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A computational approach to quantifiers as an explanation for some language impairments in schizophrenia

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ABSTRACT

We compared the processing of natural language quantifiers in a group of patients with schizophrenia and a healthy control group. In both groups, the difficulty of the quantifiers was consistent with computational predictions, and patients with schizophrenia took more time to solve the problems. However, they were significantly less accurate only with proportional quantifiers, like more than half. This can be explained by noting that, according to the complexity perspective, only proportional quantifiers require working memory engagement.

Learning outcomes: (1) Working memory deficits can be a source of language disorders in schizophrenia. (2) Processing of proportional quantifiers, like *more than half* or *less than half* involves working memory. (3) Patients with schizophrenia are less accurate only with proportional quantifiers, like *more than half*. (4) This result support the computational model of quantifiers processing.

1. Introduction

Research on cognitive impairments indicates the existence of working memory deficits (e.g. Lee and Park, 2005; Park and Holzman, 1992) and verbal functions disorders (e.g. Condray, Steinhauer, Van Kammen, and Kasparek, 1996; Goldfarb and Bekker, 2009; Thomas, Leudar, Newby, and Johnston, 2002) among patients with schizophrenia. Condray et al. (1996) as well as Bagner, Melinder, & Barch (2003) have raised the question of whether working memory disturbances are a source of language deficits in schizophrenia. They found that patients with schizophrenia did not perform as well as a control group in a reading span test (which tests working memory) and a language comprehension task. Moreover, they observed that the two tasks were strongly correlated. Even though the authors found a strong association between working memory and language, they did not specify the mechanism which underpins this relationship. In this paper, we propose a partial explanation for this phenomenon in terms of a computational model of language processing.

Similar to investigations on patients, research on normal language comprehension suggests that working memory and comprehension are strongly linked (Baddeley, 2003; Daneman and Carpenter, 1980; Just and Carpenter, 1992; King and Just, 1991). A specific relationship between working memory and language comprehension has also been found in studies devoted to quantifier processing. For example, McMillan, Clark, Moore, Devita, & Grossman (2005) examined the pattern of neuroanatomical recruitment while subjects were judging the truth-value of statements containing natural language quantifiers. The authors considered two standard types of quantifiers: definable in first-order logic (e.g. ‘all’, ‘some’, ‘at least 3’), and not definable in first-order logic, so-called higher-order quantifiers, (e.g. ‘an even number of’, ‘more than half’). They concluded 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.

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From a computational point of view to recognize first-order quantifiers we only need computability models that do not use any form of working memory. Intuitively, to check whether "Every sentence in this paper is correct" we do not have to remember anything. It suffices to read the sentences from this article one by one. If we find an incorrect one, then we know that the statement is false. Otherwise, if we read the entire paper without finding any incorrect sentence, then the statement is true. We can proceed in a similar way for other first-order quantifiers. It was proved by Van Benthem (1986) that such simple devices as finite-state automata can compute first-order quantifiers. However, for recognizing some proportional higher-order quantifiers, like "less than half" or "most", we need computability models making use of unbounded working memory. Intuitively, to check whether "Most of the sentences in this paper are correct" we must identify the number of correct sentences and hold it in working memory to compare with the number of incorrect sentences. Mathematically speaking, such an algorithm cannot be realized by a finite-state automaton, one needs a push-down machine.

Szymanik (2007) noted that there are more fine-grained complexity differences between quantifiers with potential cognitive plausibility than the distinction given by first-order definability. First of all, among first-order quantifiers we can distinguish Aristotelian and numerical quantifiers. Aristotelian quantifiers, e.g. "all", "some", are recognizable by acyclic finite-automata with only 2 states. Numerical quantifiers are of the form, e.g. "more than *n*", "fewer than *n*", and the corresponding machines are also acyclic finite-automata but this time the number of states depends on *n*. Moreover, higher-order quantifiers can also be divided into different subclasses with respect to the minimal computational power needed for recognition. Parity quantifiers, "an even number of", "an odd number of", can be also recognized by two state finite-automata but this time the machines are not acyclic, they need to loop between the two states. For example, consider statement "An even number of the sentences in this paper is false." When you find a false sentence you write "1" at the blackboard, if you find another one you erase "1" and put "0" again, then if you see another false sentence you put "1" in place of "0", and so on. At every moment you have only one digit at the blackboard no matter how long is the paper. A two state finite automaton can realize such algorithm. Finally, as we mentioned above, proportional quantifiers are recognizable by push-down automata.

Following above distinctions Szymanik (2007, 2009) proposed that the cognitive difficulty of quantifier processing could be assessed on the basis of the complexity of the corresponding minimal automata that could handle the computational task. Szymanik and Zajenkowski (2009, 2010a,b) confirmed this hypothesis in the empirical studies by comparing the processing of various classes of quantifiers (see Table 1) with respect to their computational complexity. The authors concluded that proportional quantifiers are the hardest to verify and engage working memory to the highest degree. From a theoretical perspective, they require a recognition mechanism with unbounded internal memory (Van Benthem, 1986). During computation, the sizes of two sets need to be compared that may be simulated by a push-down automata (PDA). For instance, in order to verify the sentence "More than half of the cars are red", one has to count and hold in the short-term memory the number of red cars and then compare it with the total number of cars. No such memorization/comparison is necessary when processing other quantifiers. This theory seems to be cognitively plausible, according to behavioral (Szymanik and Zajenkowski, 2010a,b), neuroimaging (McMillan et al., 2005), and neuropsychological (McMillan et al., 2006) studies.

In the present study, we investigated whether the computational theory of quantifier verification can shed some light on the working memory and language disturbances in schizophrenia. We predicted that, when asked to verify quantifier sentences, a group of patients with schizophrenia and a healthy control group would diverge to the greatest extent when dealing with proportional sentences, because they require different levels of engagement of working memory. Moreover, McMillan et al. (2005) found that higher order quantifiers (including proportional quantifiers) recruited the right dorsolateral prefrontal cortex, the same area that is associated with memory deficits in schizophrenia (Park and Holzman, 1992; Seidman et al., 1994). As far as the non-proportional quantifiers are concerned we expect our results to be consistent with the complexity predictions and previous research (Szymanik and Zajenkowski, 2009, 2010a,b), i.e., the difficulty of the task will increase as follows. Aristotelian quantifiers should be easiest, while parity and numerical quantifiers of high rank should have similar results as it comes to their difficulty.

2. Method

2.1. Participants

The participants were 30 ICD-10 diagnosed inpatients (18 males) with paranoid schizophrenia, who had been screened in order to rule out neurological disorders, mental retardation or substance abuse. Their mean age was 26.1 years old (SD = 4.5), the average duration of illness was six years (SD = 5.0) and the mean number of years of education was 13.5 (SD = 3). All of the inpatients had been receiving the same medications and dosages for at least two weeks. Thirty normal control participants

Table 1
Quantifiers and the complexity of the minimal automata (see Szymanik, 2007 for further discussion).

Quantifiers	Examples	Minimal automata
Aristotelian	All, some	Acyclic two-state finite-automata
Numerical	More than *k*, fewer than *k*	Acyclic finite-automata with a number of states depending on *k*
Parity	An even number of, an odd number of	Two-state finite-automata with loops
Proportional	More than half, fewer than half	Push-down automata

were recruited who matched the group of patients in terms of age (mean = 24.0, SD = 4.6), gender (18 males) and number of years spent in education (mean = 14.7, SD = 1.8).

2.2. Materials and procedure

The task we used consisted of 32 grammatically simple propositions in Polish containing a quantifier that referred to the color of a car on display. The same number of color pictures of a car park with cars in it accompanied the propositions (see Fig. 1). Each picture contained 15 objects in two colors and was presented simultaneously with a proposition containing a quantifier e.g. "More than half of the cars are red".

Eight different quantifiers were presented to each subject in four trials. The quantifiers were divided into four groups: Aristotelian quantifiers ("all", "some"), parity quantifiers ("odd", "even"), numerical quantifiers of high rank ("more than seven", "fewer than eight") and proportional quantifiers ("more than half", "fewer than half"). Half of the number of each type of item was true and half was false. Each proposition and a stimulus array were presented for 15,000 ms. Subjects were asked to decide whether or not the proposition accurately described the picture.

3. Results

ANOVA with group (patients/controls) as a between subject factor and the type of quantifier (Aristotelian, numerical, parity or proportional) as a within-subject factor were used in order to examine the differences in the mean RTs and accuracy. The Greenhouse-Geisser adjustment was used where needed.

3.1. Reaction time (RT)

The average RTs are presented in Table 2.

The main effects of group ($F(1, 58) = 38.07$, $p < 0.001$, $\eta^2 = 0.40$), quantifier type ($F(2.22, 128.74) = 289.64$, $p < 0.001$, $\eta^2 = 0.84$) and group x quantifier interaction ($F(2.22, 128.74) = 20.63$, $p < 0.001$, $\eta^2 = 0.26$) were significant (see Fig. 2).

One-way ANOVA indicated that the two groups were significantly different with respect to all of the quantifiers. Namely, the patients' RTs were longer in comparison to the controls. In order to analyze the within-subject effect, post-hoc pairwise

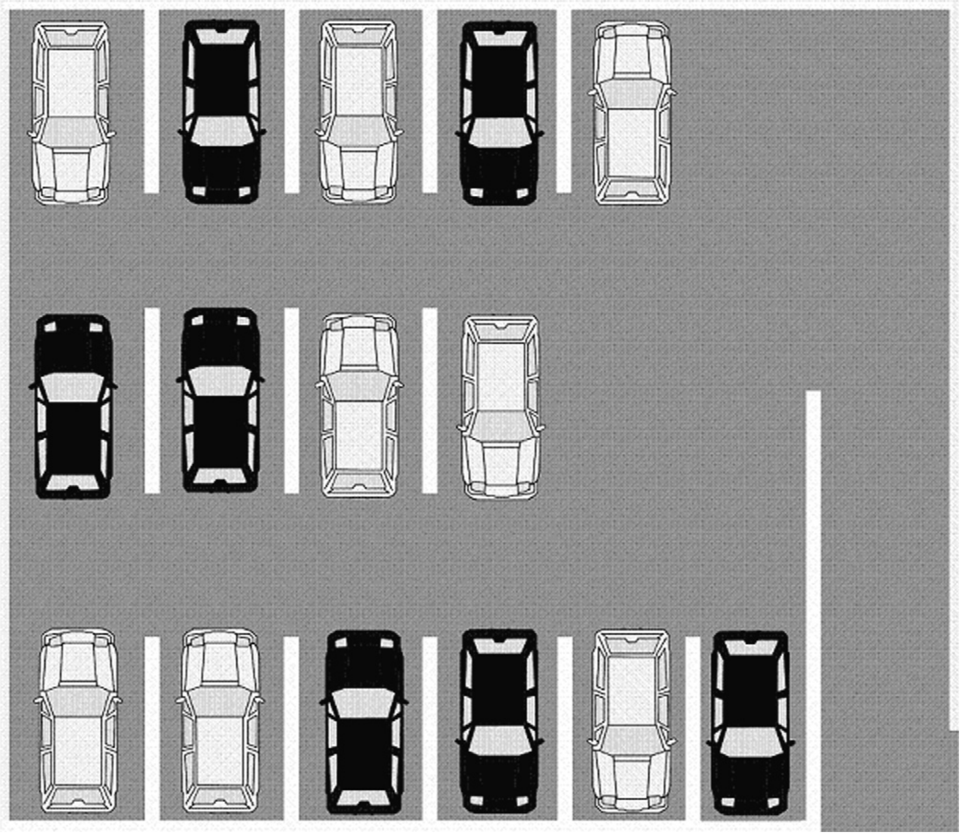

Fig. 1. An example of a stimulus used in the study. Each picture contained 15 objects in two colors and was presented simultaneously with a proposition containing a quantifier e.g. "More than half of the cars are red".

Table 2
Means (*M*) and standard errors (SE) of the reaction time (RT) in ms and the accuracy (ACC) for each quantifier type in patients and controls.

Group	Quantifier's, *M* (SE)							
	Aristotelian		Numerical		Parity		Proportional	
	RT	ACC	RT	ACC	RT	ACC	RT	ACC
Patients	3157 (145.2)	7.73 (0.17)	7286 (298.0)	6.80 (0.24)	7220 (277.5)	6.73 (0.22)	10947 (467.7)	5.50 (0.27)
Control	2221 (135.4)	7.80 (0.07)	5625 (261.3)	7.23 (0.16)	5723 (234.3)	7.00 (0.25)	6921 (400.0)	6.73 (0.30)
Group difference effect size (η^2)	0.28	0.02	0.23	0.04	0.23	0.01	0.43	0.14

The accuracy of each participant was the number of the correctly verified sentences (maximum = 8).

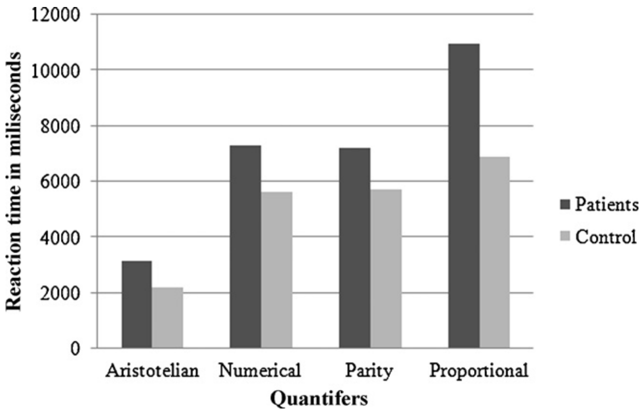

Fig. 2. The interaction effect between groups (patients and controls) and quantifier type in mean reaction times.

comparisons were conducted using the Bonferroni adjustment. The analyses performed separately for the patients and the controls indicated that in both groups all of the quantifiers differed significantly from one another ($p < 0.001$), with the exception of the pairing of parity-numerical (see Table 3).

3.2. Accuracy

Table 2 presents the means and standard deviations of the accuracy.

We found the significant main effect of group ($F(1, 58) = 4.99$, $p = 0.029$, $\eta^2 = 0.1$), quantifier type ($F(2.28, 132.54) = 27.15$, $p < 0.001$, $\eta^2 = 0.32$) and group × quantifier interaction ($F(2.28, 132.54) = 3.88$, $p = 0.018$, $\eta^2 = 0.07$) (see Fig. 3).

The analysis of the group effect indicated that in the cases of Aristotelian, numerical and parity quantifiers there were no differences between the patients and the controls. The only significant result was related to proportional quantifiers, for which the controls scored better than the patients.

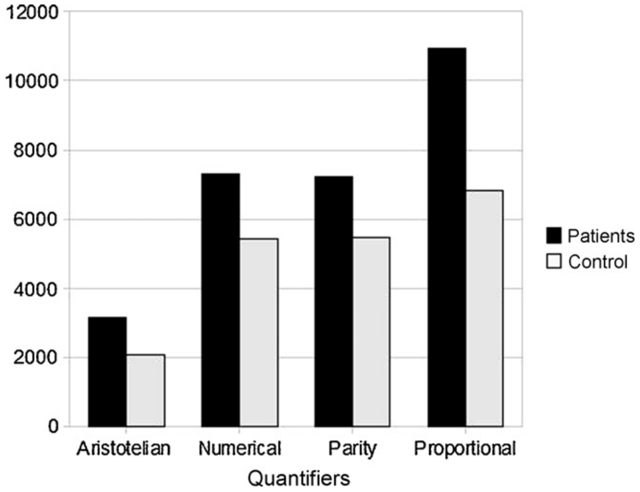

Fig. 3. The interaction effect between groups (patients and controls) and quantifier type in mean accuracy.

Table 3
Post-hoc pairwise comparisons with Bonferroni corrections between different quantifier types for the reaction time (RT) and the accuracy (ACC) separately in patients and controls - p-values (p) and effect sizes (η^2).

Quantifiers		Patients				Control			
		RT		ACC		RT		ACC	
		p	η^2	p	η^2	p	η^2	p	η^2
Aristotelian	Numerical	<0.001	0.878	=0.003	0.484	<0.001	0.893	=0.001	0.349
	Parity	<0.001	0.878	<0.001	0.341	<0.001	0.929	=0.050	0.196
	Proportional	<0.001	0.917	<0.001	0.616	<0.001	0.874	=0.001	0.359
Numerical	Parity	=1,000	0.001	=1,000	0.002	=1,000	0.001	=1,000	0.003
	Proportional	<0.001	0.793	=0.001	0.327	<0.001	0.562	=0.484	0.092
Parity	Proportional	<0.001	0.767	=0.005	0.383	<0.001	0.434	=0.119	0.158

Pairwise comparisons with Bonferroni corrections between the means, which were conducted separately for patients and controls, indicated that in both groups there were significant differences between the quantifiers ($p < 0.05$), with the exception of the pairing of parity-numerical. Additionally, the pair parity-proportional was not significant ($p = 0.119$) in the control group (see Table 3).

4. Discussion

We observed that in both the group of patients with schizophrenia and the controls the difficulty of various types of quantifiers increased according to the predictions derived from computational theory (Szymanik, 2007). This result is consistent with previous investigations (Szymanik and Zajenkowski, 2010a,b). Most importantly, in the present study we observed that the greatest difference between the controls and the patients appeared when they were faced with proportional quantifiers. The differences that appear to be observed between non-proportional quantifiers, i.e., Aristotelian, numerical, and parity, for both patient and control groups are consistent with the quantifier complexity account (Szymanik, 2007, 2009) and with previous research (Szymanik and Zajenkowski, 2009, 2010a,b). Therefore, the findings provide important additional confirmation of the theory's predictions.

The patients generally took more time to verify the sentences. However, they were less accurate only when dealing with proportional sentences. Presumably, their longer RT allowed the patients to verify Aristotelian, numerical and parity quantifiers at the same level as the controls. This is consistent with the theory that memory deficits in schizophrenia may be partly accounted for by the slowing of processing speed (Brebion, Amador, & Smith, Gorman, 1998). However, in terms of proportional quantifiers, slower processing did not enable the patients to match the controls' scores, as the verification of the statements required a different cognitive mechanism. According to computational theory, the high engagement of working memory, which is necessary for comparing sizes of two sets, hinders the verification of proportional sentences. Switching between processing and sustaining stored information may be too distracting for individuals with schizophrenia, especially given that they show deficits in such executive functions as control or the supervision of cognitive processes (Hutton et al., 1998; Velligan et al., 1997). In other words, it seems that patients are unable to use more complex cognitive strategies associated with high demands on working memory to an adequate extent.

Our results shed some light on the investigations of Condray et al. (1996) and Bagner et al. (2003), who found differences between patients and controls in language comprehension, measured using the reading span task. Interestingly, the effect sizes of accuracy and RT reported by Bagner et al. (2003), as in our experiment, increased as the complexity of the sentences increased. In the light of our results, one could argue that patients' slower processing is responsible for their poor performance when faced with simple sentences; however, in the case of more difficult stimuli, like proportional sentences, the significant increase in the difference in RT and accuracy between the patients and the controls can be explained in terms of computational thresholds. In particular, in our tasks one can refer to the difference between tasks computable by finite state machines (Aristotelian, numerical, and parity quantifiers) and those falling outside that realm (proportional quantifiers). Apparently patients' working memory deficits impede efficient usage of complicated cognitive strategies, like comparing sizes of two sets. Inability to execute complex mental algorithms based on extensive use of working memory resources might be one of the reasons of language impairments in schizophrenia.

The last conclusion is more an assumption rather than a statement and is limited by the fact that the working memory capacity was not assessed directly. There are strong reasons to believe that working memory, on the one hand, is highly related with quantifiers processing (Szymanik and Zajenkowski, 2010b, in press), and on the other hand, with language deficits of schizophrenic patients (e.g. Bagner et al., 2003; Condray et al., 1996). However, to substantially strengthen the thesis of this paper further research should assess participants' quantifier verification together with working memory capacity. We predict that likewise in the study of Bagner et al. (2003) patients and controls should differ in both tasks. Moreover, we know from the previous studies (e.g. Szymanik and Zajenkowski, 2010b) that working memory is highly associated with performance of quantifier processing task among healthy subjects, and that is why we expect similar result in patients. Additionally, basing on the latest findings (Szymanik and Zajenkowski, in press) we assume that it is not the storage, but rather the executive functions that are responsible for poorer quantifier verification of patients with schizophrenia. Therefore, in the future research different aspects of working memory should be controlled.

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Appendix A. Continuing Education Unit Questions

1. Working memory:
   a. is related to language processing only in normal population
   b. is related to language processing in both normal population and patients with schizophrenia
   c. doesn't have any effect on quantifiers comprehension
   d. is necessary to verify quantifiers definable in first-order logic
2. An example of a proportional quantifier could be:
   a. all
   b. more than half
   c. every
   d. an even number
3. Which type of quantifier is performed less accurate by schizophrenic patients in comparison to healthy subjects?
   a. parity quantifiers
   b. numerical quantifiers
   c. Aristotelian quantifiers
   d. proportional quantifiers
4. Which cognitive function is involved in processing proportional quantifiers to the highest degree?
   a. working memory
   b. only short term memory
   c. selection
   d. vigilance
5. Patients with schizophrenia:
   a. need more time to process all types of quantifiers
   b. need more time to process only numerical quantifiers
   c. need more time to process only parity and proportional quantifiers
   d. need more time to process only proportional quantifiers

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