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Quantifier processing can be dissociated from numerical processing: Evidence from semantic dementia patients

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ABSTRACT

Quantifiers such as frequency adverbs (e.g., "always", "never") and quantity pronouns (e.g., "many", "none") convey quantity information. Whether quantifiers are processed as numbers or as general semantics has been a matter of much debate. Some neuropsychological and fMRI studies have found that the processing of quantifiers depends on the numerical magnitude comprehension system, but others have found that quantifier processing is associated with semantic representation. The selective impairment of language in semantic dementia patients provides a way to examine the above controversy. We administered a series of neuropsychological tests (i.e., language processing, numerical processing and semantic distance judgment) to two patients with different levels of severity in semantic dementia (mild vs. severe). The results showed that the two patients had intact numerical knowledge, but impairments in semantic processing. Moreover, the patient with severe/late semantic dementia showed more impairment in quantifier and semantic processing than the patient with mild/early semantic dementia. We concluded that quantifier processing is associated with general semantic processing, not with numerical processing.

1. Introduction

Research on neural basis of numerical processing has recently received increasing attention (Ansari, 2008; Ansari & Dhital, 2006; Cantlon & Brannon, 2005; Dehaene, Piazza, Pinel, & Cohen, 2003; Kadosh, Bien, & Sack, 2012; Park, Park, & Polk, in press). There is a consensus that number processing typically is housed in the brain regions around the intraparietal sulcus (IPS) (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Park, Hebrank, Polk, & Park, 2012; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Thioux, Pesenti, Costes, De Volder, & Seron, 2005). For example, studies have demonstrated that number processing (e.g., "Is six larger than five?") elicited greater activation in the IPS compared with the processing of ferocity of animals (Thioux et al., 2005). Numbers also produced greater activation in the IPS than did colors and letters, regardless of the modality of stimuli (i.e., auditory and visual) (Eger et al., 2003). The IPS's role in number and quantity processing has also been supported by lesion studies (Dehaene & Cohen, 1997). Based on the multiple lines of evidence, Dehaene has proposed that the IPS is the neural basis of quantity processing.

Other than with numbers in various notations (e.g., Arabic digits, number words) and numerosities, quantity can also be expressed by quantifiers (e.g., some, many, and little) in natural language. There are several types of quantifiers, such as numerical quantifiers, logical quantifiers, frequency adverbs, and quantity pronouns (Morgan et al., 2011; Troiani, Peelle, Clark, & Grossman, 2009; Wei, Chen, Yang, Zhang, & Zhou, in press). Numerical quantifiers (e.g., "at least three") include number words as part of the quantifiers. Logical quantifiers (e.g., "some", "all") are based on a logic system that involves quantity. Frequency adverbs (e.g., "always", "occasionally", and "seldom") describe the number of times certain events take place (Bass, Cascio, & Oconnor, 1974; Schriesheim & Novelli, 1989). Quantity pronouns (e.g., "some", "many", "plenty") are a group of indefinite pronouns used to represent unknown or unnamed amounts. How are these quantifiers processed in the brain? Previous research has yielded inconsistent results. Several fMRI studies have showed that quantifier processing is subserved by the parietal lobe, a critical brain area for numerical magnitude processing (McMillan, Clark, Moore,

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Devita, & Grossman, 2005; Troiani et al., 2009). For example, McMillan and colleagues (2005) asked participants to judge whether sentences with quantifiers were true or false (e.g., “at least 3 of the balls are blue”). Results showed that processing quantifiers engaged the right parietal areas. Similarly, Troiani et al. (2009) found that the comprehension of numerical quantifiers such as “at least three” depended on the lateral parietal area. Several neuropsychological studies also showed that quantifier processing is linked to the numerical magnitude comprehension system. For example, corticobasal degeneration patients who had deficits in numerical abilities also showed impaired understanding of quantifiers (McMillan et al., 2005; Morgan et al., 2011; Troiani, Clark, & Grossman, 2011; Troiani et al., 2009). In parallel, patients with semantic dementia are impaired in general semantic processing but seemed to perform almost at the ceiling level in numerical, calculation and quantifier tasks (e.g., number comparison, subtraction problems and quantifiers comparison) (Cappelletti, Butterworth, & Kopelman, 2006).

Other studies, however, have found that quantifier processing is similar to language processing, rather than numerical processing. For example, Gerstmann's Syndrome patient CG was impaired in numerical processing when number words were above 4, but could correctly choose which of two measurement terms (e.g., meter, centimeter) had greater quantity (Cipolotti, Butterworth, & Denes, 1991). Corticobasal degeneration patients failed the questions on cardinal quantifiers (e.g., “more than three flowers”), but they showed normal performance in the comparison of magnitude for logical quantifiers (e.g., “some”, “all”) (Morgan et al., 2011).

Neuroimaging studies have also investigated the differentiated neural mechanisms for numerical quantifiers (e.g., “at least three”, “more than two”) and logical quantifiers (e.g., “some”, “many”, and “few”) (Troiani et al., 2009). Whereas numerical quantifiers activated the parietal-dorsolateral prefrontal network more than did logical quantifiers, the latter elicited greater activation in the prefrontal-posterior cingulate network. Recently, researchers found that quantifiers and animal names elicited greater activation than did numbers and dot arrays in the left inferior frontal gyrus and left middle temporal gyrus, and quantifiers and animal names did not differ from each other (Wei et al., in press). These results suggest that quantifiers depend on brain regions for general semantic processing, but not for numerical processing.

To help resolve the question of whether quantifiers are processed as numerical or linguistic concepts, it is useful to examine patients with selective impairment in either the numerical or the semantic system. Patients with semantic dementia show selective impairment in semantic comprehension and have been used to examine the neural bases of quantifier processing. They usually demonstrate impoverished knowledge in semantic meanings of words, objects and abstract concepts (Hodges, Patterson, Oxbury, & Funnell, 1992; Snowden, Thompson, & Neary, 2004), but show preservation of number knowledge and calculation skills (Cappelletti, Butterworth, & Kopelman, 2001; Crutch & Warrington, 2002). Cappelletti et al. (2006) found that semantic dementia patient AM showed normal performance on the tasks involving quantifying pronouns (e.g., “many”, “a few”) and numerical knowledge (e.g., number comparison), which suggested that the organization of quantifiers was within the numerical domain. In contrast, frontotemporal dementia (FTD) patients were impaired in their comprehension of logical quantifiers (e.g., “Not all the cows are in the barn.”) and majority quantifiers (e.g., “More than half of the birds are on the branch.”) (Morgan et al., 2011). The severity of semantic impairments might have contributed the differences between the two types of patients. For example, patient AM (Cappelletti et al., 2006) received a full score on the color naming task, whereas the FTD patients received lower scores than controls on a similar color-word naming task (i.e., the Stroop task) (Morgan et al., 2011). Therefore, it seems important to consider the severity of semantic dementia in a study of the neural basis of quantifier processing. Early neural diseases might spare quantifier processing, but late neural diseases might affect all lexical-semantic processing including quantifier processing.

The current study tested this hypothesis by recruiting two patients with different levels of severity of semantic dementia. We hypothesized that the patient with mild/early semantic dementia could process many semantic categories, whereas the patient with severe/late neural diseases would have lost more semantic knowledge from the long-term memory system. If quantifiers are associated with the semantic system, the patient with severe semantic dementia would show poorer performance in quantifier processing than the one with mild semantic dementia.

Two types of quantifiers (frequency adverbs and quantity pronouns) were used in the current study. These two types of quantifiers were selected because they do not contain any number words and hence would not confound quantifier processing with numerical processing.

2. Method

2.1. Participants

2.1.1. Two patients with semantic dementia

CDT was a 69 year-old right-handed man with 11 years of education. He was a technician before his retirement. He was diagnosed at the age of 64 years as having semantic dementia according to the guidelines established by Neary et al. (1998). He had difficulty in finding suitable words to name objects. During the two years prior to this study, his language ability declined rapidly and did not know even some daily objects (e.g., potatoes, eggplants). He could neither recognize nor write complex Chinese characters correctly. His comprehension ability decreased.

XHZ was a 61 year-old right-handed woman with 11 years of education. She had worked in a semiconductor company. She was diagnosed one year before this study as having semantic dementia according to Neary's diagnostic criteria (1998). Starting one year earlier, she had not been able to provide the names of her colleagues and to read and understand familiar Chinese characters. In addition to semantic dementia, she also suffered from high blood pressure and cervical spondylosis.

For both patients, the T1-weighted MRI images and T2-weighted fast-spin echo (FSE) MRI images (see Fig. 1) revealed that bilateral temporal lobe, but especially in the left hemisphere, had remarkable atrophy. Performance on a semantic memory test was used to determine these two subjects' levels of severity in semantic dementia (mild vs. severe). Patients were asked to report the name and function of the objects shown in pictures. The task was similar to the word-picture matching test used by Julien, Thompson, Neary and Snowden (2008) to diagnose the severity of semantic dementia. Patient CDT showed a lower score (39 correct responses) than patient XHZ (69 correct responses) on the 104-trial semantic memory test (Snodgrass & Vanderwart, 1980), χ^2 (1)=16.20, $p<0.001$. Both patients performed within normal limits on the orientation, expression, attention, calculation and memory tasks from the Mini Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975), but they had impaired performance in the language task (see Table 1).

2.1.2. Controls

Control participants were 6 healthy volunteers (3 men, 3 women) who were matched with the two patients in gender, age, and years of education. Exclusion criteria included any history of neurological disorders, head injuries or alcohol abuse. The six participants gave their informed written consent. They had a mean age of 65.5 years (S.D.=2.2) and 11 years (S.D.=0) of education.

2.2. Assessments of cognitive abilities

All the tasks were programmed using Web-based applications available at www.dweipsy.com (Wei et al., 2012). All tests were administered to both patients and controls in 2011 unless otherwise noted. There was no time constraint for any of the tests. The first complete response was scored for each test.

2.2.1. Language processing tests

The language processing tests included picture naming, word reading, verbal fluency, word rhyming, sentence completion, and common knowledge. These tests were used to assess the basic language abilities in daily life. Except for verbal fluency, all other language tests were analyzed in terms of the percentage of correct responses. For the verbal fluency task, we analyzed the correct number of semantic examples.