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The Understanding of Quantifiers in Semantic Dementia: A Single-Case Study

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Abstract

This study investigates the processing of quantifiers in a patient (AM) with semantic dementia. Quantifiers are verbal expressions such as “many” or “a few”, which refer semantically to quantity concepts although lexically they are like non-quantity words. Patient AM presented with preserved understanding of quantifier words and impaired understanding of non-quantifier words of the same frequency. In parallel to this, he showed preserved numerical knowledge and impaired comprehension of the meaning of words, objects, and of linguistic concepts. These results suggest that the neural organization of quantifiers is within the numerical domain as they pattern with numerical concepts rather than linguistic concepts. These data reinforce the evidence that numerical knowledge is functionally distinct from non-numerical knowledge in the semantic system and indicate that the semantic referent rather than the stimulus format is more relevant for semantic processing.

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Introduction

Quantifier expressions in natural language refer to numerical concepts. The most obvious ones are the counting words, “one”, “two”, “three” …, but there is another class of quantifiers which refers to numerical concepts, usually without explicit specification of an exact number. These quantifiers are typically tied closely to the conversational context, and make reference to sets of objects mentioned or assumed (Jackendoff, 1968; Brookes and Braine, 1996). They include words like “all”, “some”, “every”, etc., and even determiners such as “the” and “a” carry a quantification implication. Although the semantics of quantifiers has been extensively discussed by linguists and philosophers (see Barwise and Cooper, 1981) little is known about the neural organization of these expressions.

In this study we investigate whether the meanings of quantifier words are preserved when the meaning of other words is lost. We considered common quantifier expressions with a variety of syntactic forms, some of which can only be used with count nouns, such as “many”, “several”, and “a few”, while others can be used also with mass nouns as “little”, “most” and “half”. These expressions refer to quantities in a way that is tied to explicitly mentioned or implicated context. Thus, “*a lot* of books” means something different depending on whether we refer to a public library or to our own office. Many of these terms

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refer to approximate rather than exact quantities, though we also considered terms such as "a pair" or "a couple" which refer to exact numerical quantities.

Quantifiers are among the most common words in any language but have attracted almost no neuropsychological attention. By contrast, the processing of quantifiers in the form of number words has been extensively examined. Several lesion studies showed that number words are functionally distinct from other (non-number) words both at phonological level (Cohen *et al.*, 1994; Bachoud-Levi and Dupoux, 2003; Marangolo *et al.*, 2004) and at semantic level (Cipolotti *et al.*, 1991; Butterworth *et al.*, 2001; Cappelletti *et al.*, 2002a). For instance, Bachoud-Levi and Dupoux (2003) presented an aphasic patient with a phonological impairment in production that spared certain syntactic and semantic categories, specifically numbers, days of the week and months. Marangolo and colleagues (2004) showed the opposite dissociation, namely a selective deficit to the production system of sporen numbers in an aphasic patient. In a very few cases, quantifiers different from number words have been examined in neuropsychological patients. For instance, patient MC was asked to define 'quantity words' such as "dozen" or "half" (Polk *et al.*, 2001), and patient CG was tested with verbal expressions consisting of measure terms like "gram" or "kilo" (Cipolotti *et al.*, 1991). Both patients performed poorly with 'quantity words' or measure terms in parallel with impaired performance in numerical and quantity tasks. None of these studies, however, has systematically examined the processing of quantifiers and, most importantly, the question of whether quantifiers pattern with numerical or linguistic concepts has not yet been investigated.

One way to address this question is to examine patients with selective impairment of either numerical or verbal comprehension. Patients with semantic dementia seem to be particularly appropriate for this purpose as their profound and extensive impairment in understanding the meaning of words, objects and of abstract concepts (Snowden *et al.*, 1989; Hodges *et al.*, 1992) usually contrasts with intact numerical knowledge (Cappelletti *et al.*, 2001; Crutch and Warrington, 2002). Although not exhaustive, some indication of the processing of quantifiers comes from a single-case study of a patient with semantic dementia (Butterworth *et al.*, 2001; Cappelletti *et al.*, 2002a). Patient IH was tested on comprehension, reading and writing tasks with a variety of numerical and non-numerical stimuli. Numerical stimuli consisted of cardinal number words (e.g., "one", "two", "three"…), ordinal number words (e.g., "first", "second", "third"…), and a small set of 'number related' words, some of which referred to quantification, such as "minus", "add", and "equals". The patient showed preserved reading and writing of all numerical stimuli, and better performance in reading and writing 'number related' words compared to non-number words. This may suggest that performance on 'number related' words is more closely associated with number words than non-number words. This conclusion, however, remains speculative as only a few of the 'number related' stimuli used to test patient IH consisted of quantifier words. Moreover, although the patient was better with these stimuli than with non-number words, he only performed 50% correct with 'number related' words.

In this investigation we systematically examined the understanding of quantifiers in a patient with semantic dementia.

Case Report

At the time of the present investigation (2003), AM was a 72-year-old, right-handed, retired merchant seaman with 9 years of education. He was referred to the Neuropsychiatry and Memory Disorders Clinic at St. Thomas' Hospital in London in 2001. He complained of memory problems that had been progressive over the previous two to three years, mainly involving memory for names of people, word finding difficulties, and comprehension problems. On examination, AM was fully oriented in time and space and was able to give good account of recent events in the news, but with a pronounced anomia for objects and people's names which emerged both in spontaneous conversation and in formal neuropsychological assessment (see performance in fluency and naming tests). He was able to name high frequency items, such as jacket, and watch, but not low frequency words such as lapel or skirting board. He seemed to have lost the meaning of many words.

A MRI brain scan with coronal slices showed a focal atrophy of the left temporal lobe involving the lateral, inferior, and medial temporal neocortex as well as the left hippocampus with a grossly enlarged left temporal horn (see Figure 1). There was also some atrophy in the right temporal lobe and at the frontal poles, but it was considerably less.

Neuropsychological Investigation

General Intelligence, Language and Memory

The patient was administered a neuropsychological battery evaluating general intellectual functioning, memory and executive functions. The results are reported in Table 1. The patient had weak recognition, verbal and autobiographical memory (Warrington, 1984; Wechsler, 1987; Kopelman *et al.*, 1989), and some frontal executive deficits were also present (Shallice and Evans, 1978). In contrast, I.Q.[1] (Nelson, 1976; Wechsler, 1981), digit span and visual recall memory were normal (Wechsler, 1987).

Several tasks have been administered to assess AM's semantic knowledge. These tasks have been extensively used in patients with semantic impairments (Cappelletti, 2002b). They are based on a range of living and man-made items presented in verbal and pictorial modality (for more detailed information see Cappelletti *et al.*, 2001). In addition, other standardized tests were used, such as the Graded Naming Task (McKenna and Warrington, 1983) and the Pyramids and Palm Tree Test (Howard and Patterson, 1992). AM's scores on the semantic tasks are reported in Table 2.

AM performed poorly on semantic and lexical fluency tasks (Benton *et al.*, 1995), and in word retrieval tasks (McKenna and Warrington, 1983; Snodgrass and Vanderwart, 1980). He was impaired in classifying words and pictures as belonging to a semantic category, in defining words and concepts, in describing objects' functions and in deciding in what two objects are alike or different. The patient was also impaired in tasks based on the semantic associations between objects (‘Semantic links’) although he performed better, but significantly worse than controls, in the Pyramids and Palm Tree Task (Howard and Patterson, 1992). He performed well on a name-to-picture matching task (Butterworth *et al.*, 1984) and in word retrieval for the category of colors.

Comment

The investigation on AM's performance on several comprehension tasks revealed a semantic impairment. AM made errors even on very easy tasks, such as word and picture classification and semantic association, suggesting that he was unable to access a full semantic representation. In some cases, when the number of semantic distracters increased and their semantic proximity with the target objects decreased, the error rate increased. AM's impairment was similar for words and pictures, indicating a central locus of impairment. On the basis of clinical and neuropsychological evidence, a diagnosis of semantic dementia was made. This was consistent with Neary *et al.*'s (1998) criteria for the diagnosis of semantic dementia.

[1]Note that AM made 30 errors on the NART-R (Nelson and Willison, 1991), which may reflect some degree of surface dyslexia.

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Control Subjects

Fifteen control subjects (6 males) matched as closely as possible to the patient for age and education were tested on the semantic and numerical tasks (mean age = 70.7 years, SD = 5.1; mean education 9.9, SD = 1.78). These subjects were selected from a larger group of controls that was originally tested to validate the semantic and numerical battery (Cappelletti *et al.*, 2001; Cappelletti, 2002b). Moreover, 6 additional control subjects (5 males) were tested on the tasks specifically designed to assess processing of quantifiers in AM (mean age = 72.8; education = 8.2).

Experimental Investigation

The experimental investigation is divided in two parts, the first assessing AM's numerical knowledge and the second his understanding of quantifiers.

Investigation of Numerical Knowledge

Methods and Materials—Two types of paper-and-pencil numerical tasks were used. First, non-verbal numerical tasks, consisting of tasks that require only a minimal amount of linguistic resources to be performed. Second, verbal numerical tasks which are more dependent upon language. These tasks have been extensively used in neurological patients (Cappelletti, 2002b; for a more detailed description see Cappelletti *et al.*, 2001). In addition, AM was administered a computerized version of the number comparison task, typically an index of intact semantic representation of numbers. He was asked to judge the larger of two single-digit numbers by pressing one of two pre-defined keys on the computer keyboard. Accuracy and response times were recorded. Preserved semantic representation of numbers usually corresponds to an increase in response times as the distance between the two numbers decreases (e.g., deciding the larger between the numerals ‘2’ and ‘9’ is easier than between the numerals ‘2’ and ‘3’). This effect is known as ‘distance effect’ (Moyer and Landauer, 1967). If the automatic access to the magnitude of numbers is difficult or impossible, alternative strategies, such as counting, have to be employed to compare the two numbers. In this case, the longer the distance between the numbers, the longer it takes to indicate the larger. This would result in an abnormal distance effect.

Results

AM's results on numerical tasks are reported in Table 3. AM performed at ceiling on nonverbal numerical tasks: he could process dots, recognize numbers and order them in sequences. He could place numbers on an analogue number line and compare the magnitude of numerical stimuli and of objects. AM's ability to compose the value of spoken numbers using tokens was normal. The patient's performance on the computerized number comparison task revealed a normal ‘distance effect’ (Moyer and Landauer, 1967, see Figure 2), although the patient was slower than control subjects. This is taken as evidence of AM's intact semantic representation of numbers.

AM performed well on verbal numerical tasks. He could enumerate dots and count flawlessly both forward and backwards; he was able to indicate the number before or after a given one, or between two. The patient could correctly read and write Arabic numbers and number words and transcode numbers from one format to another. AM performed almost at ceiling on mental calculation tasks (i.e., operations with numbers from 1 to 9), including the Graded Difficulty Arithmetic Test, which consists of multi-digit operations (Jackson and Warrington, 1986). Similarly, AM performed well on written calculation (i.e., operations with numbers bigger then 9). Overall, the patient made a few errors only in simple division problems and in some multi-digit operations. In a task assessing calculation approximation the patient performed well. The patient's scores in calculation tasks are presented in Table 4.

In sum, AM performed well on a variety of numerical and calculation tasks, with a few errors in complex arithmetical operations but still within the normal range.

The Understanding of Quantifiers

Several tasks based on verbal and pictorial material were used to test the processing of quantifiers in patient AM.

Methods and Material

The set of stimuli included only items that: 1) could be unambiguously expressed pictorially and did not require complex verbal analysis; 2) indicated a quantity rather than a variation around a quantity; therefore expressions such as “almost”, “circa”, “roughly”, “ nearly” were not used; 3) were ‘real’ quantifiers rather than adjectives embedding some quantification, such as “leftmost” or “brightest”. According to these criteria, the following quantifiers were selected: a bit of, a couple of, (a) few, (at) least, both, dozen, fewer, half (of), less, little, lots, many, most, more, much, pair of, several, twin (N = 18).

Both pictorial and verbal material was used to test AM. Verbal material consisted of short sentences or single words written on individual cards presented to the patient and at the same time read aloud by the experimenter. Cards were left in front of the patient for the duration of each stimulus' presentation and there was no time constraint to produce an answer. Verbal material was kept as simple as possible considering the patient's difficulty in understanding words. Pictorial material consisted of simple black and white drawings, each, presented on a separate card.

Sentence Verification

Twenty-four sentences containing quantifiers, such as “Summer days have more light than winter days”, were presented to AM, who was asked to decide whether each sentence was true or false. For half of the sentences the correct answer was ‘true’, for the other half ‘false’. Sentences were randomly presented to the patient.

Sentence-picture Matching

i. Multiple pictures and one sentence. Twenty short sentences containing quantifiers were each presented with two or more pictures. For example, the sentence “A couple of people” was presented with the picture of (a) several people; (b) one person; (c) two people; (d) three children. The patient was asked to indicate the picture that best matched the sentence.

ii. Pairs of sentences and one picture. Twenty pairs of sentences were each presented with one picture. For instance, the sentences: (a) “several apples” and (b) “a couple of apples” were presented with the picture of two apples. The patient was asked to choose the sentence that best matched the picture.

Magnitude Comparison with Quantifiers

i. Quantifiers comparison. Twenty-four pairs of short sentences containing quantifiers were presented to AM for comparison, for example “several people” and “a few people”. For half of the sentences, the patient was asked to indicate the quantifier referring to the larger quantity, for the other half the one referring to the smaller quantity.

ii. Order of quantifiers. Twelve triplets of short sentences containing quantifiers were presented to AM who was asked to order them from the one indicating the smaller quantity to the one indicating the larger quantity, e.g. from “a lot of cars – fewer cars – a few cars” to “fewer cars – a few cars – a lot of cars”.

Tasks Assessing Quantifiers within a Context

Since quantifiers indicate quantities in relative contexts, we tested AM's comprehension of quantifiers within specific contexts. The patient was presented with fifteen sentences together with three options for each of them. For example, he was asked to decide whether “A couple of shops in a city” is an adequate, too small or too large quantity for a real life situation.

Sentence-picture Matching with Non-quantifier Words

Given the patient's impairment in comprehension, an additional series of 20 sentences was used; these were similar in structure and complexity to those used in the sentence-picture matching but did not include quantifiers. The task aimed at excluding that impairments in understanding the instructions were the basic difficulties in tasks involving quantifiers. As before, two tasks were administered: in the first, one sentence was presented with two or more pictures (N = 10) and the patient was asked to indicate which picture best matched the given sentence. For example, the sentence “the girl with blond hair” was presented with the picture of: (a) a girl with brown hair; (b) a girl with blond hair; (c) a baby. In the second task, two sentences were presented with one picture, for example the sentences (a) the squared object and (b) the rounded object with the picture of a ball (N = 10). The patient was asked to indicate the sentence that best matched the picture. The words used were all known by AM.

Results

On all tasks involving quantifiers, AM performed almost at ceiling (see Table 5). On a few occasions, the patient had difficulties understanding some of the words contained in the sentences (e.g. ‘pony tail’ or ‘vegetables’), but once helped he had no troubles answering the questions. Control subjects performed at ceiling or nearly at ceiling on these tasks.

Intermediate Discussion

These results suggest that AM's understanding of quantifiers was preserved although he was impaired with non-quantifier words. A straightforward account for this dissociation is to locate AM's impairment at semantic level. That is, quantifier words were preserved because the understanding of their semantic referent, namely the quantity they indicated, was preserved. Conversely, non-quantifier words were impaired because their semantic referent was in turn impaired.

There are, however, other potential explanations that need to be examined. First, it may be possible that the dissociation between quantifier and non-quantifier words is an artifact reflecting some intrinsic difference between the stimuli. Specifically, quantifiers may be high frequency words, and therefore better preserved. Indeed, semantic impairments are known to be sensitive to frequency effects (Funnell, 1992; Hodges *et al.*, 1992). Second, quantifiers could be better preserved because AM's phonological and orthographical lexicons, rather than his semantic knowledge, were preserved for quantifiers and impaired for non-quantifier words. Thirdly, AM's better performance with quantifiers could be an effect of task difficulty namely, the tasks involving quantifiers were easier than those involving non-quantifier words.

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A Frequency Effect?

In order to test whether quantifiers were better performed because higher in frequency, we checked the frequency of use of the words that the patient performed incorrectly in semantic tasks. We used the Thorndike-Lorge database (Thorndike and Lorge, 1944) of the frequency of written words. We considered items that AM performed incorrectly from a series of semantic tasks (Snodgrass Naming Test, Graded Naming Test, Naming semantic category, Definition of words, Picture and Word classification tasks) and compared their frequency of use with those of quantifiers. A significant difference in frequency may be a reason for the different performance in tasks with and without quantifiers. However, we found that the overall frequency of use of quantifiers was not significantly higher than the frequency of other words that the patient failed to perform in semantic tasks (327.64 and 412.54 for quantifier and non-quantifier words respectively, χ^2 (1df) = 0.22, *ns*). Therefore, we can exclude the hypothesis that AM's better performance with quantifiers depended on their frequency of use.

Quantifiers and Other Words at Lexical Level

AM's better performance with quantifiers could be due to selectively preserved phonological and orthographical lexicons. That is, quantifiers could be preserved because they are intact at phonological and orthographical level, whereas non-quantifier words might not. In order to investigate this possibility, we administered AM two spelling tasks investigating the lexicon of non-quantifier words.

In the first task the patient was presented with a series of spoken irregular words (e.g., yacht, sugar, mortgage) and asked to spell each of them aloud using alphabetic letters (total items = 12). AM provided 9 out of 12 correct answers. This result suggests that AM recognized the spoken word form and was able to access the spelling of the word and to read out the letters. In the second task AM was given a set of orally spelled irregular words, presented quite quickly and was asked to say each of them aloud (total items = 12). He produced 12 out of 12 correct answers. This indicates that AM could convert the series of letter names into an orthographic word form.

Together, these results suggest that the phonological and orthographic lexicons of words were intact in patient AM. Therefore, his better performance with quantifiers cannot be explained in terms of selectively preserved phonological and orthographic lexicons of quantifiers words.

Better Understanding or Difficulty Effect?

AM's better performance with quantifiers could be an artifact related to the tasks used. That is, the tasks assessing quantifiers and non-quantifier words could have been different in terms of their level of difficulty. In order to exclude this possibility, we carry out a qualitative analysis of the tasks used. The following points were observed. First, some of the tasks used to test quantifiers were very similar to those used to test AM's general semantic knowledge in terms of instructions and general structure. Nevertheless, the patient's performance in these tasks was different. For instance, both the ‘magnitude comparison with quantifier’ and the ‘word or picture classification’ tasks required the patient to assign a stimulus to a given category (‘larger’ or ‘smaller’ in the first case and ‘animals’, ‘fruit’, etc. in the second). However, the patient performed well in the first task and was impaired in the second. Similarly, the tasks ‘quantifiers within a given context’ and ‘semantic link’ required AM to choose among alternatives the correct match to a given stimulus. AM's performance, however, was good in the former task and impaired in the latter. Therefore, it seems that the patient's different performance on these tasks cannot be attributed to the features of the tasks or to the instructions given. A second aspect concerned the visual complexity of the pictorial stimuli used, which was similar in the two sets of task. Pictorial stimuli consisted of simple black and white drawings, usually presented on individual cards. There was no evidence that AM was impaired in recognizing the stimuli depicted in tasks with quantifier and non-quantifier words. Thirdly, the two sets of tasks did not differ in terms of the linguistic complexity of the verbal stimuli; in fact, in many semantic tasks, single words were used compared to short sentences used in tasks with quantifiers. However, AM's good performance with quantifiers and poor with non-quantifier words does not seem to be explained in terms of preserved sentence comprehension and impaired single-word comprehension, respectively. If that was the case, performance in general neuropsychological and semantic tasks based on short sentences (e.g., WMS logical memory, AMI and definition of words, objects' function tasks, respectively) should have also been preserved. However, this was not the case. We can therefore rule out the possibility that AM's preserved processing of quantifiers could be just accounted for in terms of preserved sentence-comprehension. Thus AM's better performance with quantifiers does not appear to be an artifact related to the tasks used.

Summary

In all the tasks administered, patient AM showed good understanding of quantifier words. This was not due to the frequency of use of the stimuli, to the selective intactness of their lexicons, or to task-difficulty effects. These results combined with the patient's intact knowledge of numerical concepts and contrasted with his impaired understanding of linguistic concepts.

Discussion

This study explored the understanding of quantifiers in a patient with semantic dementia. Quantifier expressions refer semantically to the domain of numbers but lexically ‘behave’ like non-quantifier words. The present study aimed to find out whether quantifiers patterned with numerical or with linguistic concepts within the semantic system. To address this question we investigated how quantifiers are processed when the meaning of other concepts is lost. We tested a patient unable to understand linguistic but not numerical concepts and showed that his processing of quantifiers was intact despite his impairment in processing other (non-quantity) concepts expressed verbally. For instance, AM was able to determine the numerical content or the amount of material in a set as indicated both by quantifiers and by numerals. He could determine the magnitude indicated by the words “several” and “a few” in the expressions “several people” and “a few people” and likewise he could compare the magnitude indicated by the numbers “3” and “7”. Good performance with quantifiers and numerals contrasted with the patient's impairment in processing linguistic concepts not referring to a quantity. This dissociation did not depend on the frequency of the stimuli used, on their lexical features, or on the difficulty.

We suggest that AM's pattern of performance can be explained in terms of the preservation of the semantic referents that quantifiers indicate, namely, quantity concepts. As those concepts were intact in AM, all the expressions referring to them were in turn preserved despite being verbal. The fact that quantifiers are verbal expressions which lexically ‘behave’ as other linguistic concepts in the semantic system did not seem relevant. This case reinforces the idea that the ability to process a concept depends upon the preservation of its semantic referent rather than on the intactness of its verbal format (Caramazza, 1994). Should the verbal format be relevant, all verbal expressions would have been equally impaired in patient AM. In the literature of number processing, other neuropsychological cases also suggest that the intact processing of numerical concepts depend on the intactness of their semantic referent. For instance, patient IH was impaired at reading and writing words he had lost the meaning of, but he could still correctly read and write numerical stimuli as his understanding of these concepts was well preserved (Butterworth *et al*., 2001; Cappelletti *et al*., 2002a). Patient MC was impaired in processing all types of symbolic expressions referring to numbers (Arabic numbers, number words, and ‘quantity words’), but had no problems in processing other verbal expressions not referring to quantity. This dissociation corresponded to impaired quantity processing when quantities were expressed with symbols, and intact processing of non-numerical concepts (Polk *et al*., 2001). Similarly patient CG could not process number words and Arabic numbers above number ‘4’ as she was impaired at processing the quantity indicated by these numbers (Cipolotti *et al*., 1991). Although quantifier words were not systematically investigated in patients MC and CG, there seemed to be an association between their poor performance in quantity words and in numerical tasks. Patient AM's pattern of performance may represent the opposite dissociation, namely, preserved performance in numerical tasks and in those requiring quantifiers. This double dissociation seems to exclude that the effects found in AM could be accounted for just in terms of task-difficulty effects.

Another possible explanation of our results arises from the previous account. That is, numbers and quantifiers (and possibly colors since they were well preserved in AM) represent circumscribed semantic categories, which would in turn be represented in language through small and distinct lexicons that might be selectively spared. Conversely, words not belonging to these categories would be represented by larger lexicons. Indeed, selective impairment of number words at a lexical level has already been reported (Cohen *et al*., 1994; Bachoud-Levi and Dupoux, 2003; Marangolo *et al*., 2004). However, since AM's lexicon was preserved for numerals, quantifiers and non-numerical concepts, this hypothesis remains to be tested.

Patient AM's preserved performance with quantifiers corresponded to spared parietal regions and to a brain lesion that mainly involved the left temporal areas. The intactness of numerical processing in the context of intact parietal regions is consistent with other patients' pattern of performance (Cipolotti *et al*., 1995; Dehaene and Cohen, 1997; Thioux *et al*., 1998; e.g., Cappelletti *et al*., 2001; Crutch and Warrington, 2002) and with neurophysiological evidence (see Dehaene *et al*., 2003). Crucially, preserved understanding of quantifiers in the context of preserved parietal regions is consistent with a recent neuroimaging study investigating the understanding of quantifiers. McMillan and colleagues (2005) asked healthy volunteers to judge as true or false a series of sentences containing quantifiers. The authors showed that tasks requiring the understanding of quantifiers engaged the right parietal areas, together with the inferior frontal and the dorsolateral prefrontal areas. These results are consistent with the fact that quantifiers refer to numerical concepts and therefore with the involvement of the parietal regions which are known to be engaged in numerical processing (see Dehaene *et al*., 2003 for a review).

In conclusion, we have reported an investigation on the ability to process quantifiers in a patient with semantic dementia. Despite a severe impairment in understanding concepts verbally expressed, the patient showed preserved comprehension when verbal expressions referred to the domain of numbers. We suggest that this performance can be explained in terms of the preservation of the semantic referent that quantifiers indicate, namely, quantity concepts. As those concepts were intact in AM, all the expressions referring to them were in turn preserved despite being verbal. This case reinforces the evidence that numerical concepts are functionally distinct from non-numerical concepts in the semantic system. Moreover, it suggests the existence of a further distinction between linguistic concepts that refer to quantities on the one hand (i.e., number words and quantifiers), and those that do not on the other (i.e., all the other words).

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Fig. 1.
Patient AM's MRI scan in 2001

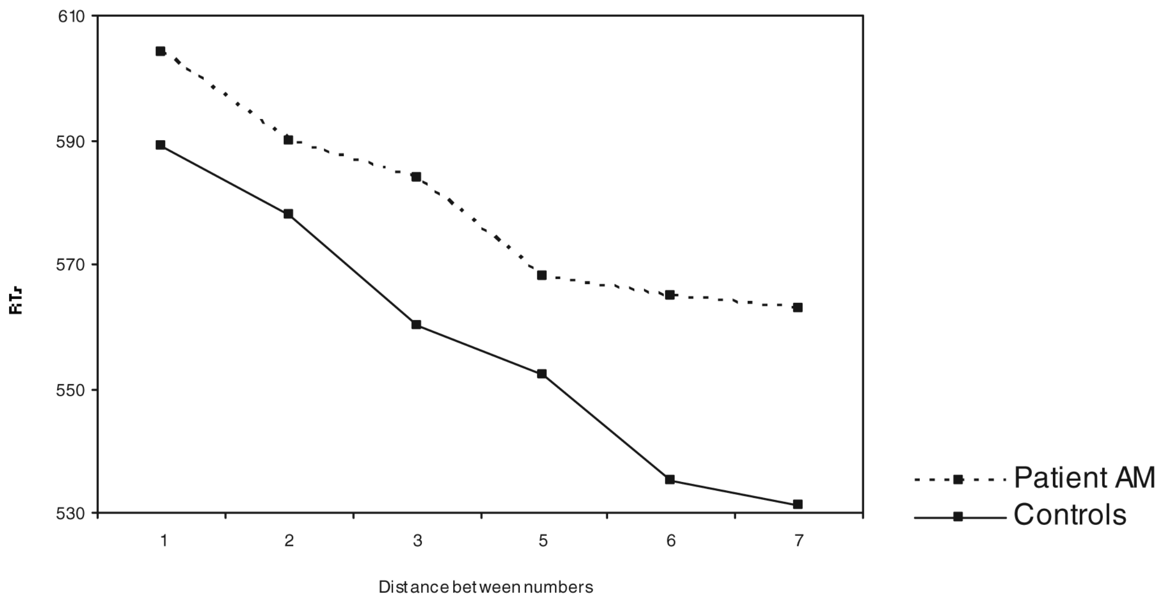

Fig. 2.
Number comparison task. Patient AM's and healthy controls' reaction times.

Table 1

Summary of cognitive scores

Tasks performed	Patient AM
General Intelligence	
NART	I.Q. = 94
WAIS-R	I.Q. = 109
Memory	
Digit span Forward	6 (within normal range)
Backward	5 (within normal range)
Recognition memory Test	
Words	41/50 (38th%ile)
Faces	37/50 (7th%ile)
WMS-R Logical memory	
Immediate	6/50 (3rd%ile)
Delay	4/50 (10th%ile)
WMS-R Visual reproduction	
Immediate	29/41 (72nd%ile)
Delay	20/41 (66h%ile)
Autobiographical Memory Interview	
Childhood	p.s. = 7/21; a.i. = 8/9 (p.s. impaired performance)
Early adult life	p.s. = 10/21; a.i. = 4/9 (a.i. impaired performance)
Recent life	p.s. = 15.5/21; a.i. = 8/9 (p.s. impaired performance)
Executive functions	
Cognitive Estimate	No. of errors = 7 (borderline abnormal)
WCST Categories attended	5/6 (preserved performance)
Total errors	15 (within normal range)
Perseverative errors	2 (within normal range)

Legend.

NART = National Adult Reading Test.

WMS-R = Wechsler Memory Scale-Revised.

WCST = Wisconsin card sorting test.

p.s. = personal semantic; a.i. = autobiographical incidences.

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Table 2

Summary of semantic scores (percent correct unless specified)

Tasks performed	Patient AM	Control subjects
Fluency [*]		
Semantic (6 categories)	43[a]	117[a]
Lexical (3 categories)	27[a]	39[a] (+/−12)
Word retrieval [*]		
Graded Difficulty Naming Test (N = 30)	16.7	‘Low average’ range
Snodgrass pictures (N = 130)	74.6	
Semantic categories (N = 70)	32.8	99
Colours (N = 10)	100	100
Classification [*]		
Words (N = 70)	80	100
Pictures (N = 70)	81.4	100
Matching		
Name-to-picture (N = 40)	100	97
Semantic associations [*]		
Pyramid and Palm Tree Task (N = 52)	90.4	98.07
Semantic link 1 (N = 20)	80	100
Semantic link 2 (N = 20)	75	95
Semantic link 3 (N = 45)	66.6	95.6
Semantic features [*]		
Definition of words and concepts (N = 70)	62.8	100
Objects' functions (N = 20)	60	100
Similarities (N = 26)	61.5	96.1
Differences (N = 26)	38.4	92.3

Notes:

[a]Total items produced for all categories

[*]Significantly different from normal controls (fluency [$X^2 = 3.99$, p<.001]; word retrieval [$X^2 = 5.62$, p<.001]; classification [$X^2 = 8.78$, p<.001]; semantic associations [$X^2 = 4.6$, p<.001]; semantic features [$X^2 = 3.64$ p<.001].

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Table 3

Summary of numerical scores (percent correct; standard deviation in brackets)

Tasks performed	Patient AM	Control subjects
Non-verbal numerical tasks		
Dot seriation (N = 18)	100	100
Dot magnitude comparison (N = 18)	100	100
Number recognition (N = 36)	100	100
Number seriation (N = 18)	100	100
Number comparison[a] (N = 20)	100	100
Number composition with token (N = 48)	100	100
Placing numbers on a line (N = 36)	75	100
Verbal numerical tasks		
Counting (N = 70)	100	100
Dot enumeration (N = 20)	100	100
What comes		
next (N = 20)	100	100
before (N = 20)	100	100
Bisection task		
Numbers (N = 10)	100	100
Letters/Months/Days (N = 30)	100	100
Knowledge of number facts		
Personal (N = 10)	100	100
Non-personal (N = 10)	100	100
Knowledge of arithmetical signs (N = 8)	100	100
Transcoding		
Reading		
one to four-digit (N = 100)	100	99.6 (0.5)
five–digit (N = 10)	100	98.4 (2.1)
six–digit (N = 10)	100	96 (1.8)
number words (N = 50)	100	100
Writing		
one to four-digit (N = 50)	98	99.2 (0.7)
five–digit (N = 10)	100	91.5 (8.7)
six–digit (N = 10)	90	91.5 (7.4)
number words (N = 20)	100	100
6 → SIX (N = 20)	100	100
SIX → 6 (N = 20)	100	100

Notes:

[a]See also the patient's performance in a computerized version of the same task.

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Table 4

Summary of calculation scores (percent correct; standard deviation in brackets)

Tasks performed	Patient AM	Control subjects
Mental calculation		
Addition problems (N = 100)	100	100
Subtraction problems (N = 100)	100	100
Multiplication problems (N = 50)	100	90 (6.8)
Division problems (N = 50)	90	88 (8.2)
Written calculation		
Addition problems (N = 25)	100	99 (0.4)
Subtraction problems (N = 25)	96	98 (2.4)
Multiplication problems (N = 25)	92	95 (6.6)
Division problems (N = 25)	76	90 (7.3)
GDA Test (N = 28)	57(Bright average level); 85.7[a]	
Approximation to the correct result (N = 24)	83.3	92.4 (7.2)

Legend. GDA = Graded Difficulty Arithmetic Test.

[a]Score according to timing criteria and without, respectively.

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Table 5

Summary of scores in tasks with quantifiers (percent correct)

Tasks performed	Patient AM	Control subjects
Sentence verification (N = 24)	91.6	100
Sentence picture-matching (N = 40)	100	99.5
Multiple pictures-one sentence	100	99
Pairs of sentences-one picture	100	100
Processing of magnitude (N = 36)	100	98
Magnitude comparison	100	99
Order of quantifiers	100	97
Quantifiers within a given context (N = 15)	100	97
Total correct answer (N = 115)	98.3	98.6