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Current controversies

Magnitude and parity as complementary attributes of quantifier statements

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Szymanik and Zajenkowski (this issue) present investigations regarding computational modeling techniques as they apply to the comprehension of quantifiers, or noun phrases that assert a property from a set of items (e.g., “at least 3”, “some”, or “most”). The authors present behavioral results from two experiments and distinguish several quantifier classes using reaction time data to support theoretical predictions. These findings demonstrate that reaction time increases significantly as a function of quantifier complexity and complement previous studies of quantifier comprehension (McMillan, Clark, Moore, Devita, & Grossman, 2005; McMillan, Clark, Moore, & Grossman, 2006; Troiani, Peelle, Clark, & Grossman, 2009). We broadly agree with these authors’ observations—namely, that the complexities in quantifier processing may be predicted in part using neural systems modeled with minimally corresponding automata. However, these findings are best understood in the larger context of our findings that emphasize the importance of a decision-based mechanism where complexity is a function of numerical magnitude and corresponding numerical distance effects. Furthermore, parity as a property of quantifiers (odd, even) appears to be a unique semantic attribute of numerals which can interact both with task and strategy in studies of quantifier comprehension, and may not be easily described using automata-based models.

In the first experiment reported by Szymanik and Zajenkowski, mean reaction times were ordered as follows: logical quantifiers, parity quantifiers, numerical quantifiers, and proportional quantifiers. These results are used to support the conclusion that parity quantifiers can be recognized using a two-state finite automaton with alternating transitions between these two states. However, such a model cannot completely account for the full complexity of parity knowledge observed. While parity can certainly be evaluated using the non-numerical strategies outlined in Szymanik (2007), parity is also a semantic property of symbolic numerical representation. Judgments of supposedly categorical concepts such as “evenness” indicate that numbers are not subjectively treated as equally odd or even (Armstrong, Gleitman, & Gleitman, 1983). Also, the numerical property of parity has been exploited to demonstrate the presence of a spatial mental number line in magnitude processing (Dehaene, Bossini, & Giraux, 1993). This effect is present in children as early as age 10 (Berch, Foley, Hill, & Ryan, 1999) and is additionally accompanied by a linguistic effect based on associations between the unmarked adjectives “even” and “right” and the marked adjectives “odd” and “left” (Nuerk, Iversen, & Willmes, 2004). Thus, parity is inextricably linked with magnitude and language, and simple reaction time differences are not enough to fully capture the complexity of processes by which the brain represents, recognizes, or judges parity.

The authors propose that a two-state cyclic automaton can account for the difference between first-order and parity quantifiers, and that this difference should correspond to recruitment of an executive resource relying on dorsolateral prefrontal cortical support. In our previous study (Troiani et al., 2009), numerical and parity quantifiers were analyzed together, resulting in a recruitment pattern including right parietal, dorsolateral prefrontal, and inferior frontal cortex. As described in the previous article, there were no differences in neural activation between numerical and parity quantifiers. However, we did find reaction time differences, which were slightly different from those reported by Szymanik and Zajenkowski. Significant mean reaction time increases were observed between the following categories of quantifiers: logical quantifiers, cardinal quantifiers, and parity quantifiers. The disparity between our observed reaction time increases and those of Szymanik and Zajenkowski are likely due to the differences in magnitudes used. Our studies used small magnitudes (less than 3, more than 2), as compared to the larger magnitudes (less than 8, more than 7) examined in Szymanik (2007). Because the mental number line is represented logarithmically, assessing whether 7 and 8 are different will take longer than the same assessment of 2 and 3

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(Dehaene, 2003). The observation that parity judgments take longer than numerical judgments in our study, whereas they took significantly less time in the Szymanik and Zajenkowski study, reflects the increase in response latency necessary to compare numbers of higher magnitude.

This is not to say that parity judgments *cannot* be performed by a neural system approximating a two-state finite automaton. In fact, it is likely that in the absence of access to magnitude processing regions—such as in cases of lesion or atrophy—a two-state system would provide a sufficient strategy to assist in parity judgment. This strategy can be illustrated by two patients with corticobasal degeneration (CBD), re-examined from our previous study of serial quantifier processing (Troiani et al., 2009). In this study, patients assessed quantifier statements including numerical quantifiers (e.g., “at least 3”) and parity quantifiers. While overall patient performance did not differ on the quantifier types, two patients performed well above chance on parity judgments (93.8% and 86.1%). However, the judgments made by these same patients involving numerical quantifiers were much closer to chance (64.2% and 51.5%). These data suggest that some patients are able to use a strategy to assess parity, despite impairment assessing quantity, and that this strategy may utilize a two-state finite automaton.

Lastly, Szymanik and Zajenkowski suggest that a similarity-based categorization deficit, rather than difficulty with magnitude processing, may underlie the poorer performance of CBD patients in Troiani et al. (2009). Although the specific nature of the materials used always has potential to influence experimental results, we do not believe that a similarity-based categorization deficit can explain the quantifier comprehension deficit in these patients. First, we used familiar, perceptually simple stimuli (balls, stars, etc.). Each trial consisted of only one type of object, and the only required feature discrimination in each trial was that of color. Second, if patients' impairment was due to a similarity-based categorization deficit, this would have been evident across all categories of stimuli (which it was not). Third, the experiments previously identifying semantic categorization deficits in these patients used either novel (Koenig, Smith, Moore, Glosser, & Grossman, 2007) or ambiguous (Antani, Dennis, Moore, Koenig, & Grossman, 2004) stimuli, and both identified a *relative* deficit in these patients in similarity-based vs. rule-based processing, with manipulations based on subtle instruction differences. Finally, because deciding the truth-value of a quantifier proposition is in part a *rule-based* categorization process, we would not expect poor performance due to the types of processing deficits that we observed in studies examining instruction-based differences.

Overall, the current evidence is consistent with a role for the involvement of a finite automaton-type neural system in the evaluation of logical quantifiers. This process is likely to be supported by a network involving rostral medial frontal-posterior cingulate regions of cortex. Any quantifier requiring access to magnitude knowledge will recruit parietal regions. Furthermore, a dorsolateral frontal-parietal network is necessary for evaluations involving size differences, as both frontal and parietal regions are activated when making numerical or non-symbolic size judgments (Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). It would follow that any quantifier requiring access to symbolic or non-symbolic magnitude would recruit both dorsolateral frontal and parietal cortex, consistent with our previous findings (Troiani et al., 2009). In typical instances, parity and magnitude are intricately related (Dehaene et al., 1993; Nuerk et al., 2004), and likely rely on parietal lobe magnitude processing regions. However, other strategies of parity assessment may exist, compatible with a neural, two-state, automata-based model. Szymanik and Zajenkowski's approach thus is not inconsistent with our model, where we emphasize the importance of magnitude processing regions in support of quantifier comprehension. It is clear that both experimental and theoretical approaches can provide complementary evidence regarding the role of quantifier representation in the brain, particularly when computational models are able to furnish concrete predictions about human data.

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