Cortical representation of quantification: The role of the left anterior temporal lobe

Quantifiers like 'all' and 'some' play a key role in how we construct meaning from language. Quantificational elements are universal across languages and even emerge within the first generation of new languages (Kocab et al., 2022), suggesting they reflect a core aspect of human cognition. Recent psycholinguistic research shows that comprehenders process quantified sentences such as "every big circle is blue" by mentally representing the set of big circles but not representing the set of blue things, relative to a visual dot display (Knowlton et al., 2023). This finding challenges Generalized Quantifier theory (GQ), a major framework for quantifier semantics (Barwise and Cooper, 1981). However, little is known about how quantifier meanings are computed in the human brain.

A key challenge for unpacking the neural processing of quantifiers is that although language processing is rapid, quantifier processing spans the entire sentence. Thus, neural activity specific to the quantifier as it composes with "big circle" and "blue" must be disentangled from serial predictive processing. In this MEG study, we addressed this challenge by presenting full sentences in parallel, giving the system access to both arguments of the quantifier at once. Parallel presentation has been shown to elicit rapid detection of sentence-level properties as early as 130ms in MEG signals (Fallon & Pylkkänen, 2024; Flower & Pylkkänen, 2024). We focused on the role of the left anterior temporal lobe (LATL), as previous work has shown this region to be sensitive to Boolean set intersection during conceptual combination (Poortman et al., 2016). Given this, it could plausibly also contribute to quantifier interpretation as specified by GQ theory.

24 native English-speaking participants read 4-word English sentences flashed for 300ms using parallel presentation. The sentences contained quantified phrases as in "all cats are nice" (Fig. 1), using either the Aristotelian quantifiers *all*, *some*, or *no* or the definite determiner *the*. Participants reported whether an immediately following stimulus was the same or different as the first stimulus, with mismatches created by swapping out one word (e.g., *all dogs are nice*). MEG data were analyzed from the first stimulus only.

If the LATL is involved in processing quantifier meaning, there are two possible activity patterns that could reflect the aforementioned theories of quantification. The first is that the LATL composes quantifier meanings via set-intersection of the quantifier's arguments, consistent with GQ theory. This hypothesis predicts the following ranking of quantifier elicited LATL activation: *all* > *some* > *no*. The second is that the LATL reflects processing specific to the quantifier's referential properties. Restricted Quantifier theory (RQ, Knowlton et al., 2022, 2023) proposes that certain quantifiers, such as *all* and *no*, involve plural definite semantics, unlike existential quantifiers like *some*. In light of research showing increased LATL activation for unique entities (Grabowski et al., 2001) and MEG findings that LATL tracks the extent to which determiners *restrict* the domain of referents in a discourse situation (Leffel et al.,2014), the Restricted Quantifier theory would predict greater activation for *all* and *no* compared to *some*.

A spatiotemporal clustering test over the LATL revealed a significant main effect of determiner type at 210-410ms after the first sentence onset (p = 0.0347) (Fig. 2). Pairwise comparisons within the cluster showed two patterns: First, *the* elicited greater activation than all Aristotelian quantifiers. Second, *all* and *no* both elicited more activation than *some* as predicted by RQ, though *all* and *no* did not differ significantly. Finally, a generalized linear model analysis indicated that these LATL effects were not solely due to bigram frequencies across the stimuli.

In sum, we found evidence that the LATL contributes to the computation of quantified meaning representations, with a pattern of activity consistent with the restricted theory of quantification. A whole-brain analysis revealed no other significant effects of quantification after correcting for multiple comparisons. Our results align with prior evidence that the LATL is involved in referential processing, such as the representation of unique entities like celebrity names (Damasio et al., 1996) and have important implications for representational-level theories of quantification.

Figure 1.

Sentence Type	Determiner	Example	Logical Form
Grammatical	all	all cats are nice	∀x [cat(x) → nice(x)]
	some	some cats are nice	∃x [cat(x) & nice(x)]
	no	no cats are nice	¬∃x [cat(x) & nice(x)]
	the	the cats are nice	nice(ιx.cat(x))
Reversed	all	nice are cats all	+!++#!%+==%&+$*=!!!&
	some	nice are cats some	%=!+&=&%+%++%=#$%@
	no	nice are cats no	#*$=$%!&%*%%%+#+&#
	the	nice are cats the	%&=%@&%*$!=!&+@!&!+#

Figure 2.