Generalized Quantifiers and Working Memory: Disentangling Encoding from Verification

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Elevator Pitch

To probe working memory demands associated to the *canonical specification* of distinct quantifiers, we measured increases in pupil size relative to two interest periods:

- **Encoding** (before the onset of the color predicate)
- **Verification** (at key press).

Introduction

The semantic representation of a quantifier plays a crucial role in identifying the corresponding verification procedure [3,4,6]. But are there meaning effects when the subject is not engaging in verification? We select quantifiers from four categories, according to their logical/complexity characterizations, and ask:

I. whether there are effects of quantifier type on working memory before engaging in verification is possible

II. which theories of quantifier/verification would these eventual effects be consistent with?
⇒ We consider the ANS [1] vs. Semantic Automata [7]

Pupillometry: event-related measures of the variations in pupil size. Studies [2,5] show:

- a correspondence between pupillary dilation and working memory load in visual search tasks
- pupil size sensitive to local resource demands in sentence comprehension.

Methods

Participants (age: 20 – 35; n = 17) were asked to judge auditory sentences of the type:

<Quantifier> of the dots are <Color>

against a visual display showing two sets of colored dots.

- The onset of the visual display was delayed until the onset of the disambiguating predicate (i.e. the color predicate).
- Each quantifier was associated to two target colors (*blue*, *yellow*) in two verification conditions (*true*, *false*)
- Each quantifier-color combination was presented for 6 trials in true condition, and 6 trials in false condition.
- Proportions of colors in the visual arrays varied to avoid fixed counting strategies.
- Each quantifier presented 24 times, for a total of 216 trials.

Data recorded with an SR Research EyeLink 1000 desktop system using 35mm lens, at a sampling frequency of 500 Hz.
For each interest period, we fit linear-mixed models in R with RT, mean, and max. pupil response as dependent variables; Quantifier Category (4 levels) and Proportion (14 levels) as fixed effects; and Participant as a random effect.

Materials

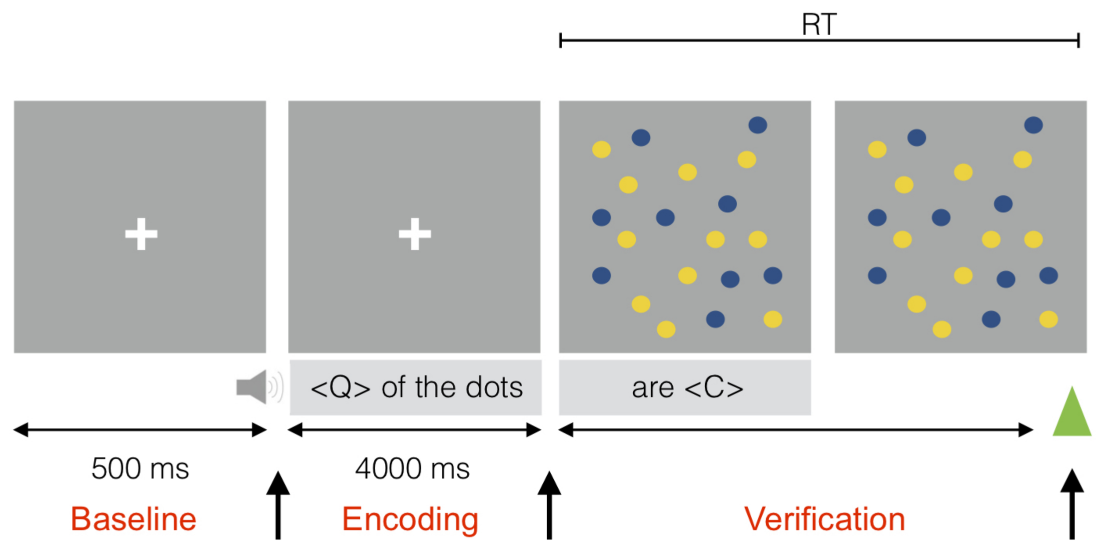


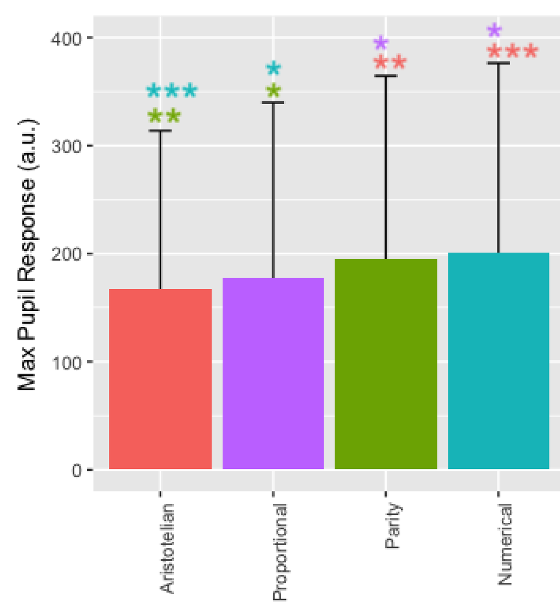
Figure: Trial Design

Quantifier	Magnitude	Category	Logic
All No Some		Aristotelian	FO
At least n At most n	$n = 2 \dots 7;9 \dots 14$	Numerical	FO
An even number of An odd number of		Parity	SO
Most More than half		Proportional	SO

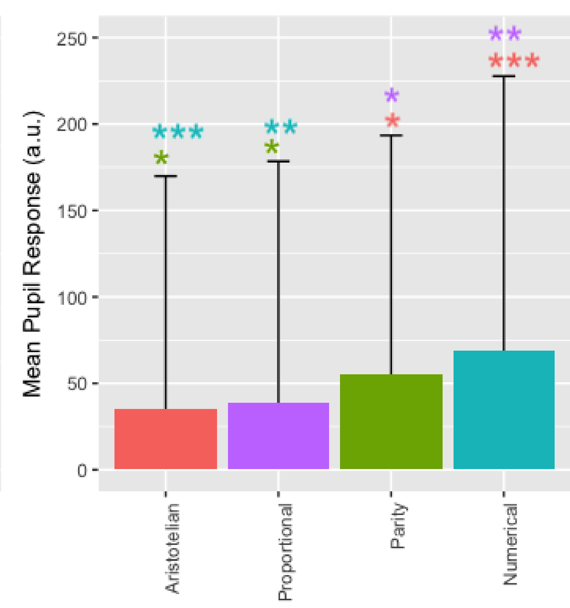
Table: Quantifiers grouped by Category

Results

Pupillometry

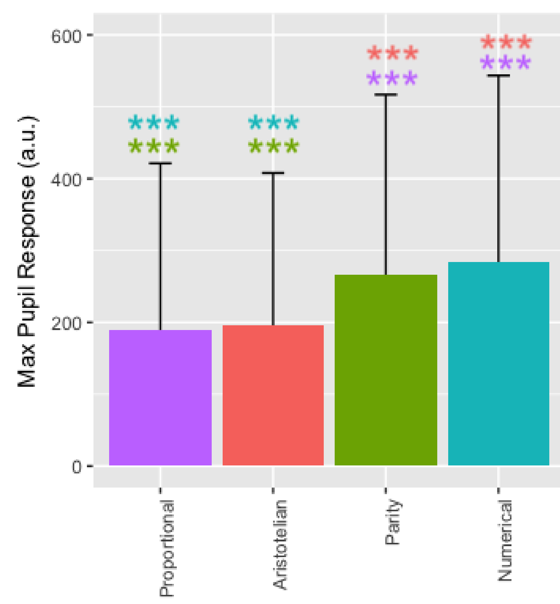


(a)

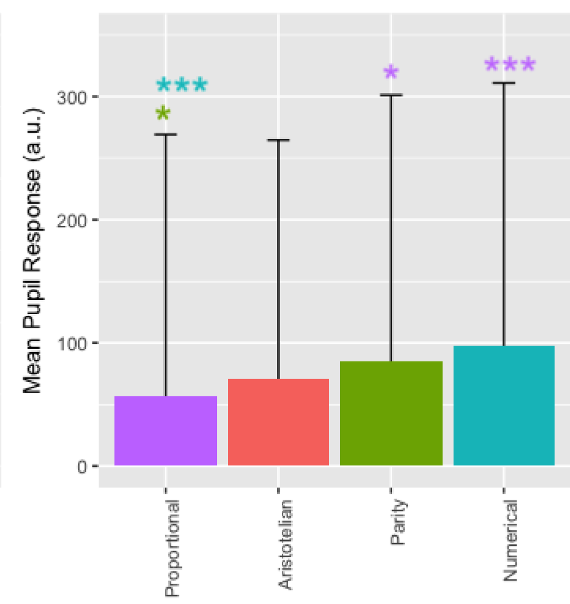


(b)

Figure: Max. (a) and Mean (b) pupil size during **Encoding**



(a)



(b)

Figure: Max. (a) and Mean (b) pupil size during **Verification**

RTs

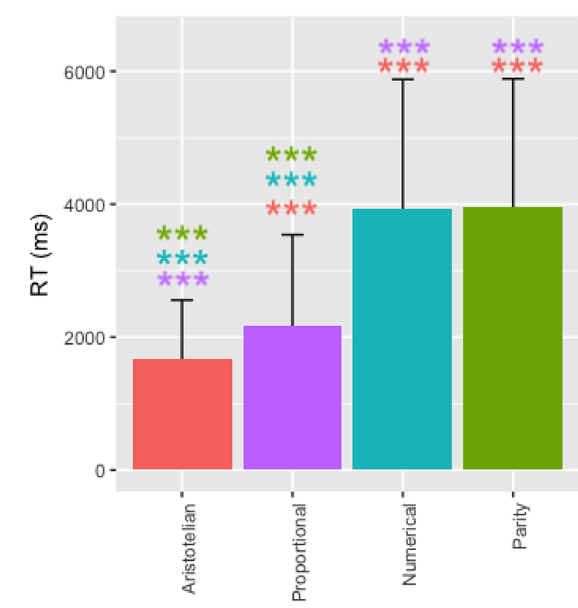


Figure: RTs (in ms) from image onset to end of trial

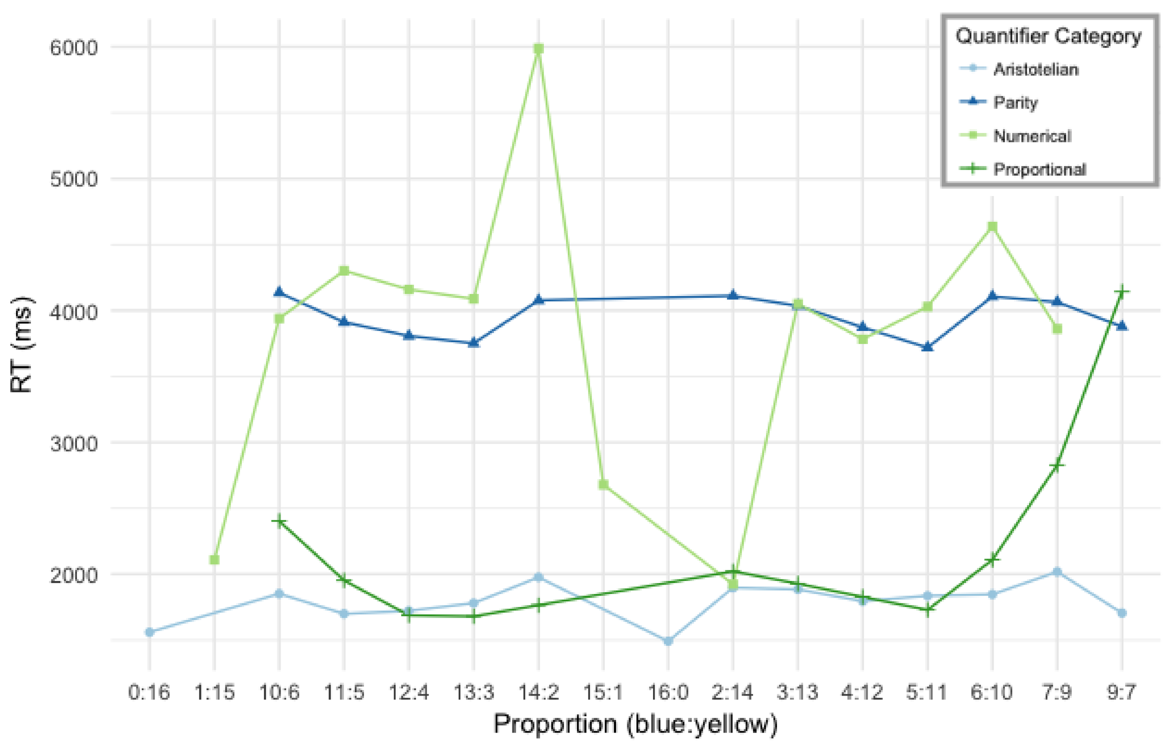


Figure: RTs by quantifier Category and Proportions of colored dots (blue:yellow) during verification.

Discussion

Pupillometry Effects. Quantifier effects on mean ($F(3, 3190) = 7.36$, $p < 0.001$) and max ($F(3, 3190) = 8.14$, $p < 0.001$) pupil response during **encoding** clustered in two main groups:

Aristotelian-Proportional << Parity-Numerical

suggesting comprehension effects on working memory guided by the semantic content of different quantifiers.
Similar cluster effects found on mean ($F(3, 3189) = 5.117$, $p < 0.01$) and max ($F(3, 3190) = 31.740$, $p < 0.001$) pupil response during **verification**.

RTs. Effects on RT for quantifier category ($F(3, 3189) = 662.23$, $p < 0.001$) and proportion ($F(15, 3189) = 11.37$, $p < 0.001$), with:

Aristotelian < Proportional < Parity/Numerical

Contra [7], suggests a distinction between:

- the amount of working memory recruited by a quantifier (as indexed by pupil response)
- the length of the verification procedure (as in the RTs).

Consistently, RTs divided by proportion show:

- Proportional RTs pattern as Aristotelian while the colored sets' cardinalities are far from each other
- Increase towards Numerical/Parity quantifiers when they are close to each other.

Complexity of Quantifiers? These effects do not mirror the complexity hierarchy of precise enumeration models like the *semantic automata* [7], which predicts:

Aristotelian < Parity < Numerical < Proportional

Suggest instead:

- Initial specification of Proportional quantifiers relies on approximate comparison between sets instead of precise one-to-one counting [4,6].
- Bigger pupil effects for Numerical and Parity quantifiers ⇒ additional working memory load dedicated to the encoding of precise numerical concepts [3,4].
- Complexity effects arise only if precise counting is forced [7].
- But: Preliminary! A number of confounds to be addressed.

References

[1] Dehaene, S. (1999). *The number sense: How the mind creates mathematics.* OUP USA. **[2]** Engelhardt P. E., *et al.* (2010). Pupillometry reveals processing load during spoken language comprehension. *The Quarterly Journal of Experimental Psychology.* **[3]** Heim, S., *et al.* (2012). The language number interface in the brain: A complex parametric study of quantifiers and quantities. *Front. in Evolutionary Neuroscience.* **[4]** Lidz J., *et al.* (2011). Interface transparency and the psychosemantics of most. *Natural Language Semantics.* **[5]** Mathot, S., *et al.* (2018). Safe and sensible preprocessing and baseline correction of pupil-size data. *Behavior research methods.* **[6]** Pietroski P., *et al.* (2009). The meaning of *most*: Semantics, numerosity and psychology. *Mind & Language.* **[7]** Szymanik, J. (2016). *Quantifiers and Cognition: Logical and Computational Perspectives.* Springer International Publishing.