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Current controversies

Improving methodology of quantifier comprehension experiments

Jakub Szymanik[a,*], Marcin Zajenkowski[b]

[a] *University of Amsterdam, Institute for Logic, Language and Computation, Valckenierstraat 65, 1018 XE Amsterdam, Netherlands*
[b] *University of Warsaw, Faculty of Psychology, Poland*

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1. Introduction

Recently, research devoted to computational modeling of quantifier comprehension has been extensively published in this journal. McMillan, Clark, Moore, Devita, and Grossman (2005) using neuroimaging methods examined the pattern of neuroanatomical recruitment while subjects were judging the truth-value of statements containing natural language quantifiers. The authors were considering two standard types of quantifiers: first-order (e.g., "all", "some", "at least 3") and higher-order quantifiers (e.g., "more than half", "an even number of"). They presented the data showing that all quantifiers recruit the right inferior parietal cortex, which is associated with numerosity, but only higher-order quantifiers recruit the prefrontal cortex, which is associated with executive resources, like working memory. In the latest paper Troiani, Peelle, Clark, and Grossman (2009) assessed quantifier comprehension in patients with corticobasal degeneration (CBD) and healthy subjects. They compared numerical quantifiers, like "at least 3", which require magnitude processing, and logical quantifiers, like "some", which can be understood using a simple form of perceptual logic. Their findings are consistent with the claim that numerical quantifier comprehension depends on a lateral parietal–dorsolateral prefrontal network, but logical quantifier comprehension depends instead on a rostromedial prefrontal–posterior cingulate network.

According to the authors of the mentioned studies, their results verify a particular computational model of natural language quantifier comprehension posited by linguists and logicians (see e.g., van Benthem, 1986). One of the authors of the present comment has challenged this statement by invoking differences – missed in (McMillan et al., 2005) – between logical (expressibility) and computational (working memory) properties of quantifiers (Szymanik, 2007). It was suggested that the distinction between first-order and higher-order quantifiers does not coincide with the computational resources required to compute the meaning of quantifiers. Cognitive difficulty of quantifier processing might be better assessed on the basis of complexity of the minimal corresponding automata. For example, both logical and numerical quantifiers are first-order. However, computational devices recognizing logical quantifiers have a fixed number of states while the number of states in automata corresponding to numerical quantifiers grows with the rank of the quantifier. This observation partially explains the differences in processing between those two types of quantifiers (Troiani et al., 2009) and links them to the computational model. Taking this perspective, below, we suggest the experimental setting extending the one by McMillan et al. (2005) and Troiani et al. (2009).

There is an additional problem with the study of Troiani et al. (2009). The poorer performance of CBD patients could be partially associated with specific materials used in the research. It is known that CBD patients have a similarity-based categorization deficit (see e.g., Antani, Dennis, Moore, Koenig, & Grossman, 2004; Koenig, Smith, Moore, Glosser, & Grossman, 2007). In the experiment of Troiani et al. (2009), subjects were asked to determine the accuracy of propositions containing a quantifier that probed a color feature of an object (e.g., balls, cars) in serially presented visual arrays. In each trial, a stimulus differed in color but also in shape and texture. Therefore, there were other independent variables besides color, which could influence CBD patients' performance, especially taking into account the patients' categorization problems. That was not controlled in the Troiani et al. (2009) experiment.

Below, we present preliminary findings from our two experiments (see Szymanik & Zajenkowski, 2008, for more details). We believe that the new setup deals with difficulties described above and can lead to better understanding of quantifier processing in natural language.

* Corresponding author. Tel.: +31 20 525 5654.
E-mail address: j.szymanik@uva.nl (J. Szymanik).

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2. Experimental evidence

In the first study, we compared reaction time with respect to the following classes of quantifiers: recognized by acyclic finite-automata AFA (logical), recognized by FA finite automata (parity) and recognized by push-down automata, PDA (see Szymanik, 2007). We predicted that reaction time will increase along with the computational power needed to recognize quantifiers. Hence, parity quantifiers (even, odd) will take more time than first-order quantifiers (all, some) but not as long as proportional quantifiers (less than half, more than half). Additionally, we compared logical quantifiers with numerical quantifiers of higher rank (e.g., "less than 8"). In the study of McMillan et al. (2005) and Troiani et al. (2009) only numerical quantifiers of relatively small rank was taken into consideration. We predicted that complexity of the mental processing of numerical quantifiers depends on the number of states in the relevant automata. Therefore, numerical quantifiers of high rank should be more difficult than logical quantifiers.

We conducted an experiment in which 40 subjects had to solve a task comprising 80 grammatically simple propositions containing a quantifier that probed a color feature of cars on a display. Colored pictures presenting a car park with 15 randomly distributed cars were accompanying each proposition. Cars differed from one another only in color. Each quantifier was presented in 10 trials. The sentence matched the picture in half of the trials. Subjects were asked to decide if the proposition was true of the presented picture.

We observed that the increase in reaction time was determined by the quantifier type and that four types of quantifiers differed significantly from one another. The mean reaction time increased as follows: logical quantifiers, parity quantifiers, numerical quantifiers, and proportional quantifiers (see Szymanik & Zajenkowski, 2008 for more details).

In the second study, we assumed that ordering of elements can be treated as an additional independent variable in investigating the role of working memory capacity. In particular, over specifically ordered universes proportional quantifiers can be computed by PDA (see Szymanik, 2007). Hence, we expected that reaction time of judging the truth-value of statements containing proportional quantifiers over suitably ordered universes will be shorter than over randomized universes.

Thirty subjects were presented with 16 grammatically simple propositions containing proportional quantifiers that probed a color feature of cars on a display. Color pictures presenting a car park with 11 cars were constructed to accompany the propositions. Two different proportional quantifiers (less than half, more than half) were presented to each subject in 8 trials. Each quantifier was accompanied with four pictures presenting cars ordered in two rows with respect to their colors and four pictures presenting two rows of randomly distributed cars. As we expected, proportional quantifiers over randomized universes were processed significantly longer than these over ordered models (more details in Szymanik & Zajenkowski, 2008).

3. Conclusions and perspectives

Our investigation enriches and explains some data obtained by McMillan et al. (2005) and Troiani et al. (2009). We have shown that the computational model correctly predicts that quantifiers computable by finite-automata are easier to understand than quantifiers recognized by push-down automata. It improves the results of McMillan et al. (2005), which compared only first-order quantifiers with higher-order quantifiers, putting in one group quantifiers recognized by finite-automata as well as those recognized by push-down automata. Moreover, we have assessed differences between logical, parity, and numerical quantifiers.

Additionally, decreased reaction time in the case of proportional quantifiers over ordered universes supports findings of McMillan et al. (2005), who attributed the hardness of these quantifiers to the necessity of using working memory.

Our experimental setting – avoiding methodological problems described in Section 1 – can be used for further neuropsychological studies. On the basis of our research and findings of McMillan et al. (2005), we predict that comprehension of parity quantifiers – but not first-order quantifiers – depends on executive resources that are mediated by dorsolateral prefrontal cortex. This would correspond to the difference between acyclic FA and FA. Moreover, we expect that only quantifiers recognized by PDA but not FA activate working memory (inferior frontal cortex). Additionally, the inferior frontal cortex should not be activated when judging the truth-value of sentences with proportional quantifiers over ordered universes. Finally, our findings contribute to the understanding of the comprehension of differences between logical and numerical quantifiers described by Troiani et al. (2009).

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