

# Quantifier Verification Between Computational and Algorithmic Level

Jakub Szymanik

3rd Workshop on Semantic Processing, Logic and Cognition



university of  
 groningen

# Quantifiers



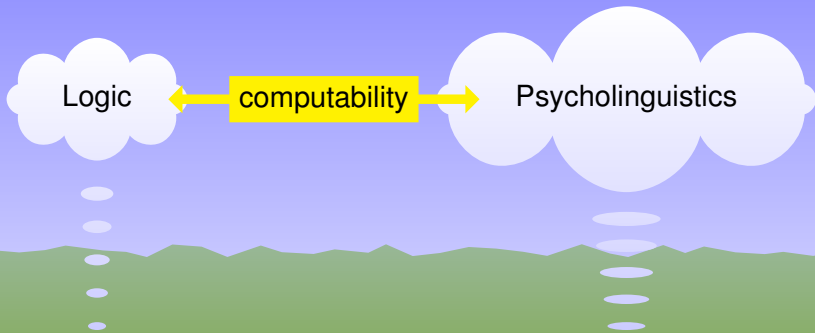
Logic

Quantifiers

Logic

Psycholinguistics

Quantifiers



# Quantifiers

Cognition and computability

Quantifiers and cognitive strategies

Generalized Quantifier Theory

Computing quantifiers

Intermezzo: "most" vs. "more than half"

Complexity and reaction time

Complexity and working memory

Dual task

Storage or comparison?

Schizophrenic patients

Outlook

# Outline

## Cognition and computability

Quantifiers and cognitive strategies

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# Marr's 3 levels of explanation

1. computational level:
  - ▶ problems that a cognitive ability has to overcome



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2. algorithmic level:
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1. computational level:
  - ▶ problems that a cognitive ability has to overcome
2. algorithmic level:
  - ▶ the algorithms that may be used to achieve a solution
3. implementation level:
  - ▶ how this is actually done in neural activity



Marr, *Vision: a computational investigation into the human representation and processing of the visual information*, 1983

# Between computational and algorithmic level

## Claim

*Logic can inform us about inherent properties of the problem.*

Level 1,5 Complexity level:

- ▶ complexity of the possible algorithms

## Example

The shorter the proof the easier the syllogism.



Geurts, Reasoning with quantifiers, 2003

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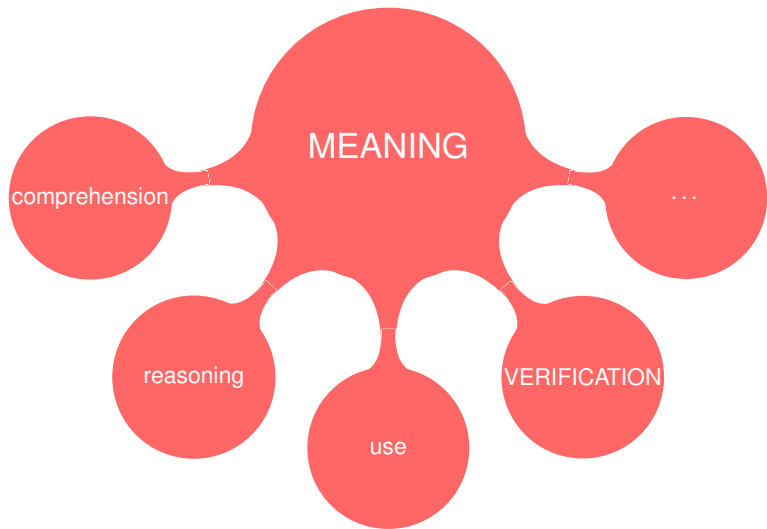
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# Aspects of meaning



# How are people doing it?

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  - ▶ cognitive architecture;
  - ▶ visual clues;
  - ▶ level of precision subjects want to achieve;
  - ▶ quantifiers;
  - ▶ ...



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- ▶ Those depend on:
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  - ▶ level of precision subjects want to achieve;
  - ▶ quantifiers;
  - ▶ ...

We discussed many examples at that workshop.

Expression  $\xRightarrow{\textit{computation}}$  denotation

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- ▶ Capacity of recognizing their truth-values.

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- ▶ Long-standing tradition.
- ▶ Meaning is a procedure for finding extension in a model.

# Expression $\xRightarrow{\text{computation}}$ denotation

- ▶ Ability to understand sentences.
- ▶ Capacity of recognizing their truth-values.
- ▶ Long-standing tradition.
- ▶ Meaning is a procedure for finding extension in a model.
- ▶ Adopted often with psychological motivations.

# Explicit formulation

Pavel Tichý “Intension in terms of Turing machines”, 1969:

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Pavel Tichý “Intension in terms of Turing machines”, 1969:

*[...] the fundamental relationship between sentence and procedure is obviously of a semantic nature; namely, **the purpose of sentences is to record the outcome of various procedures.***

*Thus e.g. the sentence “The liquid X is an acid” serves to record that the outcome of a definite chemical testing procedure applied to X is positive.*

*For what does it mean to understand, i.e. to know the sense of an expression? It does not mean actually to know its denotation but to know how the denotation can be found, how to pinpoint the denotation of the expression among all the objects of the same type. E.g. to know the sense of “taller” does not mean actually to know who is taller than who, but rather to know what to do whenever you want to decide whether a given individual is taller than another one. In other words, it does not mean to know which of the binary relations on the universe is the one conceived by the sense of “taller”, but to know a method or procedure by means of which the relation can be identified. (Tichý, 1969)*

# Psychological motivation

*The basic and fundamental psychological point is that, with rare exceptions, in applying a predicate to an object or judging that a relation holds between two or more objects, we do not consider properties or relations as sets. We do not even consider them as somehow simply intensional properties, but **we have procedures that compute their values for the object in question**. Thus, if someone tells me that an object in the distance is a cow, I have a perceptual and conceptual procedure for making computations on the input data that reach my peripheral sensory system [ . . . ] Fregean and other accounts scarcely touch this psychological aspect of actually determining application of a specific algorithmic procedure. (Suppes 1982)*



# Meaning as a collection of procedures

*I have defended the thesis that **the meaning of a sentence is a procedure or a collection of procedures** and that this meaning in its most concrete representation is wholly private and idiosyncratic to each individual. (Suppes 1982)*

# Main question

## Question

*How are different mechanisms related?*

## Question

*How we can classify them?*

## Question

*What can we gain by a logical analysis (Level 1.5)?*

## Question

*What are we computing in the case of quantifiers?*

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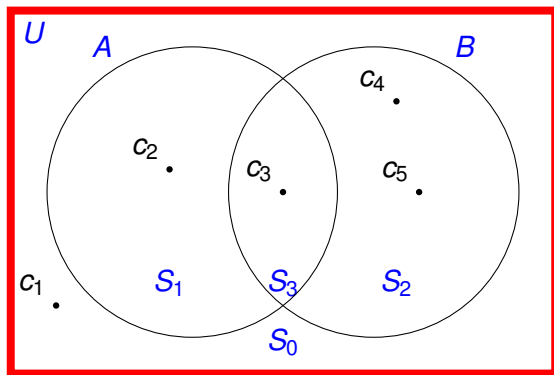
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# What is the semantic assigned to quantifiers?

1. Every poet has low self-esteem.
2. Some dean danced nude on the table.
3. At least 7 grad students prepared presentations.
4. An even number of the students saw a ghost.
5. Most of the students think they are smart.
6. Less than half of the students received good marks.

# Illustration



# Monadic quantifiers of type (1, 1)

## Definition

A monadic generalized quantifier of type (1,1) is a class  $Q$  of structures of the form  $M = (U, A_1, A_2)$ , where  $A_1, A_2 \subseteq U$ . Additionally,  $Q$  is closed under isomorphism.

# Examples

$\text{every} = \{(M, A, B) \mid A, B \subseteq M \text{ and } A \subseteq B\}$ .



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most =  $\{(M, A, B) \mid A, B \subseteq M \text{ and } \text{card}(A \cap B) > \text{card}(A - B)\}$

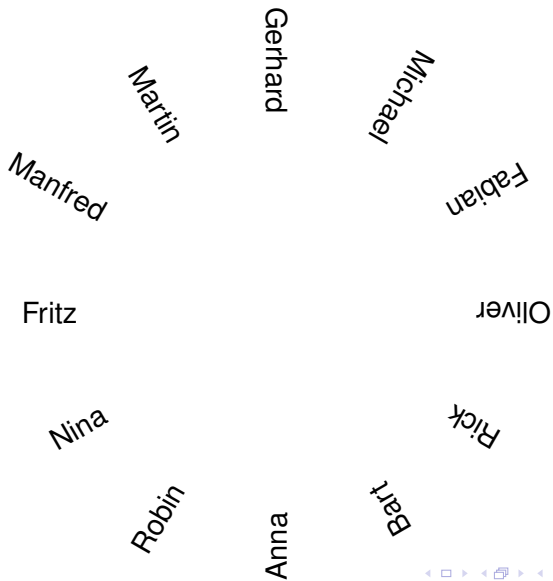
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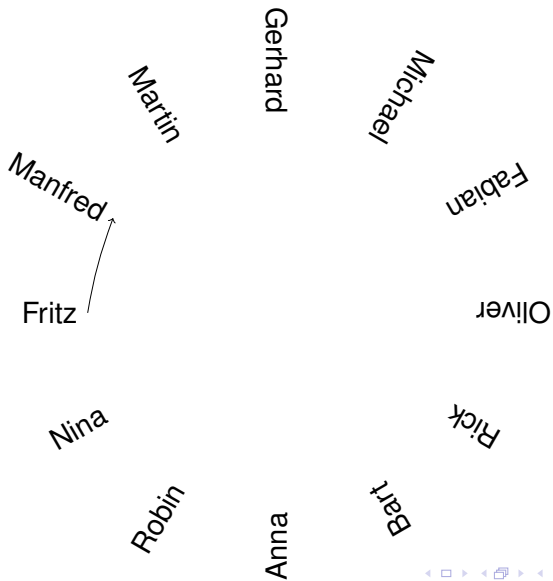
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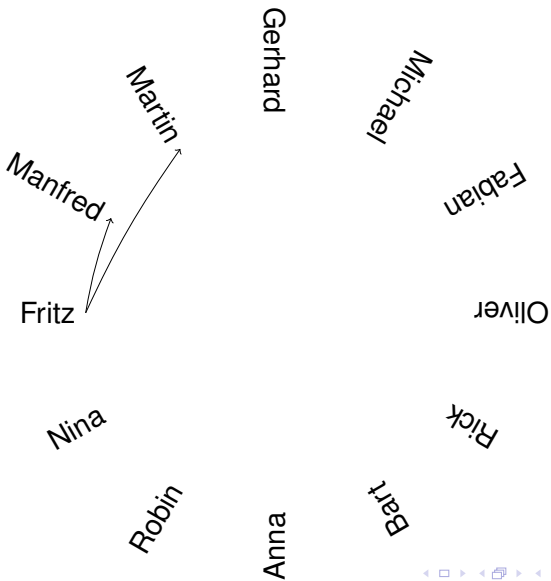
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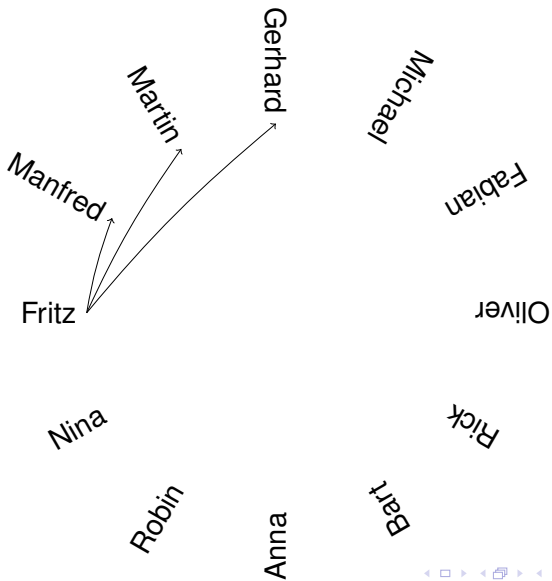
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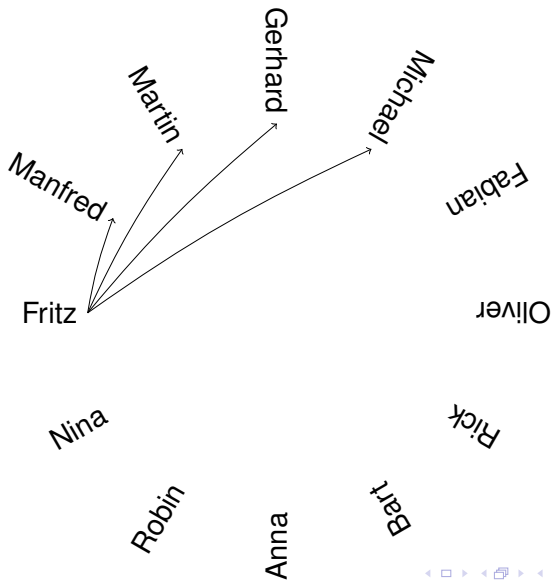
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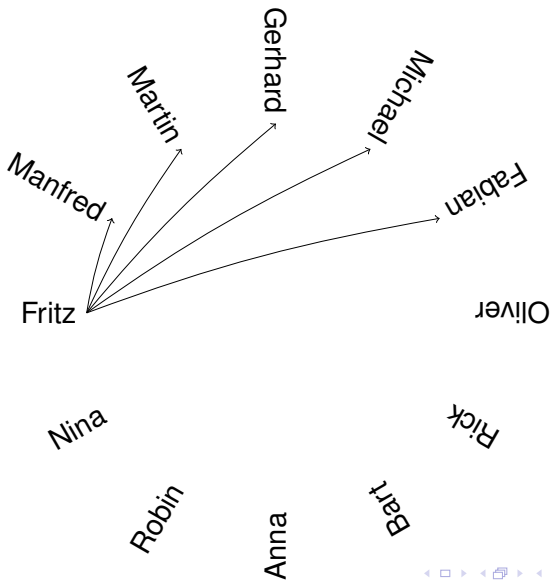
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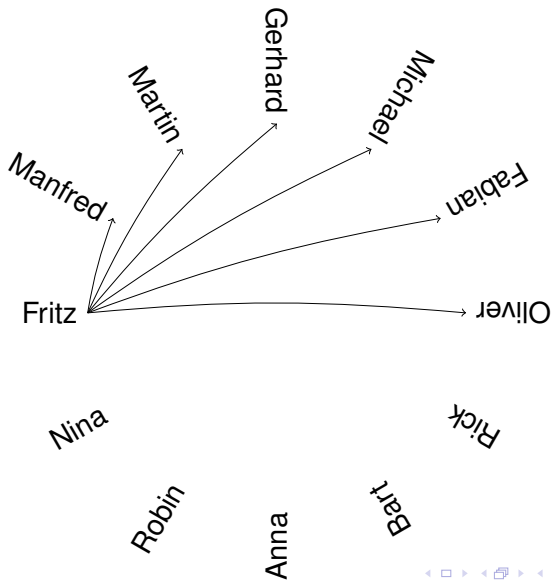
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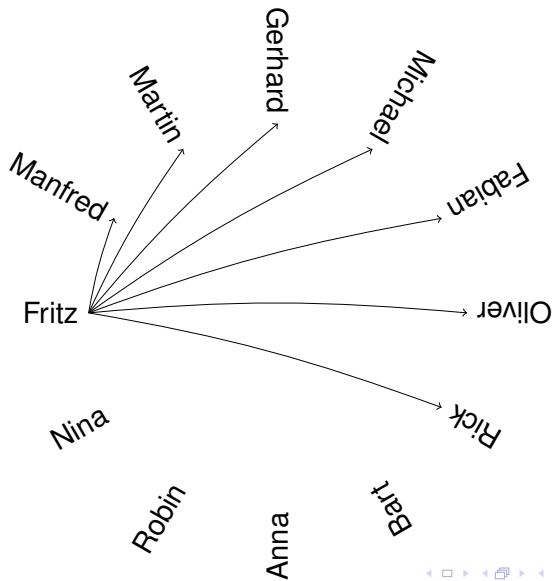
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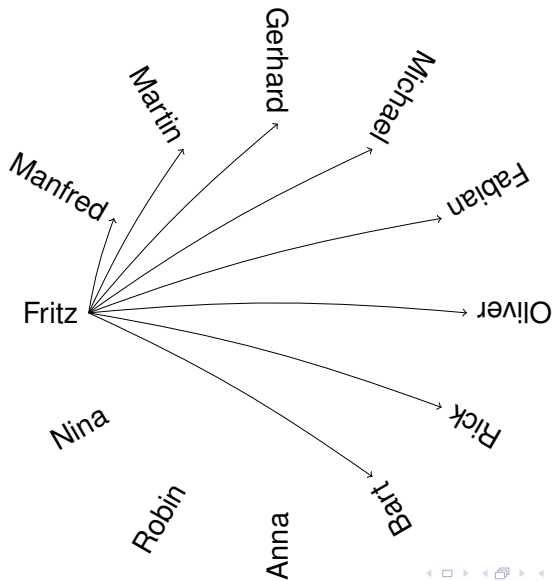
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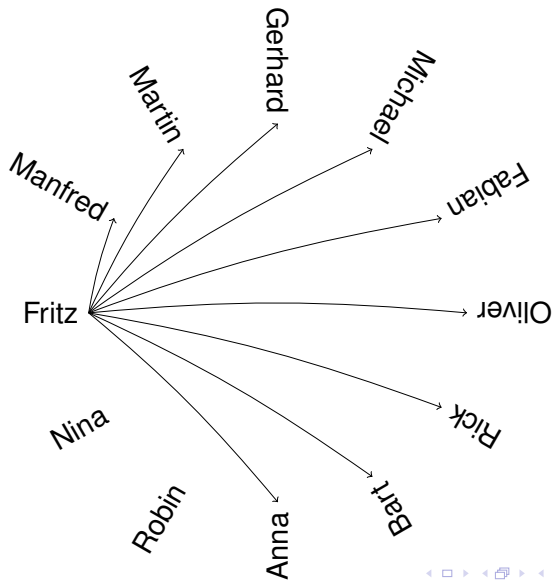
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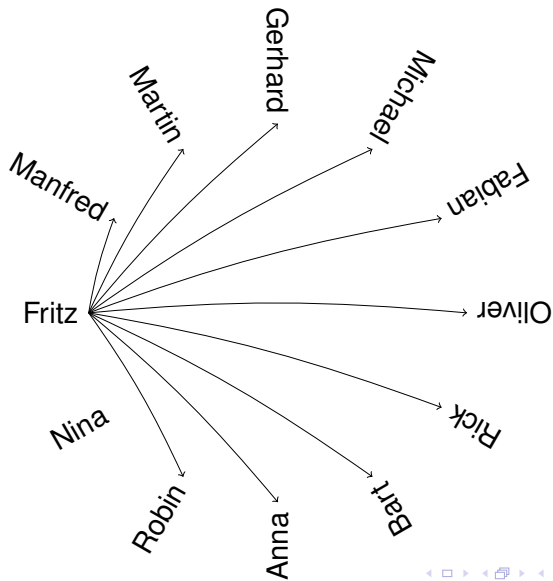
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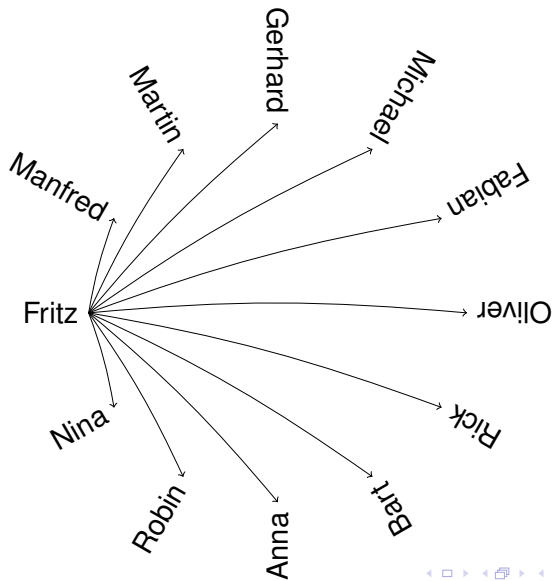
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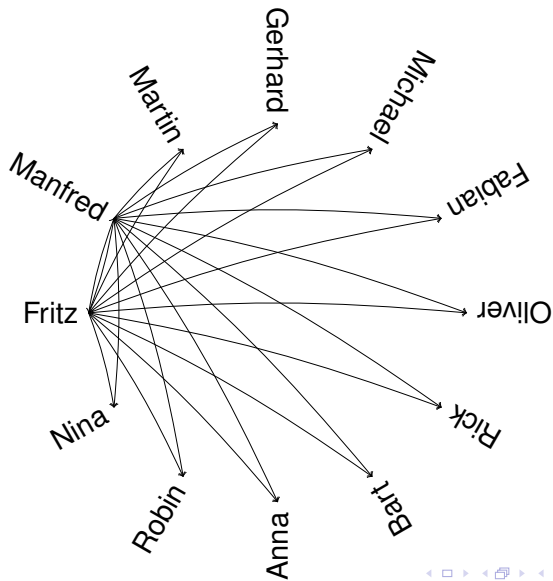
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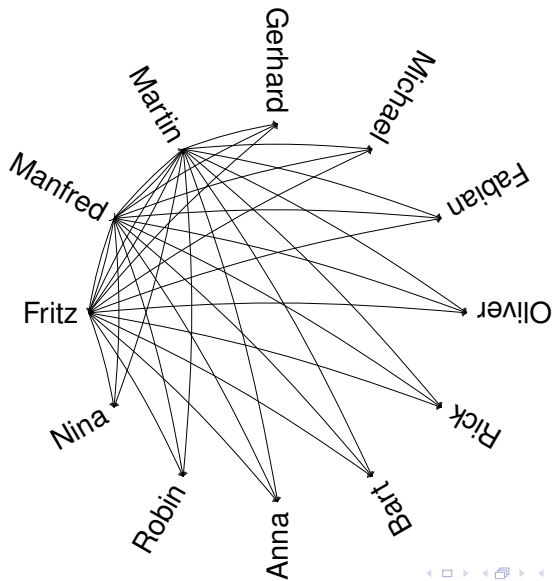
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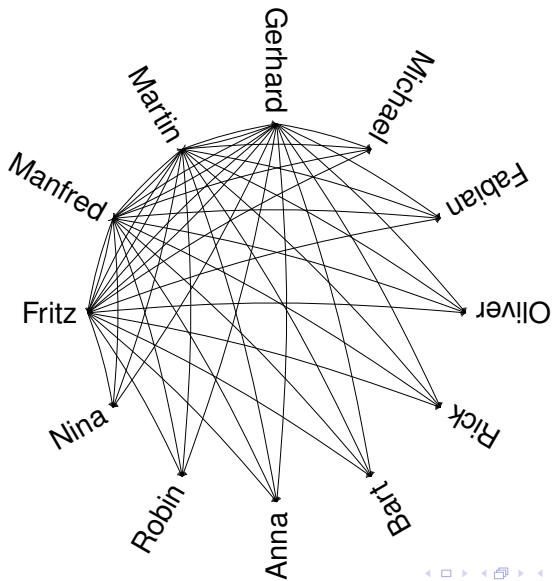
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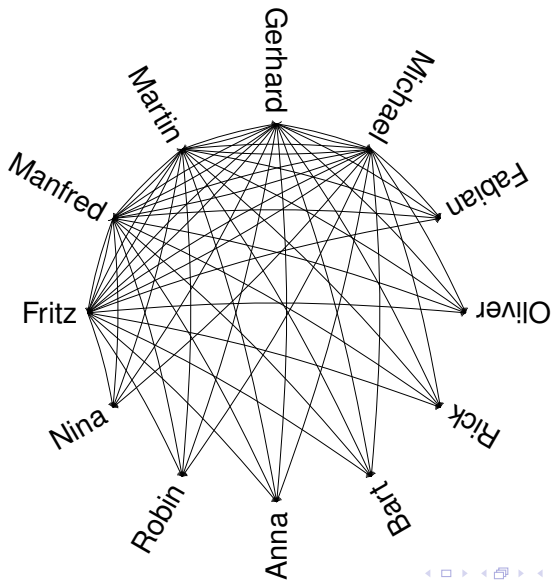
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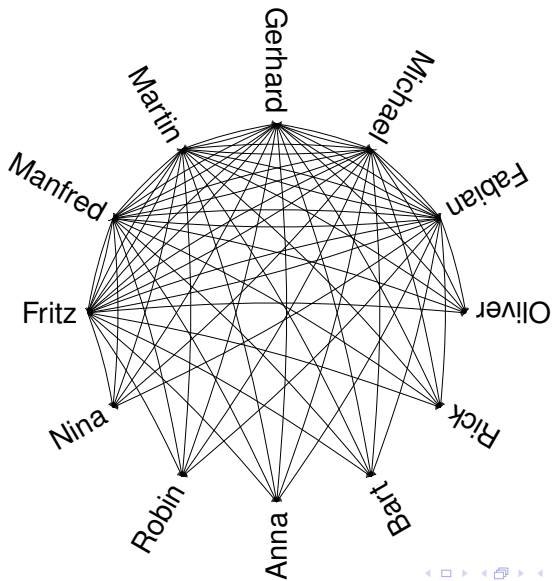
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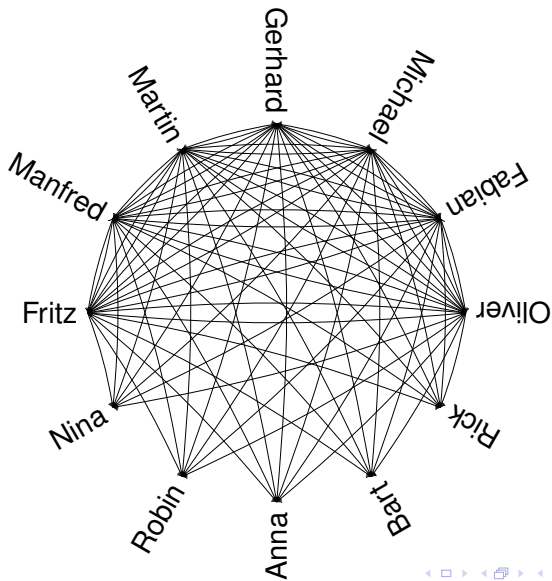
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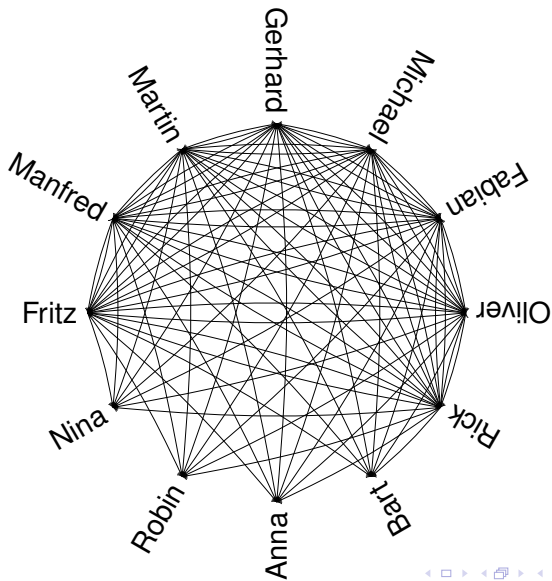
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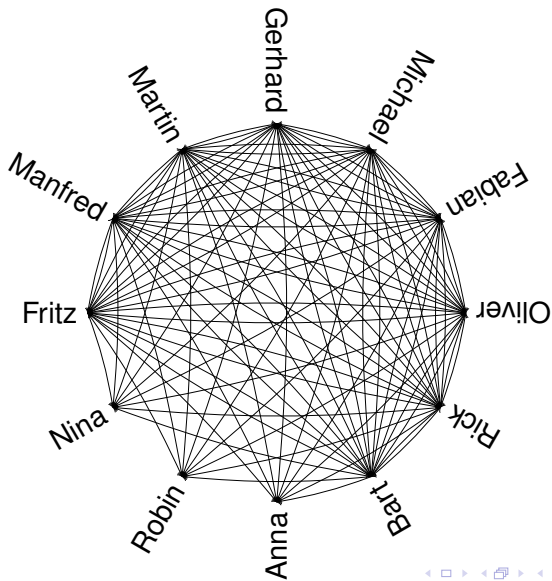
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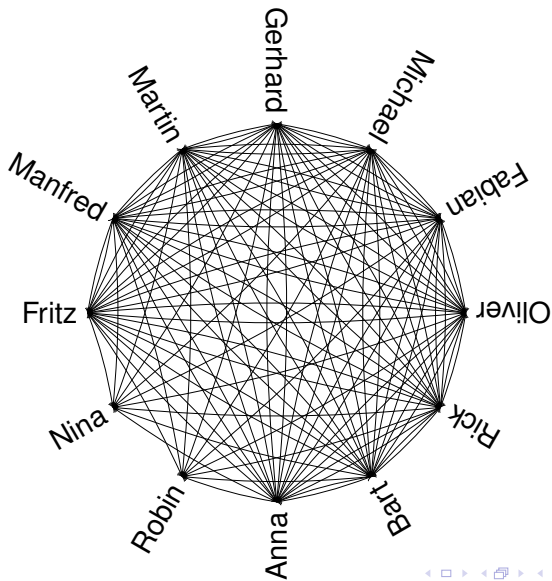
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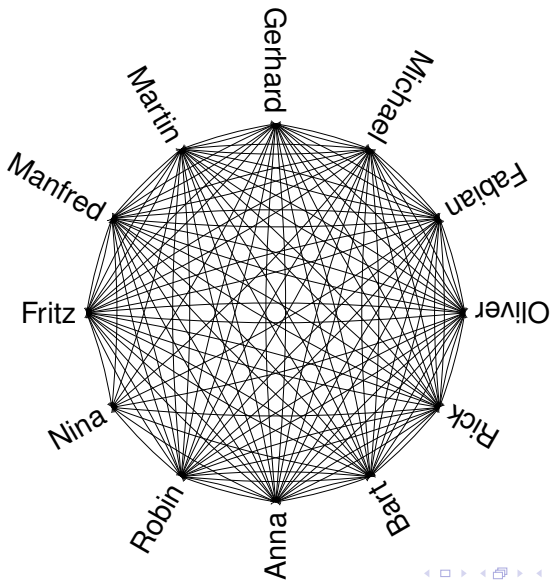
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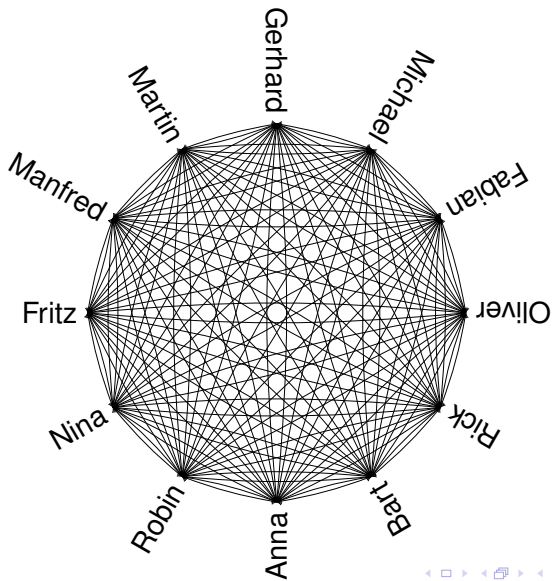
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We know what GQs denote. Now, it's time to see how we compute those denotations.

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Quantifiers and cognitive strategies

Generalized Quantifier Theory

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Intermezzo: "most" vs. "more than half"

Complexity and reaction time

Complexity and working memory

- Dual task

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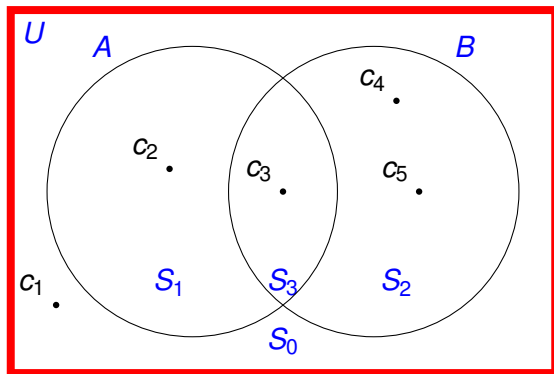
Outlook

# Automata perspective

*An attractive, but never very central idea in modern semantics has been to regard linguistic expressions as denoting certain “procedures” performed within models for the language. (Van Benthem, 1986)*



## How do we encode models



This model is uniquely described by  $\alpha_M = a_{\bar{A}\bar{B}} a_{A\bar{B}} a_{AB} a_{\bar{A}B} a_{\bar{A}B}$

# Step by step

- ▶ Restriction to **finite models** of the form  $M = (U, A, B)$ .

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 $a_{\bar{A}\bar{B}}$ ,  $a_{A\bar{B}}$ ,  $a_{\bar{A}B}$ ,  $a_{AB}$ , according to constituents it belongs to.

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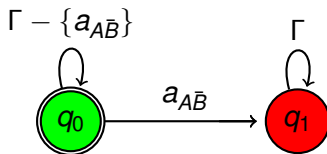
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- ▶  $\alpha_M$  describes the model in which:  
 $c_1 \in \bar{A}\bar{B}, c_2 \in A\bar{B}, c_3 \in AB, c_4 \in \bar{A}B, c_5 \in \bar{A}B$ .

# Step by step

- ▶ Restriction to **finite models** of the form  $M = (U, A, B)$ .
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 $c_1 \in \bar{A}\bar{B}, c_2 \in A\bar{B}, c_3 \in AB, c_4 \in \bar{A}B, c_5 \in \bar{A}B$ .
- ▶ **The class Q is represented by the set of words describing all elements of the class.**

# Aristotelian quantifiers

“all”, “some”, “no”, and “not all”



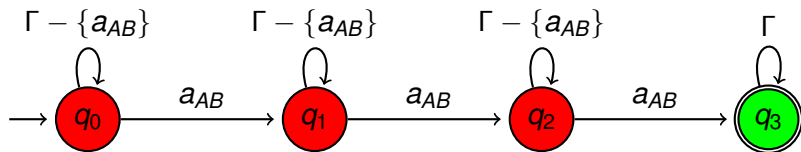
Finite automaton recognizing  $L_{All}$

$$L_{All} = \{\alpha \in \Gamma^* : \#a_{A\bar{B}}(\alpha) = 0\}$$



# Cardinal quantifiers

E.g. “more than 2”, “less than 7”, and “between 8 and 11”

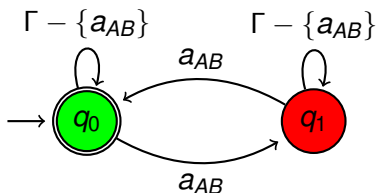


Finite automaton recognizing  $L_{\text{More than two}}$

$$L_{\text{More than two}} = \{\alpha \in \Gamma^* : \#a_{AB}(\alpha) > 2\}$$

# Parity quantifiers

E.g. “an even number”, “an odd number”

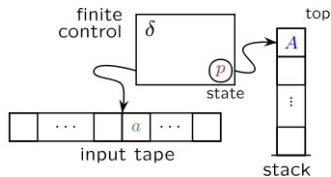


Finite automaton recognizing  $L_{\text{Even}}$

$$L_{\text{Even}} = \{\alpha \in \Gamma^* : \#a_{AB}(\alpha) \text{ is even}\}$$

# Proportional quantifiers

- ▶ E.g. “most”, “less than half”.
- ▶ Most *As are B* iff  $\text{card}(A \cap B) > \text{card}(A - B)$ .
- ▶  $L_{\text{Most}} = \{\alpha \in \Gamma^* : \#a_{AB}(\alpha) > \#a_{A\bar{B}}(\alpha)\}$ .
- ▶ There is no finite automaton recognizing this language.
- ▶ We need internal memory.
- ▶ A push-down automata will do.



# Summing up

Definability	Examples	Recognized by
FO	“all” “at least 3”	acyclic FA
$\text{FO}(D_n)$	“an even number”	FA
PrA	“most”, “less than half”	PDA

Quantifiers, definability, and complexity of automata

Van Benthem, Essays in logical semantics, 1986.

Mostowski, Computational semantics for monadic quantifiers, 1998.

# Does it say anything about processing?

## Question

*Do minimal automata predict differences in verification?*

# Does it say anything about processing?

## Question

*Do minimal automata predict differences in verification?*

We'll try to convince you that the answer is positive!

Level 1,5

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## Specific task: 'Most' vs. 'More than half'



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- ▶ Different distribution in corpus.
- ▶ They trigger different verification strategies.



Solt, On orderings and quantification: the case of *most* and *more than half*, 2010



Hackl, On the grammar and processing of proportional quantifiers, *Natural Language Semantics*, 2009

# Specific task: 'Most' vs. 'More than half'

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Solt, On orderings and quantification: the case of *most* and *more than half*, 2010



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We saw data on 'most'; let's look into 'more than half'.

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# Predictions

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- ▶ Aristotelian qua. < parity qua. < proportional qua.

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- ▶ RT will increase along with the computational resources.
- ▶ Aristotelian qua. < parity qua. < proportional qua.
- ▶ Aristotelian qua. < cardinal qua. of high rank.

# Materials

Grammatically simple propositions in Polish, like:

1. Some cars are red.
2. More than 7 cars are blue.
3. An even number of cars is yellow.
4. Less than half of the cars are black.

## Materials continued

*More than half of the cars are yellow.*



An example of a stimulus used in the first study



# Procedure

- ▶ 8 different quantifiers divided into four groups.

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# Procedure

- ▶ 8 different quantifiers divided into four groups.
  - ▶ “all” and “some” (acyclic 2-state FA);
  - ▶ “odd” and “even” (2-state FA);
  - ▶ “less than 8” and “more than 7” (FA);
  - ▶ “less than half” and “more than half” (PDA).

# Procedure

- ▶ 8 different quantifiers divided into four groups.
  - ▶ “all” and “some” (acyclic 2-state FA);
  - ▶ “odd” and “even” (2-state FA);
  - ▶ “less than 8” and “more than 7” (FA);
  - ▶ “less than half” and “more than half” (PDA).
- ▶ Quantity of target items near the criterion of validation.

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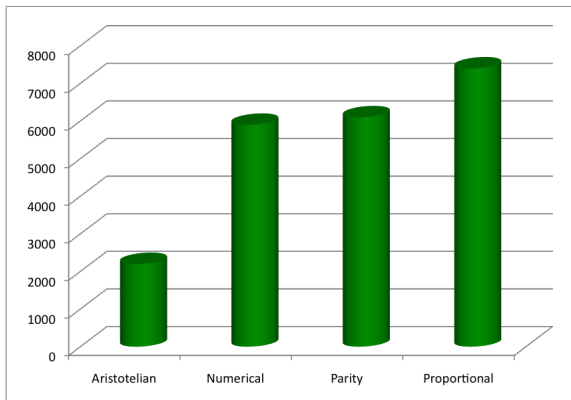
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  - ▶ “less than half” and “more than half” (PDA).
- ▶ Quantity of target items near the criterion of validation.
- ▶ Numerical and proportional quantifiers logically equivalent.

# Accuracy

Quantifier group	Examples	Percent
Aristotelian	all, some	99
Parity	odd, even	91
Cardinal	less than 8, more than 7	92
Proportional	less than half, more than half	85

The percentage of correct answers





Szymaniki & Zajenkowski, Comprehension of simple quantifiers. Empirical evaluation of a computational model, Cognitive Science, 2010

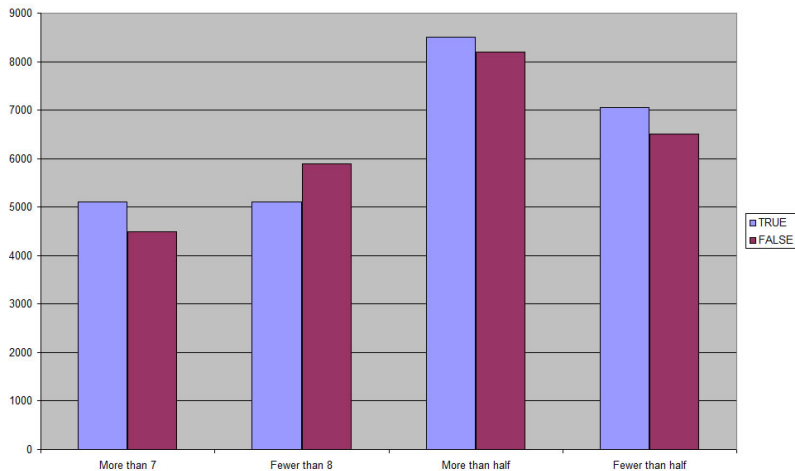
# It interacts with monotonicity and truth-value

1. “More than 7”: true > false ( $8 > 7$ ).

## It interacts with monotonicity and truth-value

1. “More than 7”: true  $>$  false ( $8 > 7$ ).
2. “Fewer than 8”: true  $<$  false ( $7 < 8$ ).

# Interaction effect



Szymanik & Zajenkowski, Computational approach to monotonicity in sentence-picture verification, 2011

# Outline

Cognition and computability

Quantifiers and cognitive strategies

Generalized Quantifier Theory

Computing quantifiers

Intermezzo: "most" vs. "more than half"

Complexity and reaction time

**Complexity and working memory**

Dual task

Storage or comparison?

Schizophrenic patients

Outlook

# McMillan et al. fMRI studies

Differences in brain activity.

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recruit right inferior parietal cortex.

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- ▶ Only higher-order activate working-memory capacity:  
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Differences in brain activity.

- ▶ All quantifiers are associated with numerosity:  
recruit right inferior parietal cortex.
- ▶ Only higher-order activate working-memory capacity:  
recruit right dorsolateral prefrontal cortex.

## Claim

*But definability seems not to be fine grained enough.*



McMillan et al., Neural basis for generalized quantifiers comprehension, *Neuropsychologia*, 2005



Szymanik, A Note on some neuroimaging study of natural language quantifiers comprehension, *Neuropsychologia*, 2007

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# Baddeley's model

WM unified system responsible for the performance in complex tasks.

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WM unified system responsible for the performance in complex tasks.

- ▶ The model consists of:
  - ▶ temporary storage units:
    - ▶ phonological loop;
    - ▶ visual loop;
  - ▶ a controlling system (central executive).



Baddeley, Working memory and language: an overview, 2003

# Span test

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- ▶ To assess the working memory construct.

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- ▶ What is:
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  - ▶ the degree of understanding?
- ▶ Engagement of processing and storage functions.



Daneman and Carpenter, Individual differences in working memory, 1980

# 'Computational' theory of WM

## Observation

*A trade-off between processing and storage functions.*

# 'Computational' theory of WM

## Observation

*A trade-off between processing and storage functions.*

## Hypothesis

*One cognitive resource – competition for a limited capacity.*



Daneman and Merikle, Working memory and language comprehension, 1996

# Experimental setup

## Question

*How additional memory load influences quantifier verification?*

# Experimental setup

## Question

*How additional memory load influences quantifier verification?*

Combined task:

- ▶ memorize sequences of digits;
- ▶ verify quantifier sentences;
- ▶ recall digits.

# Results

- ▶ Trade-off effect only for PQs.
- ▶ WM engagement in PQs is qualitatively different.



Szymanik & Zajenkowski, Quantifiers and working memory, LNCS, 2010



Szymanik & Zajenkowski, Contribution of working memory in the parity and proportional judgments, Belgian Journal of Linguistics, forthcoming

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# WM in Parity and Proportional Judgments

- ▶ Short-term memory retention in verification:
  - ▶ Sternberg's STM test;
  - ▶ Verification task;

# Sternberg's test

On each trial of the test, the subjects were presented with a random series of different digits, one at a time, for 300 ms, followed by a blank screen and the test digit. Participants had to decide whether the test digit had appeared in the previously displayed string.

# Results

- ▶ Only in 8 digit condition:
  1. Quantifiers were positively associated with memory task;
  2. The higher memory score, the better verification;
  3. The correlations were very similar.

Memory task	Quantifier accuracy		Quantifier RT	
	DQs	PQs	DQs	PQs
four items	0.18	0.21	0.24	0.24
six items	0.12	0.77	-0.25	-0.05
eight items	0.34*	0.38*	-0.16	0.03



Szymanik & Zajenkowski, Contribution of working memory in the parity and proportional judgments, Belgian Journal of Linguistics, forthcoming

# Comparison and not memorization is really hard

- ▶ Proportional and parity quantifiers differ in dual task;
- ▶ But they seem to engage STM equally;
- ▶ The difference due to the executive resources.

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# Experiment

- ▶ Compare performance of:

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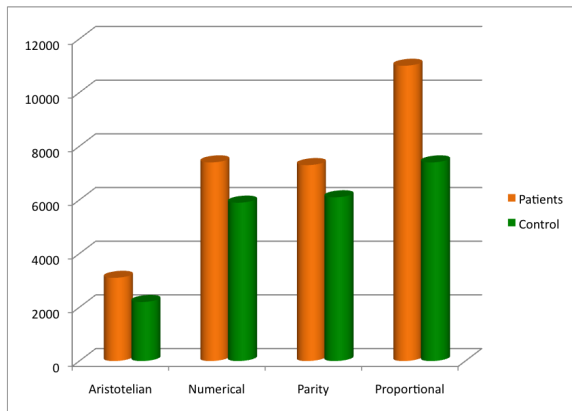
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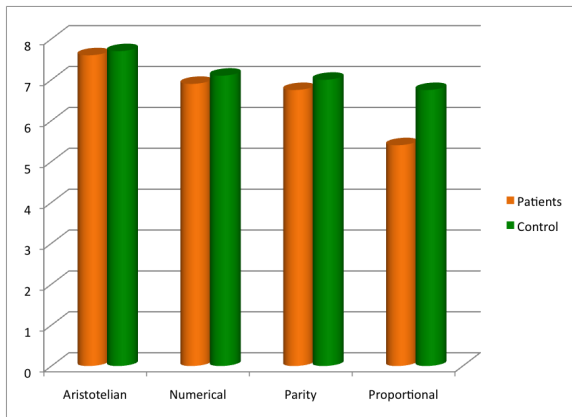
# Experiment

- ▶ Compare performance of:
  - ▶ Healthy subjects.
  - ▶ Patients with schizophrenia.
    - ▶ Known WM deficits.

# RT data



# Accuracy data



Zajenkowski et al., A computational approach to quantifiers as an explanation for some language impairments in schizophrenia, *Journal of Communication Disorders*, 2011.

# Summary

## Conclusion

*Automata model is psychologically plausible.*

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- ▶ Between Marr's level 1 and 2.

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## Conclusion

*Precision with proportional quantifiers is cognitively challenging.*

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Outlook



# Bigger picture

- ▶ Enrich the model:
  1. Approximate Number System;
  2. Visual clues;



Pietroski et al., The Meaning of 'Most': semantics, numerosity, and psychology, *Mind and Language*, 1999

# Neurocognitive computational modeling

- ▶ Mechanism selection;
  - ▶ 'more than half' vs. 'most'

# Neurocognitive computational modeling

- ▶ Mechanism selection;
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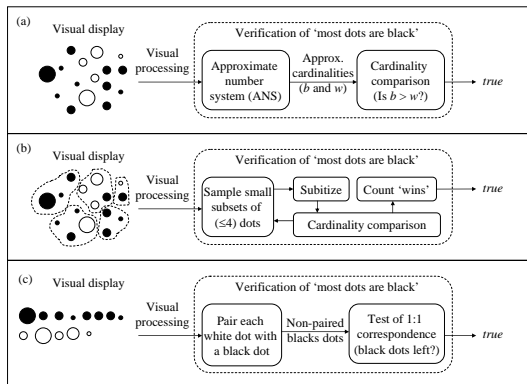
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- ▶ Translate to neurocognitive setting, e.g.;
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- ▶ Behavioral experiments:
  - ▶ determining factors influencing meaning selection.
- ▶ fMRI experiments.



Dehaene & Cohen, Cultural recycling of cortical maps, Neuron, 2007

# Modeling example





Big THANKS to the Organizers