Evaluating Semantic Automata on the Verification of Iterated Quantifiers

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Introduction. Work in formal semantics and psycholinguistics has argued that the type of quantifier in a sentence affects the verification procedure used to arrive at its truth-judgment (Knowlton et al. 2021). Semantic Automata Theory (SA; van Benthem 1986) classifies different quantifiers based on the computational complexity of the verification algorithms they instantiate. While some evidence for these characterizations has been found with single-quantifier sentences (Bremnes, et al. 2022; a.o.), SA also makes predictions for multiple (aka *Iterated*) quantifiers, as in "*Every circle is connected to some triangle*" (Szymanik et al. 2012). Building on this work, we explore the psychological reality of SA for Iterated Quantifiers in English, by examining their verification complexity and how it interacts with broader cognitive resources.

Materials & Methods. Following Szymanik et al. (2012), we tested sentences containing Iterated Quantifiers of the form *Some X - Every Y* or *Every X - Some Y*. We also included instances of Proportional (*Most*) and Aristotelian (*All*) quantifiers (Table 1). Participants read sentences in a moving-window self-paced reading (SPR) task, followed by an image determining its truth value (Fig. 1). They were then prompted to answer whether the sentence was True/False by pressing a button on their keyboard. For each Quantifier, half the trials were true and half were false, for a total of 32 target items (8 x Quantifier Condition). We included 8 filler sentences as attention checks. Before the SPR task, participants completed a Digit Span Task and a Flanker Task, as measures of working memory and cognitive control, respectively.

Predictions. Szymanik et al. (2012) predict that True instances of Every-Some should be more complex to verify than True instances of Some-Every; and False instances of Every-Some to be simpler than the respective Some-Every (Table 2). SA additionally predicts that the verification procedure for Iterated Quantifiers should be closer to the one underlying Proportional rather than Aristotelian quantifiers, in terms of verification complexity and with respect to the recruitment of cognitive resources. We expect higher Accuracy and lower Verification Time — as the RT between image presentation and participants' answer — for simpler quantifiers.

Results. L1 English speakers (N = 123) were recruited through Prolific. Regression analyses on Accuracy reveal significant effects of Quantifier ($p < .001$), and an interaction of Quantifier and Truth Value ($p < .001$). Pairwise comparisons show that participants were more accurate in True instances of Every-Some than Some-Every ($p < .001$), and no difference between their False instances ($p = .39$). Analyses on log-transformed Verification RTs reveal an effect of Quantifier ($p < .001$), and an interaction between Quantifier and Truth-Value ($p < .01$). Pairwise analyses show no significant difference between Every-Some/Some-Every by Truth Value. Instead, Proportional quantifiers as well as both Iterated ones were *significantly slower* in their True condition ($p < .001$). Finally, we find a positive effect of Digit Span on Accuracy ($p < .001$), and of the interaction between Quantifier and Digit Span ($p < .01$) for Proportional and Iterated quantifiers specifically. For Verification RTs, we find a positive interaction between Quantifier and Digit Span ($p < .01$), and between Quantifier, Truth Value, and Cognitive Tasks ($p < .05$).

Conclusion. Our results only partially support the predictions of SA. The divergence between predicted patterns and empirical results for the True/False Iterated conditions invites a deeper evaluation of SA compared to other algorithmic theories of verification (Bott et al. 2019). The comparison with Proportional quantifiers also suggests a need to further evaluate the relation between Iterated quantifiers and properties of the verification scene (Feigenson, et al. 2004).

Table 1. Sample Stimuli by condition.

Class	Quantifier	Example Sentence
Iterated	**Every-Some**	Every circle is connected to some square in the house.
Iterated	**Some-Every**	Some triangle is connected to every star in the scroll.
Aristotelian	**All**	All stars are pink in the heart.
Proportional	**Most**	Most squares are orange in the triangle.
Filler	**Filler**	There are blue circles in the house.

Figure 1. Example of True conditions for Every-Some and Some-Every.

Table 2. Predictions (>> stands for more complex: lower accuracy/slower RTs).

True	False
Every-Some >> Some-Every	Some-Every >> Every-Some

Figure 2. Verification Accuracy.

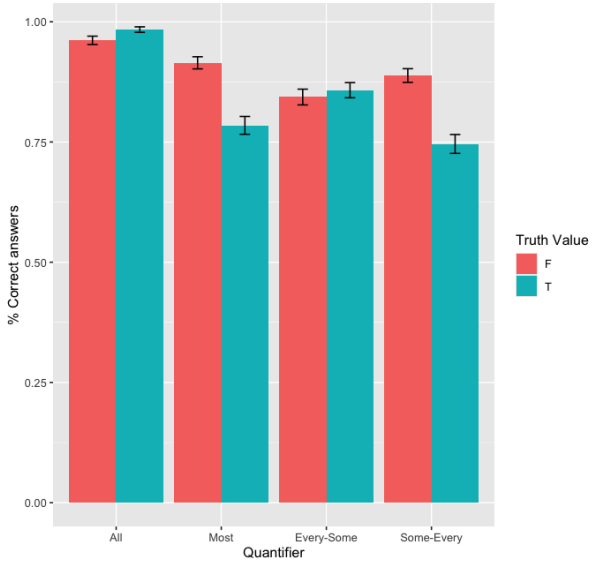
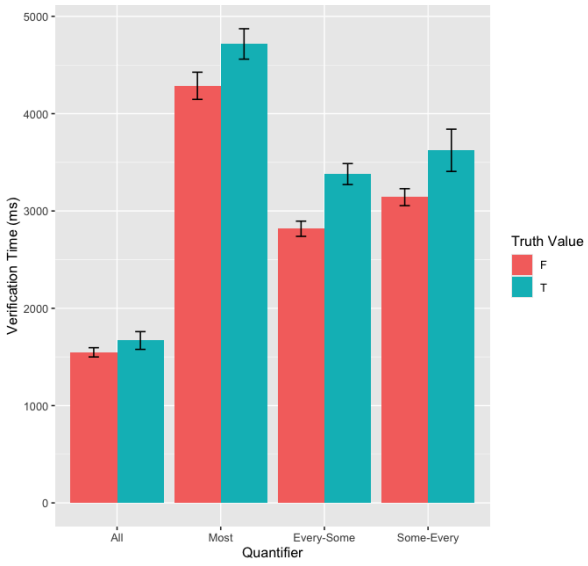


Figure 3. Verification Time.



Bott, et al. 2019. Journal of Semantics. **Bremnes, et al.** 2022. Cognition. **Feigenson, et al.** 2004. Trends in CogSci. **Knowlton, et al.** 2021. Annals of the New York Academy of Sciences. **Stoet.** 2010. Behavior Research Methods. **Stoet.** 2017. Teaching of Psychology. **Szymanik, et al. 2012.** Logic and Interactive Rationality Yearbook 2012. **van Benthem.** 1986. Essays in logical semantics.