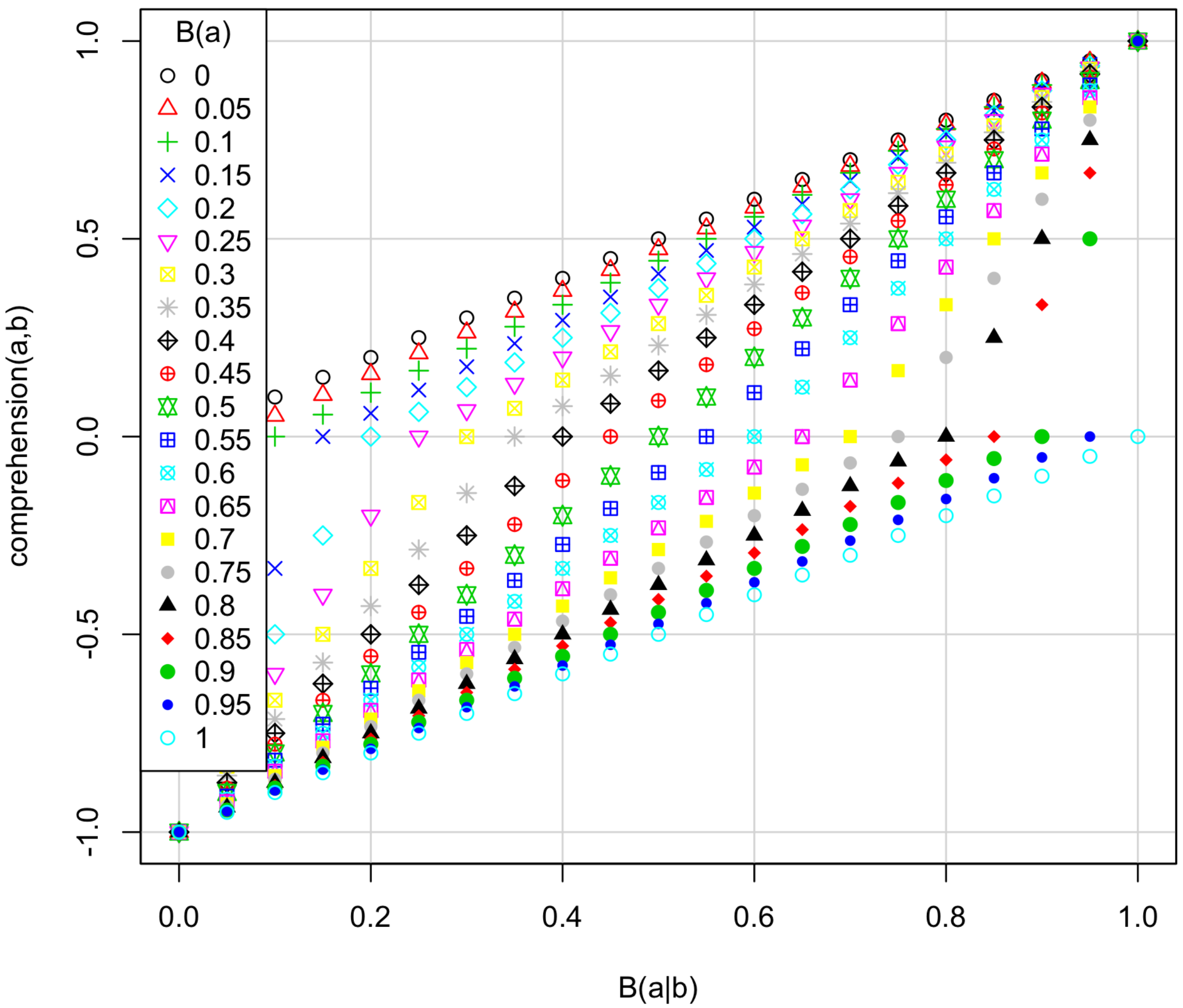
$$comprehension(a, b) = \begin{cases} \frac{B(a|b) - B(a)}{1 - B(a)} & \text{if } B(a|b) > B(a) \\ \frac{B(a|b) - B(a)}{B(a)} & \text{otherwise} \end{cases}$$

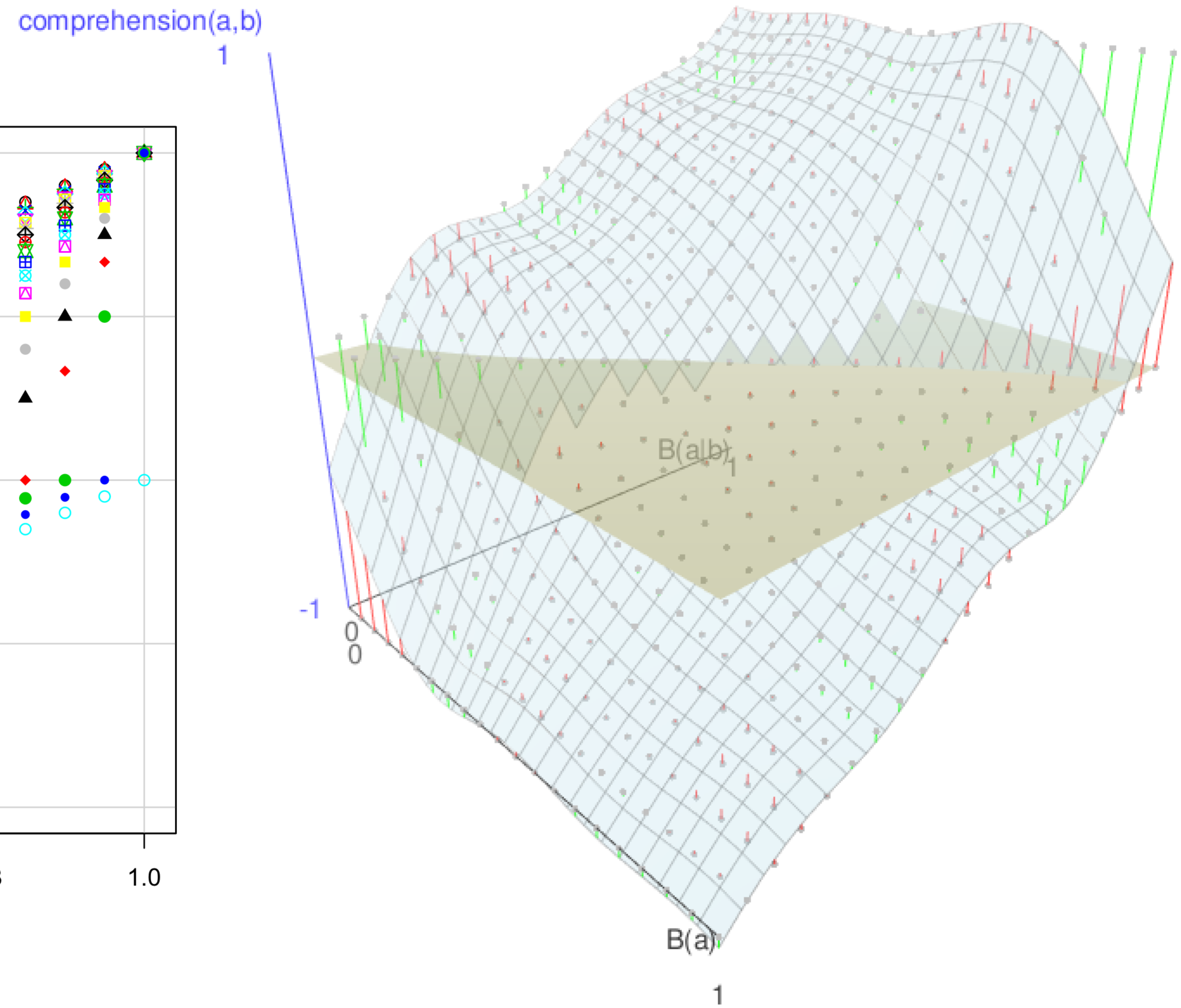
-1 ≤ comprehension(a,b) ≤ +1:

- **+1** indicates perfect **positive** comprehension: *b* took away all uncertainty in *a*
- **-1** indicates perfect **negative** comprehension: *b* took away all certainty in *a*

Frank et al. (2009). *Cognition*

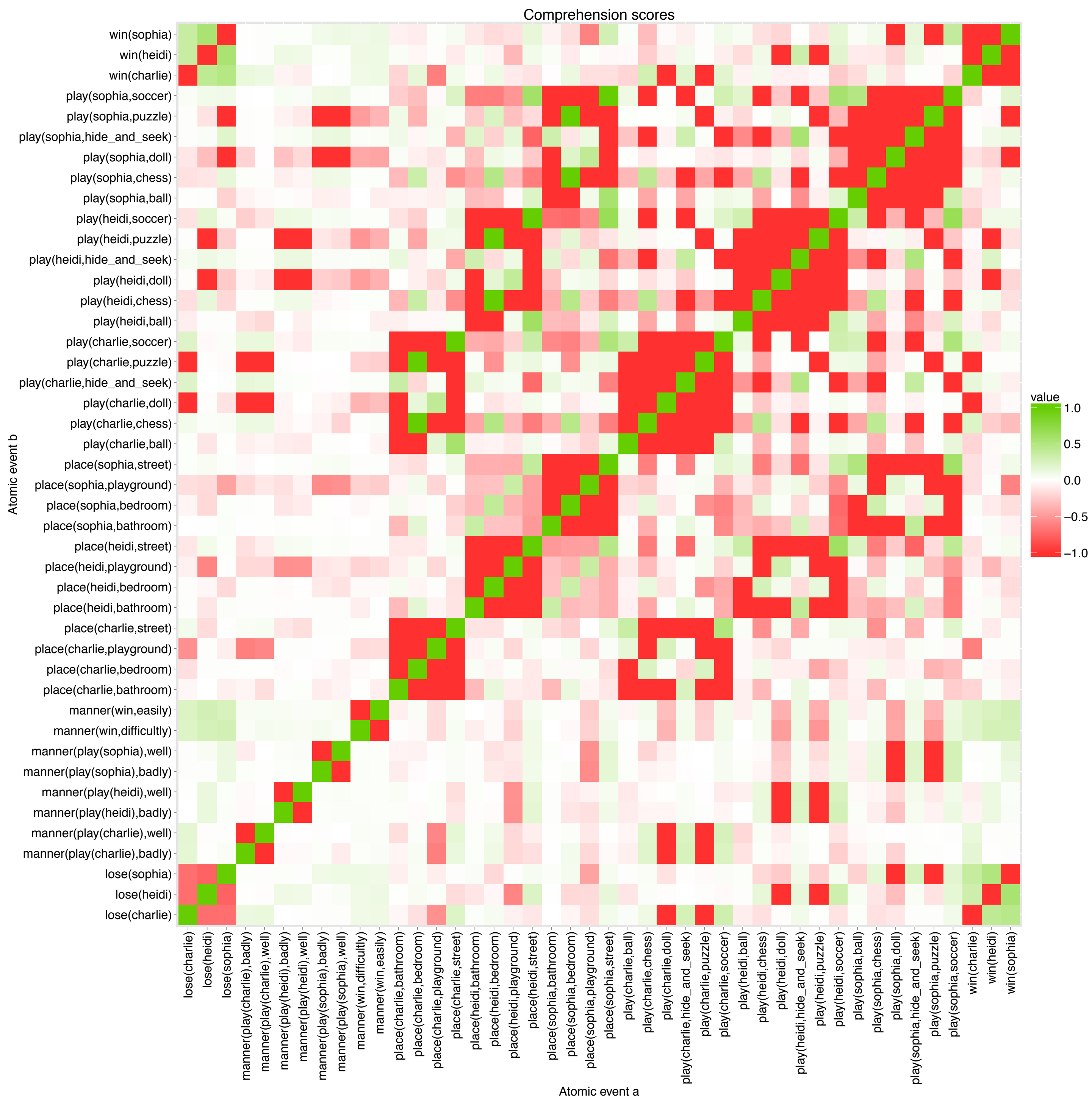
Comprehension scores





The higher *B(a)* the more difficult it is to *increase certainty* in *a*, and the lower *B(a)* the more difficult it is to *increase uncertainty* in *a*

Map of the World



Zooming in: Observation sampling

Q: how to efficiently sample ***k*** observation from 2^44 possibilities, such that *no observation violates world knowledge* and the *set of samples reflects the probabilistic nature of the world?*

> inference-driven, incremental sampling algorithm using three-valued logic (0.5: Unknown)

Step 0—start with a completely undefined observation (all ***n*** atomic event states set to 0.5);

Step 1—pick a random, undecided atomic event ***e***;

Step 2—set ***e*** to be the case (1) or not (0) on basis of its probability given the observation so far;

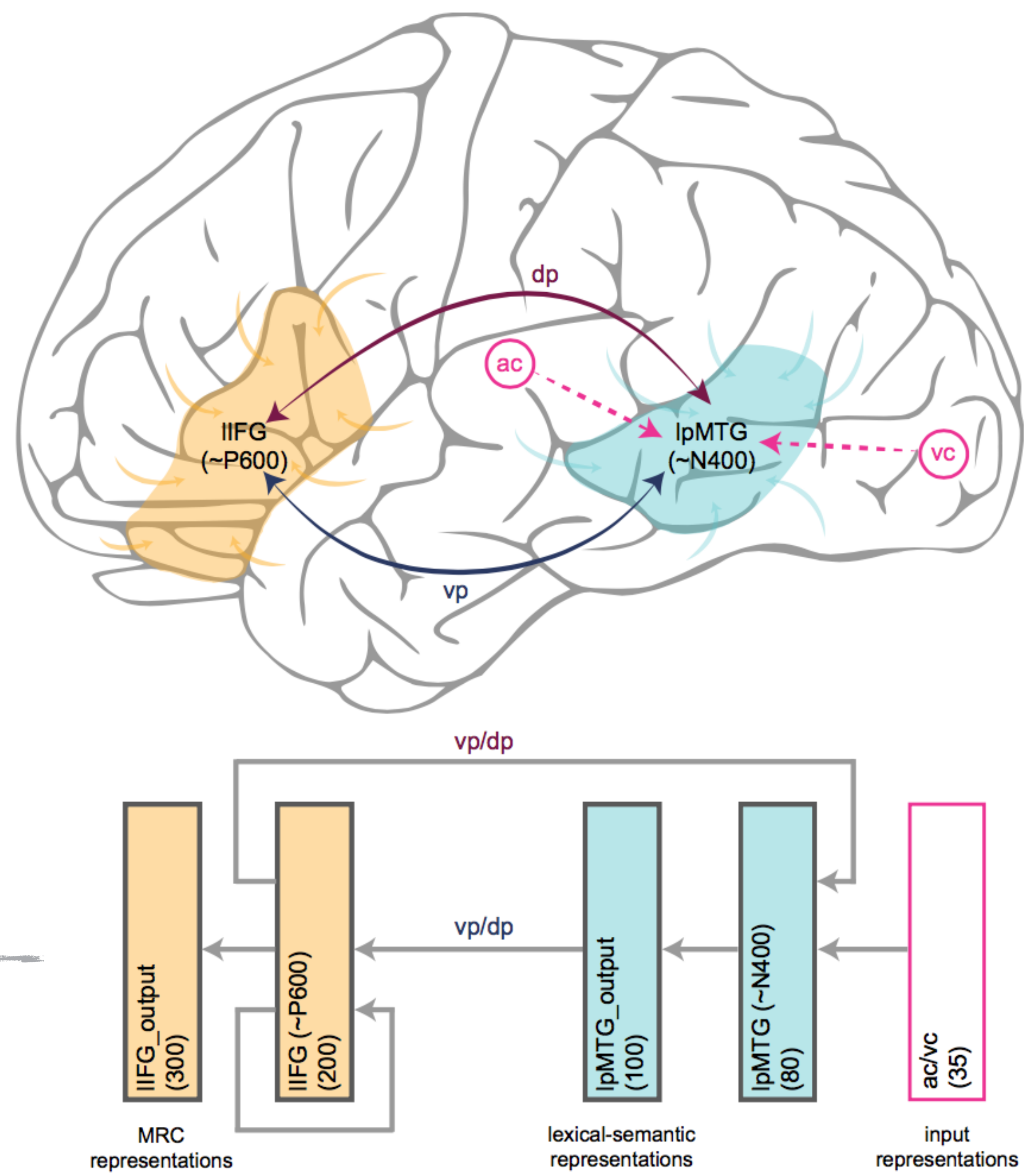
Step 3—draw all inferences that follow from deciding the state of event ***e***;

- **(a)** randomly pick the next, undecided event ***e'***;
- **(b)** construct two observations: ***s1*** in which ***e'*** is the case (1), and ***s2*** in which it is not (0)
- **(c)** check for ***s1*** and ***s2*** if they violate any hard world knowledge constraints:
  - **i.** both ***s1*** and ***s2*** are felicitous: state of e' cannot be inferred (and remains 0.5)
  - **ii.** only ***s1*** is felicitous: infer ***e'*** to be the case (its state is set to 1)
  - **iii.** only ***s2*** is felicitous: infer ***e'*** not to be the case (its state is set to 0)
  - **iv.** both ***s1*** and ***s2*** are infelicitous: prior observation is infelicitous (restart from ***step 0***)
- **(d)** repeat (b) until it has been tried to infer each undecided event

Step 4—repeat ***step 1*** until there are no more undecided events

Prize of incrementality: need to deal with undecidedness in checking world knowledge violations

DSS vectors—Plug and Play?



DSS vectors

~~thematic-role assignment~~

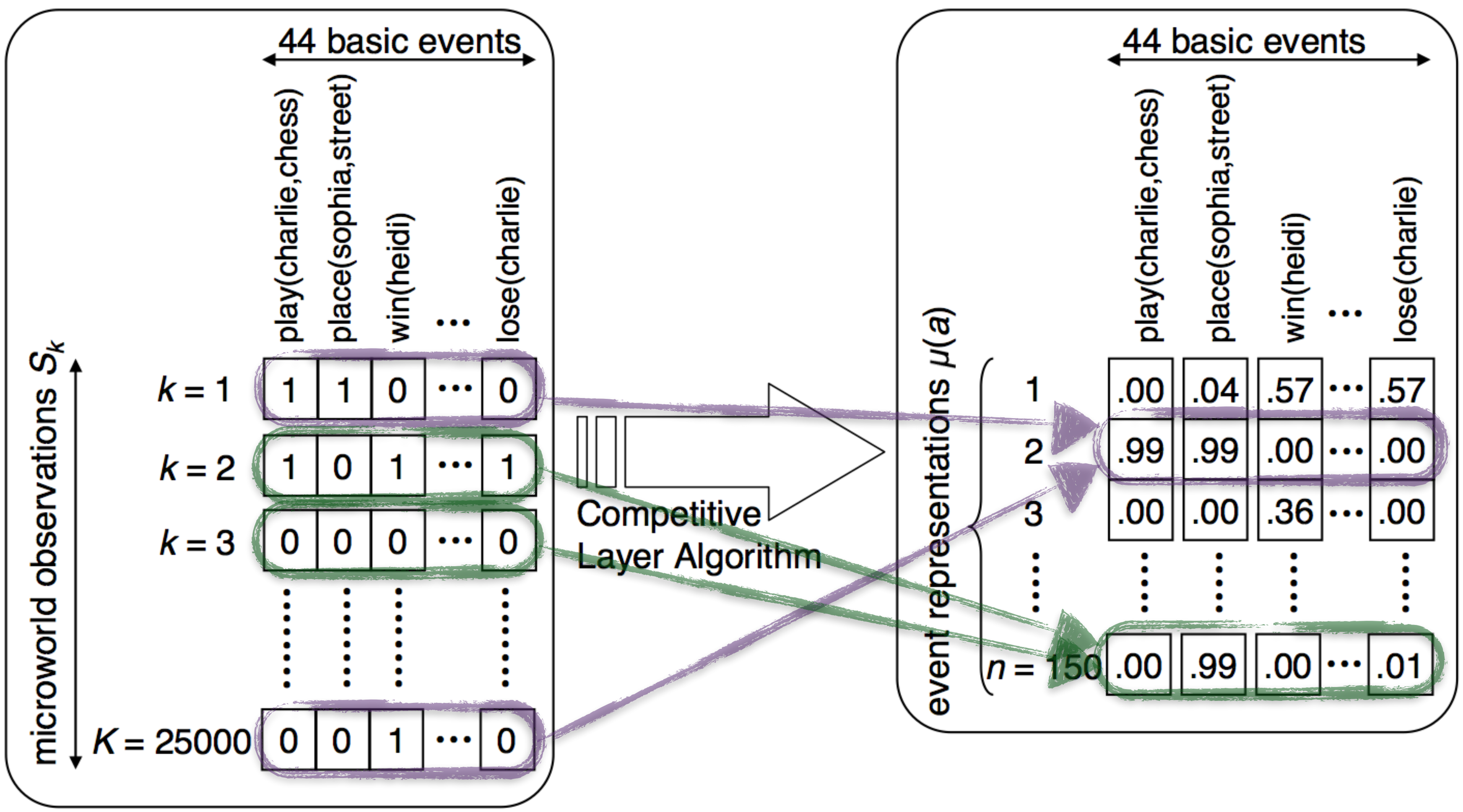
perceived word forms

word meaning/ semantics

Brouwer (2014), *PhD thesis*
Brouwer and Hoeks (under review)

Reduced situation vectors

Problem: Situation vectors are 25K-dimensional, and are hence far larger than the thematic-role assignment vectors (300D) in our neurocomputational model

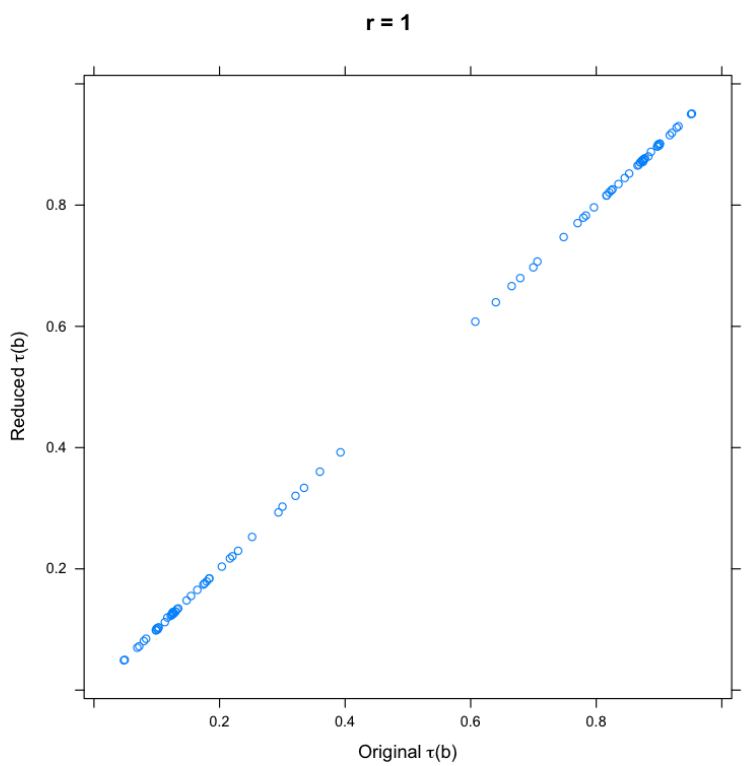


> justified if belief values estimated from original and reduced vectors are similar

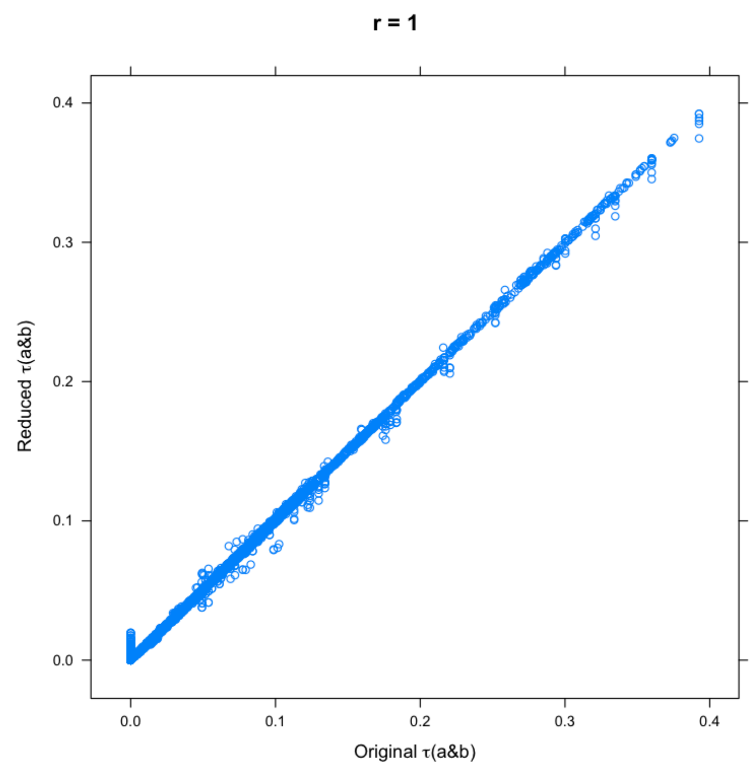
Frank et al. (2009). *Cognition*

Correlating belief values

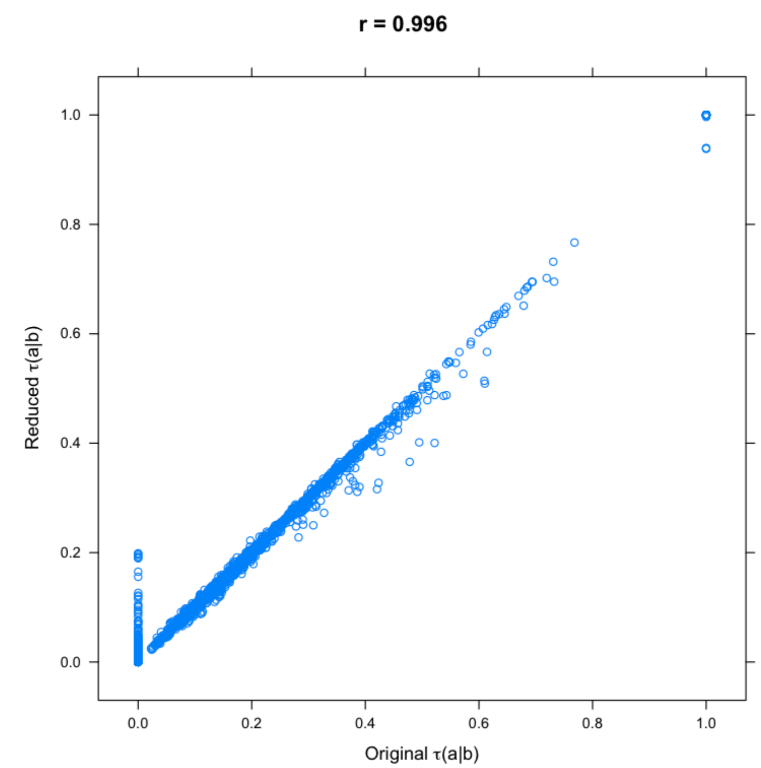
B(a)



B(a^b)



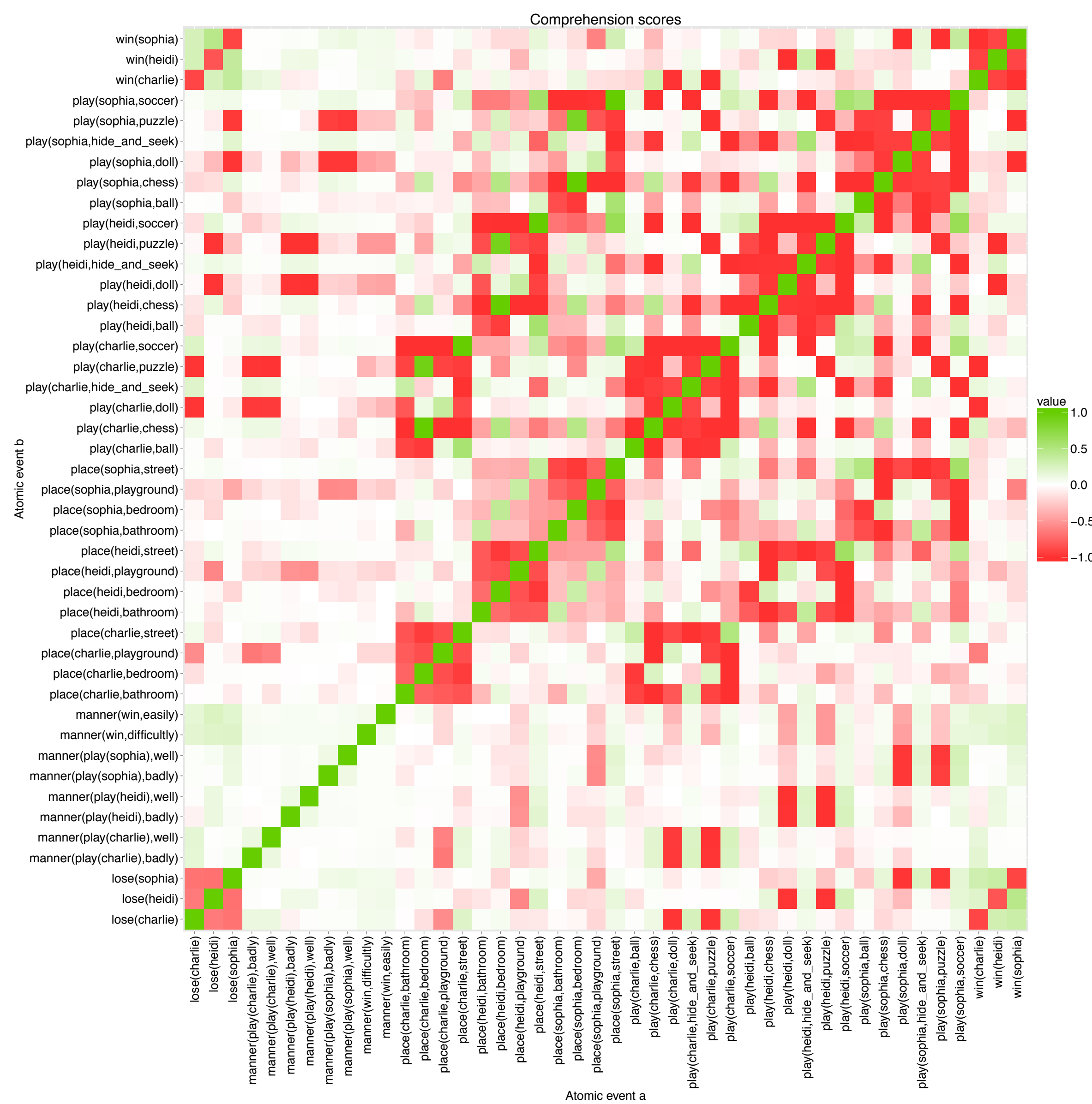
B(a|b)



Comparing world maps

Original

Reduced



The "difference" world

Zooming in: Reducing dimensionality

Q: How to go from a *m x n* (25K x 44) to a *k x n* (k=150) situation-state space?

> employ a competitive layer algorithm to classify the *m* observations into *k* classes

Step 0—define a *k x n* matrix with all cells set to 0.5, and assign each row a bias *b=1*;

Step 1—for each observation m_i in the original situation-state space, repeat:

(a) determine the cityblock distance between row m_i and each row k_j:

$$dist(m_i, k_j) = \sum_c |m_{i,c} - k_{j,c}| \quad \text{where } c \text{ is a column index}$$

(b) determine row k_w with the shortest, biased distance to m_i:

$$k_w = argmin_j(dist(m_i, k_j) - b_j)$$

(c) and update row k_w by means of

$$\Delta k_w = \alpha(m_i - k_w) \quad \text{where } \alpha \text{ is a learning rate parameter}$$

(d) next, decrease the bias b_w of row k_w (to a minimum of 1):

$$\Delta b_w = \beta b_w(1 - bw) \quad \text{where } \beta \text{ is a learning rate parameter}$$

(d) and, increase the bias of all other rows $k_j \neq k_w$:

$$\Delta b_j = \beta b_j$$

Step 2—repeat *step 1* for *N* training epochs

Frank et al. (2009). *Cognition*

From sentences to vectors

We want to train the model to map sequences of words constituting a sentence onto the DSS vector representing the meaning of this sentence

Q: How to go from sentences to DSS vectors?

Path: **sentence —> propositional logic form —> DSS vector**

Defining a Microlanguage—Lexicon

Class	Words	#
proper nouns	*charlie, heidi, sophia*	3
(pro)nouns	*boy, girl, someone, chess, hide-and-seek, soccer, football, game, puzzle, ball, doll, jigsaw, toy, ease, difficulty, bathroom, bedroom, playground, shower, street*	20
verbs	*wins, loses, beats, plays, is, won, lost, played*	8
adverbs	*well, badly, inside, outside*	4
prepositions	*with, to, at, in, by*	5
	Total	40

Frank et al. (2009). *Cognition*

Defining a Microlanguage—Grammar

$$
\begin{array}{lcl}
\mathrm{S} & \rightarrow & \mathrm{N}_n\ \mathrm{VP}_{n,v}\ \mathrm{APP}_{n,v} \\
\mathrm{N}_{\text{person}} & \rightarrow & \textit{charlie} \mid \textit{heidi} \mid \textit{sophia} \mid \textit{someone} \mid \textit{boy} \mid \textit{girl} \\
\mathrm{N}_{\text{game}} & \rightarrow & \textit{chess} \mid \textit{hide-and-seek} \mid \textit{soccer} \mid \textit{football} \mid \textit{game} \\
\mathrm{N}_{\text{toy}} & \rightarrow & \textit{puzzle} \mid \textit{ball} \mid \textit{doll} \mid \textit{jigsaw} \mid \textit{toy} \\
\mathrm{VP}_{\text{person, play}} & \rightarrow & \textit{plays} \\
\mathrm{VP}_{\text{person, win}} & \rightarrow & \textit{wins} \mid \textit{beats}\ \mathrm{N}_{\text{person}} \\
\mathrm{VP}_{\text{person, lose}} & \rightarrow & \textit{loses} \mid \textit{loses to}\ \mathrm{N}_{\text{person}} \\
\mathrm{VP}_{\text{game, play}} & \rightarrow & \textit{is played} \\
\mathrm{VP}_{\text{game, win}} & \rightarrow & \textit{is won} \\
\mathrm{VP}_{\text{game, lose}} & \rightarrow & \textit{is lost} \\
\mathrm{VP}_{\text{toy, play}} & \rightarrow & \textit{is played with}
\end{array}
$$

$$
\begin{array}{lcl}
\mathrm{APP}_{\text{person, play}} & \rightarrow & [\mathrm{N}_{\text{game}}]\ [\text{Manner}]\ [\text{Place}] \mid \mathrm{PP}_{\text{toy}}\ [\text{Place}] \mid \text{Place}\ \mathrm{PP}_{\text{toy}} \\
\mathrm{APP}_{\text{person, win}} & \rightarrow & [\mathrm{PP}_{\text{manner}}]\ [\mathrm{PP}_{\text{game}}]\ [\text{Place}] \mid \mathrm{PP}_{\text{game}}\ \mathrm{PP}_{\text{manner}} \mid \text{Place}\ \mathrm{PP}_{\text{game}} \\
\mathrm{APP}_{\text{person, lose}} & \rightarrow & [\mathrm{PP}_{\text{game}}]\ [\text{Place}] \mid \text{Place}\ \mathrm{PP}_{\text{game}} \\
\mathrm{APP}_{\text{game, play}} & \rightarrow & [\text{Manner}]\ [\mathrm{PP}_{\text{person}}]\ [\text{Place}] \\
\mathrm{APP}_{\text{game, win}} & \rightarrow & [\mathrm{PP}_{\text{manner}}]\ [\mathrm{PP}_{\text{person}}]\ [\text{Place}] \\
\mathrm{APP}_{\text{game, lose}} & \rightarrow & [\mathrm{PP}_{\text{person}}]\ [\text{Place}] \\
\mathrm{APP}_{\text{toy, play}} & \rightarrow & [\mathrm{PP}_{\text{person}}]\ [\text{Place}] \mid \text{Place}\ \mathrm{PP}_{\text{person}} \\
\text{Manner} & \rightarrow & \textit{well} \mid \textit{badly} \\
\text{Place} & \rightarrow & \textit{inside} \mid \textit{outside} \mid \mathrm{PP}_{\text{place}} \\
\mathrm{PP}_{\text{place}} & \rightarrow & \textit{in bathroom} \mid \textit{in shower} \mid \textit{in bedroom} \mid \textit{in street} \mid \textit{in playground} \\
\mathrm{PP}_{\text{person}} & \rightarrow & \textit{by}\ \mathrm{N}_{\text{person}} \\
\mathrm{PP}_{\text{game}} & \rightarrow & \textit{at}\ \mathrm{N}_{\text{game}} \\
\mathrm{PP}_{\text{toy}} & \rightarrow & \textit{with}\ \mathrm{N}_{\text{toy}} \\
\mathrm{PP}_{\text{manner}} & \rightarrow & \textit{with ease} \mid \textit{with difficulty}
\end{array}
$$

> this grammar generates 13.556 different sentences

Frank et al. (2009). *Cognition*

Defining a Microlanguage—Semantics

charlie plays chess	play(c, chess)
chess is played by charlie	play(c, chess)
girl plays chess	play(h, chess) ∨ play(s, chess)
heidi plays game	play(h, chess) ∨ play(h, hide&seek) ∨ play(h, soccer)
heidi plays with toy	play(h, puzzle) ∨ play(h, ball) ∨ play(h, doll)
sophia plays soccer well	play(s, soccer) ∧ manner(play(s), well)
sophia plays with ball in street	play(s, ball) ∧ place(s, street)
someone plays with doll	play(c, doll) ∨ play(h, doll) ∨ play(s, doll)
doll is played with	play(c, doll) ∨ play(h, doll) ∨ play(s, doll)
charlie plays	play(c, chess) ∨ play(c, hide&seek) ∨ play(c, soccer) ∨ play(c, puzzle) ∨ play(c, ball) ∨ play(c, doll)

Frank et al. (2009). *Cognition*

Logic forms —> Situation vectors

The situation vectors of ***atomic events*** are the columns of the situation-state matrix

The situation vectors of ***complex events*** can be found through ***fuzzy logic***:

$$\vec{v}(\neg a) = 1 - \vec{v}(a)$$

$$\vec{v}(a \wedge b) = \vec{v}(a)\vec{v}(b) \quad \text{where} \quad \vec{v}(a \wedge a) = \vec{v}(a)$$

Which gives us $\vec{v}(a \uparrow b) = \vec{v}(\neg \vec{v}(a \wedge b))$ and hence ***functional completeness***:

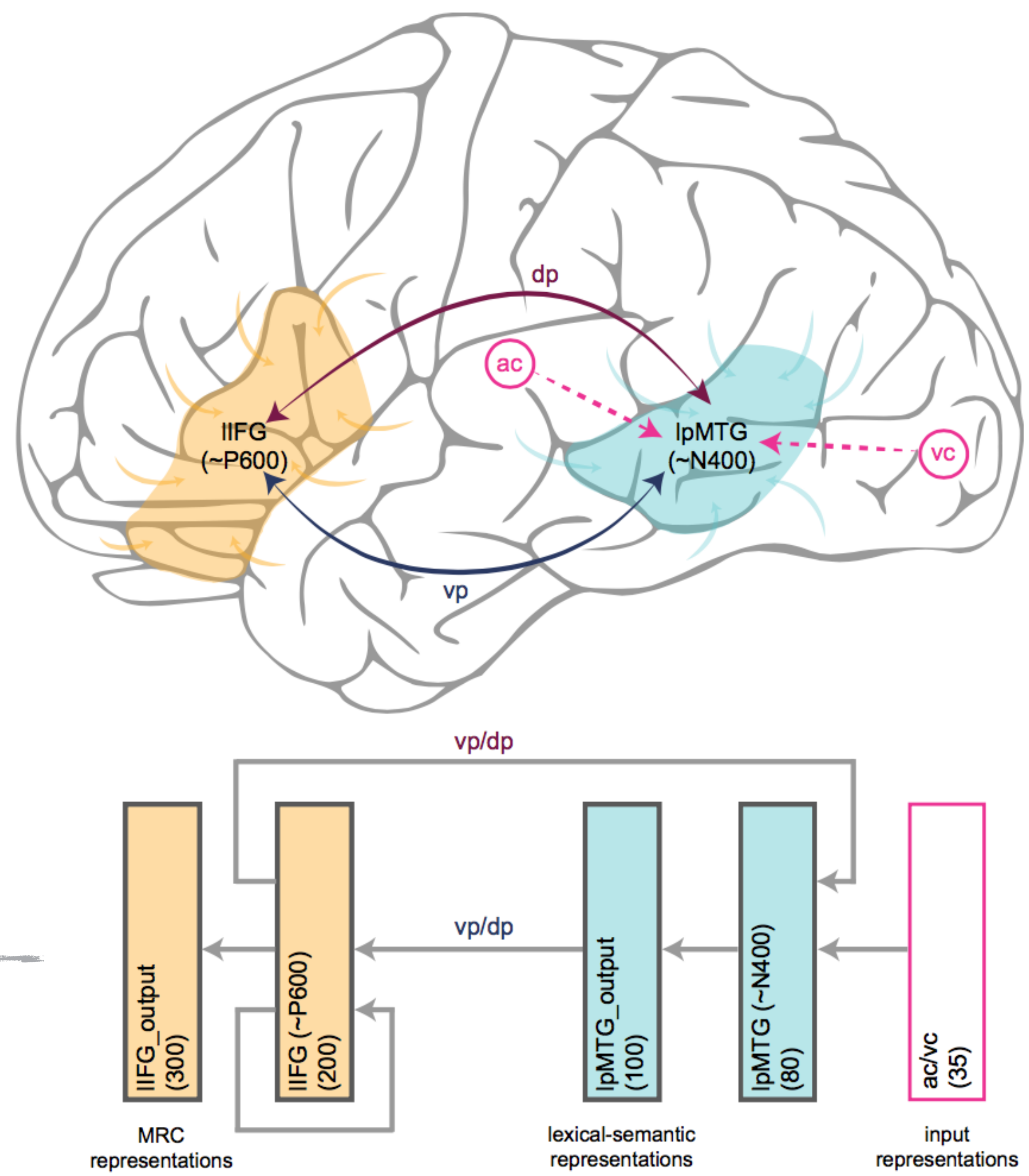
$$\vec{v}(a \vee b) = \vec{v}(\vec{v}(a \uparrow a) \uparrow \vec{v}(b \uparrow b))$$

$$\vec{v}(a \rightarrow b) = \vec{v}(a \uparrow \vec{v}(b \uparrow b)) = \vec{v}(a \uparrow \vec{v}(a \uparrow b))$$

$$\vec{v}(a \veebar b) = \vec{v}(\vec{v}(a \uparrow \vec{v}(a \uparrow b)) \uparrow \vec{v}(b \uparrow \vec{v}(a \uparrow b)))$$

> allows to derive vectors for events of arbitrary logical complexity

DSS vectors—Plug and Play!



DSS vectors ←

← perceived word forms

← word meaning/ semantics ←

Brouwer (2014), *PhD thesis*
Brouwer and Hoeks (under review)

What does the model 'understand'?

Given a sentence describing an atomic or complex event ***e***, the model will construct an output vector $\vec{v}(e')$ that is at best an approximation of $\vec{v}(e)$

> how well $\vec{v}(e')$ approximates $\vec{v}(e)$ is quantifiable through $comprehension(e, e')$

[if the model has 'understood' ***e***, the conditional belief ***B(e|e')*** should be higher than the prior belief ***B(e)***, yielding a positive comprehension score, and vice versa; moreover if ***B(e|e') = 1 iff e = e'***]

> we can also probe the state-of-affairs as 'understood' by the model, by computing $comprehension(a, e')$ for any other atomic or complex event ***a***

[for instance, for all the atomic events in the microworld]

Note—we can do both of these things after the processing of each word, and hence investigate how a state-of-affairs unfolds on word-by-word basis

Putting it all together …

```
model3 — rlwrap — 117×55
model:all_sents> dssScores basic_events "charlie plays chess"

**** Sentence:  charlie plays chess
**** Semantics: play(charlie,chess)
****
****                             charlie            plays              chess
****
****                             +0.08693  -0.01071  +0.07622  +0.72407  +0.80029
****
**** play(charlie,chess)         +0.08693  -0.01071  +0.07622  +0.72407  +0.80029  play(charlie,chess)
**** play(charlie,hide_and_seek) +0.04279  -0.01568  +0.02710  -0.77386  -0.74676  play(charlie,hide_and_seek)
**** play(charlie,soccer)        +0.12169  -0.03329  +0.08841  -0.87402  -0.78562  play(charlie,soccer)
**** play(heidi,chess)           +0.01111  +0.00486  +0.01597  +0.41746  +0.43343  play(heidi,chess)
**** play(heidi,hide_and_seek)   -0.08301  -0.00589  -0.08890  -0.77328  -0.86218  play(heidi,hide_and_seek)
**** play(heidi,soccer)          +0.00730  -0.00709  +0.00021  -0.88450  -0.88429  play(heidi,soccer)
**** play(sophia,chess)          +0.00809  +0.00035  +0.00844  +0.35767  +0.36612  play(sophia,chess)
**** play(sophia,hide_and_seek)  -0.11984  -0.00710  -0.12694  -0.71115  -0.83810  play(sophia,hide_and_seek)
**** play(sophia,soccer)         +0.03251  -0.02039  +0.01211  -0.90027  -0.88816  play(sophia,soccer)
**** play(charlie,puzzle)        -0.03140  +0.04140  +0.01001  -0.69627  -0.68626  play(charlie,puzzle)
**** play(charlie,ball)          +0.01103  -0.00114  +0.00989  -0.81493  -0.80505  play(charlie,ball)
**** play(charlie,doll)          -0.23204  +0.11227  -0.11977  -0.67018  -0.78995  play(charlie,doll)
**** play(heidi,puzzle)          -0.12599  +0.04865  -0.07733  -0.12012  -0.19746  play(heidi,puzzle)
**** play(heidi,ball)            +0.00373  -0.00318  +0.00055  -0.37581  -0.37527  play(heidi,ball)
**** play(heidi,doll)            +0.00341  -0.00959  -0.00618  -0.20651  -0.21269  play(heidi,doll)
**** play(sophia,puzzle)         -0.04606  -0.03433  -0.08039  +0.08060  +0.00021  play(sophia,puzzle)
**** play(sophia,ball)           +0.00915  -0.00004  +0.00912  -0.40594  -0.39683  play(sophia,ball)
**** play(sophia,doll)           -0.03115  +0.02611  -0.00504  -0.07983  -0.08487  play(sophia,doll)
**** win(charlie)                +0.09208  -0.03814  +0.05393  +0.19446  +0.24839  win(charlie)
**** win(heidi)                  +0.01076  -0.10392  -0.09316  -0.11974  -0.21290  win(heidi)
**** win(sophia)                 +0.01201  -0.06818  -0.05617  -0.34537  -0.40154  win(sophia)
**** lose(charlie)               +0.08350  -0.04772  +0.03578  -0.00125  +0.03453  lose(charlie)
**** lose(heidi)                 +0.01591  -0.01308  +0.00283  +0.05884  +0.06167  lose(heidi)
**** lose(sophia)                +0.02748  -0.02746  +0.00001  +0.06213  +0.06214  lose(sophia)
**** place(charlie,bathroom)     -0.45570  -0.04047  -0.49617  -0.40434  -0.90052  place(charlie,bathroom)
**** place(charlie,bedroom)      +0.11246  +0.01725  +0.12972  +0.71078  +0.84050  place(charlie,bedroom)
**** place(charlie,playground)   -0.24599  +0.07566  -0.17033  -0.65517  -0.82550  place(charlie,playground)
**** place(charlie,street)       +0.07425  -0.02316  +0.05109  -0.86119  -0.81011  place(charlie,street)
**** place(heidi,bathroom)       -0.01684  +0.02099  +0.00415  -0.44904  -0.44489  place(heidi,bathroom)
**** place(heidi,bedroom)        -0.00530  +0.00981  +0.00451  +0.45972  +0.46424  place(heidi,bedroom)
**** place(heidi,playground)     -0.02113  -0.01805  -0.03918  -0.29745  -0.33664  place(heidi,playground)
**** place(heidi,street)         +0.01236  -0.00930  +0.00307  -0.57345  -0.57038  place(heidi,street)
**** place(sophia,bathroom)      -0.03025  +0.03582  +0.00558  -0.34721  -0.34164  place(sophia,bathroom)
**** place(sophia,bedroom)       -0.01583  -0.00878  -0.02461  +0.43567  +0.41106  place(sophia,bedroom)
**** place(sophia,playground)    -0.05556  +0.01669  -0.03886  -0.15951  -0.19837  place(sophia,playground)
**** place(sophia,street)        +0.03195  -0.01436  +0.01759  -0.60041  -0.58283  place(sophia,street)
**** manner(play(charlie),well)  +0.04509  -0.00978  +0.03531  +0.05307  +0.08838  manner(play(charlie),well)
**** manner(play(charlie),badly) +0.04845  -0.01236  +0.03610  +0.05926  +0.09535  manner(play(charlie),badly)
**** manner(play(heidi),well)    -0.01155  +0.00267  -0.00888  +0.01330  +0.00442  manner(play(heidi),well)
**** manner(play(heidi),badly)   -0.02207  +0.00191  -0.02016  +0.01801  -0.00215  manner(play(heidi),badly)
**** manner(play(sophia),well)   +0.00287  -0.01083  -0.00797  -0.13684  -0.14481  manner(play(sophia),well)
**** manner(play(sophia),badly)  +0.00391  -0.00347  +0.00044  -0.02596  -0.02552  manner(play(sophia),badly)
**** manner(win,easily)          +0.01757  -0.01269  +0.00488  +0.03096  +0.03583  manner(win,easily)
**** manner(win,difficultly)     +0.01483  -0.01074  +0.00409  +0.01167  +0.01576  manner(win,difficultly)

model:all_sents>
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Discussion

> The DSS model provides a powerful framework for simulating rich situation model representations

> We have employed the DSS representations in a model of interpretation-level Surprisal

> We have also successfully used DSS vectors in a model of language production

> The use of DSS vectors paves way towards modeling pragmatic phenomena