Encoding and Verification Effects of Generalized Quantifiers on Working Memory

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Overview A large amount of literature has shown that the type of quantifier in a sentence significantly affects the verification procedure used to arrive at a truth-judgment [4, a.o.]. However, few studies have explored effects of quantifier type on cognitive load during early comprehension, in order to distinguish between quantifier characterization and verification procedures. To better understand working memory demands in the early processing of quantified sentences, this pilot study employed recordings of pupil size variation in an an auditory/visual verification task. We selected quantifiers from four different categories (*Aristotelian, Proportional, Numerical, Parity*; cf. Tbl. 1) and exploited pupillometry [2, a.o.] to (**I**) ask whether there are effects of quantifier type on working memory specifically during *encoding*, before participants are allowed to engage in verification; (**II**) if early effects on memory can be found, whether they pattern as predicted by theories of quantifier meaning grounded in the approximate number system [ANS; 1], or by computational accounts of quantifier complexity based on precise enumeration, as the semantic automata framework [5].

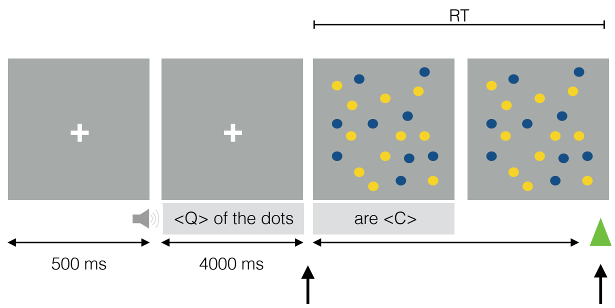


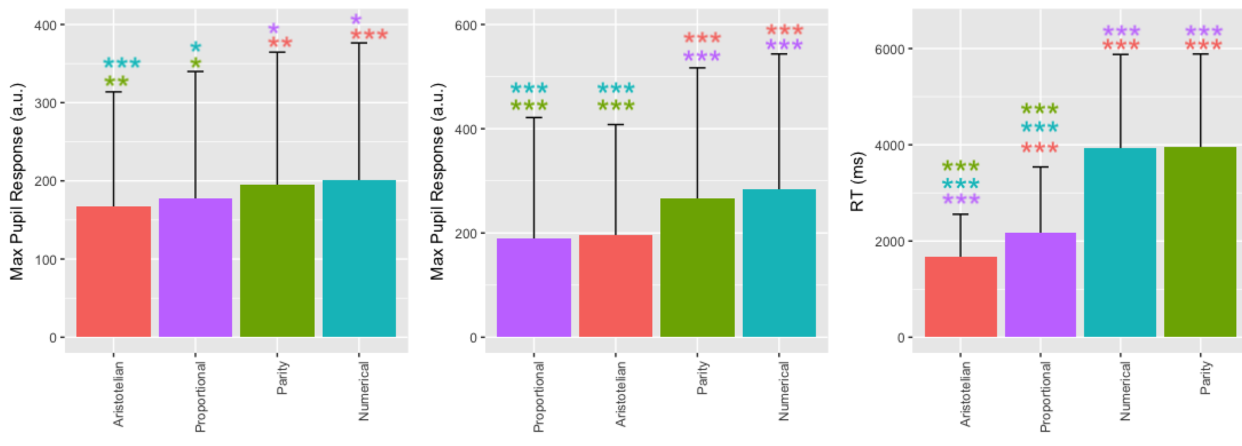
Figure 1: Experimental design.

Quantifier	Magnitude	Quantifier Category
All		
No		Aristotelian
Some		
At least n	$n = 2,\ldots,7;9\ldots14$	Numerical
At most n	$n = 2,\ldots,7;9\ldots14$	
An even number of		Parity
An odd number of		
Most		Proportional
More than half		

Table 1: Quantifiers grouped by category

Methods The experimental design we used to address these questions is shown in Figure 1. Participants (n = 17) were asked to judge auditory sentences of the type <*Quantifier*> *of the dots are* <*Color*>, against a visual display showing systematically varied proportions of two sets of colored dots. For numerical quantifiers, the numerical referents were also varied in order to probe cardinality effects on pupil size and response time (RT). The onset of the visual display was delayed until the onset of the disambiguating predicate, to measure increases in pupil size relative to each quantifier during *encoding* — prior to any disambiguating or search cue (i.e. the color predicate; the visual scene) — and during *verification* (Fig. 1). Each quantifier was associated to two target colors (*blue*, *yellow*) in two verification conditions (*true*, *false*). Proportions of colors in the visual arrays were varied so to avoid fixed counting strategies. Each quantifier was presented 24 times, for a total of 216 trials. SR Research DataViewer was used to output trial reports for three distinct interest periods: baseline, encoding, and verification. 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.

Results [ENCODING, Fig. 2a]. We found effects of quantifier type on mean ($F(3,3190) = 7.36$, $p < 0.001$) and max ($F(3,3190) = 8.14$, $p < 0.001$) pupil response during encoding, supporting the hypothesis of comprehension effects on working memory guided by the semantic content of different quantifiers. Quantifier effects clustered in two main groups: Aristotelian-Proportional (AP) quantifiers eliciting significantly smaller pupil responses than Parity-Numerical (PN), with no significant differences found within clusters.
[VERIFICATION, Fig. 2b]. Significant effects were found of quantifier type on mean ($F(3,3189) = 5.117$, $p < 0.01$) and max ($F(3,3190) = 31.740$, $p < 0.001$) pupil response during verification. Again AP quantifiers showed significantly smaller pupil responses than for PN (see Figure 2), with no significant differences within AP (mean:$p < 0.16$; max: $p < 0.94$) and PN (mean:$p < 0.63$; max: $p < 0.55$) clusters, respectively.
[RTs, Fig. 2c]. We found effects on response times both for quantifier category ($F(3,3189) = 662.23$, $p < 0.001$) and proportion ($F(15,3189) = 11.37$, $p < 0.001$), with RTs faster for *Aristotelian* $<$ *Proportional* $<$

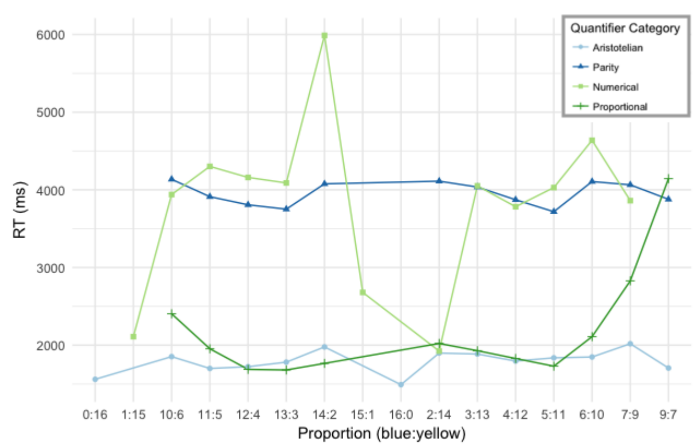


(a) **(b)** **(c)**

Figure 2: Comparisons of means by quantifier category for max pupil response (in arbitrary units) during encoding (a) and verification (b); and for RTs (in ms) from image onset to end of trial (c). Signif. codes ($*** : 0.001; ** : 0.01; * : 0.05$) are color coded by the quantifier category of reference.

Parity/Numerical, and again no significant differences between Parity and Numerical quantifiers ($p < 0.986$).

Discussion These exploratory results support the hypothesis that quantified expressions modulate working memory already during early comprehension, before any cue to verification has been given. Pupillometry effects do not seem to mirror the complexity hierarchy proposed by precise enumeration models like, for instance, the *semantic automata* — which predicts *Aristotelian* < *Parity* < *Numerical* < *Proportional* [5]. Instead, pupil response patterns suggest that the initial specification of Proportional quantifiers relies on approximate comparison between sets instead of precise one-to-one counting. Bigger effects recorded for Numerical and Parity quantifiers in encoding are consistent with the idea of additional working memory load dedicated to the encoding of precise numerical concepts, and to early recruitment of cognitive resources that will later be needed by the verification procedures of different quantifiers [3]. As for RTs, while Proportional quantifiers overall pattern similarly to pupil responses, they also show significant differences from Aristotelian quantifiers. This suggests a distinction between the amount of working memory recruited by a quantifier (as indexed by pupil response) and the length of the verification procedure (as reflected by the RTs). We would then predict Proportional RTs to be longer, the closer the target sets are to requiring precise numerical comparison. Although our design was not meant for this kind of comparison across quantifiers, and thus acknowledging possible confounds, RTs in verification behave consistently with this prediction (Figure on the right). Proportional RTs pattern as Aristotelian while the colored sets' cardinalities are far from each other, but visibly increase towards Numerical/Parity quantifiers when they are close to each other. These results open the way to future studies on the default encoding of different kinds of quantifiers, and on the relation between RTs and pupil response in verification.



[1] Dehaene, S. (1999). *The number sense: How the mind creates mathematics*. OUP USA. **[2]** Engelhardt P. E., Ferreira F., and Patsenko E. G. (2010). Pupillometry reveals processing load during spoken language comprehension. *The Quarterly Journal of Experimental Psychology*. **[3]** Lidz J., Pietroski P., Halberda J., and Hunter T. (2011). Interface transparency and the psychosemantics of most. *Natural Language Semantics*. **[4]** Pietroski P., Lidz J., Hunter T., and Halberda J. (2009). The meaning of *most*: Semantics, numerosity and psychology. *Mind & Language*. **[5]** Szymanik, J. (2016). *Quantifiers and Cognition: Logical and Computational Perspectives.* Springer International Publishing.