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Verbal numerosity estimation deficit in the context of spared semantic representation of numbers: A neuropsychological study of a patient with frontal lesions

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ABSTRACT

Patients with frontal lobe damage have been shown to produce implausible answers in cognitive estimation, a task requiring approximate answers to quantity-related questions of general semantic knowledge. We investigated a patient with frontal lobe damage who presented executive deficits and difficulties in cognitive estimation. The patient also showed difficulties in verbal numerosity estimation (approximately evaluating the quantity of visually presented sets of items), as he produced extreme answers well outside healthy participants' range of answers. A series of tasks evidenced intact number processing and well preserved semantic representation of numbers. Detailed investigation of estimation processes suggested a deficit at the level of translation from an intact semantic representation of numbers to output, whether verbal or non-symbolic. This case study allows disentangling different processes involved in estimation and contributes to a better understanding of the cognitive estimation deficits frequently reported for patients with frontal lesions.

1. Introduction

It has long been known that focal frontal lobe damage can sometimes cause relatively isolated cognitive deficits, which almost go unnoticed, as general intellectual capacities can be spared. One striking finding revealed that some patients with frontal lobe damage, whose general intellectual abilities were intact, presented specific difficulties in cognitive estimation, the capacity to give approximate answers to questions of general semantic knowledge for which no precise answer is readily known (Shallice & Evans, 1978). Indeed, these patients' performance, when presented with questions pertaining for example to the size, height, or weight of objects, was characterized by extremely implausible answers (example of an answer in response to the question "what is the length of an average man's spine?": "between 4 and 5 feet"). As intellectual capacities were spared, this type of deficit was interpreted as resulting from impairment of selective and regulative processes attributed to the frontal lobes (selecting possible answers, checking for the plausibility of each answer, etc.), rather than from degradation of general semantic knowledge.

On the other hand, patient studies (Brand, Kalbe, & Kessler, 2002a; Della Sala, MacPherson, Phillips, Sacco, & Spinnler, 2004; Mendez, Doss, & Cherrier, 1998; Taylor & O'Carroll, 1995, Experiment 3) have brought evidence that cognitive estimation deficits may not be specific to patients with focal frontal lobe damage. Indeed, cognitive estimation can also be impaired in patients with posterior lesions: in these cases the cognitive estimation deficit supposedly reflects impairment of general knowledge itself (semantic memory) known to be mainly sub-served by the temporal lobe.

Frontal lobe patients are known to show deficits in cognitive estimation, but since this task clearly also requires semantic knowledge (knowledge of the world, such as distances, weights or lengths) it is often difficult to disentangle the contribution of

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impaired semantic knowledge and impaired estimation processes. *Verbal numerosity estimation*, that is, giving a verbal estimate of the quantity of a set of items, differs from cognitive estimation because it requires a *perceptual* judgment of quantity (as would, for example, judging the length of the experimenter's spine).

Not many studies have specifically investigated the cerebral bases of verbal numerosity estimation. Three neuropsychological studies (Delazer, Karner, Zamarian, Donnemiller, & Benke, 2006; Pesenti, Thioux, Samson, Bruyer, & Seron, 2000; Warrington & James, 1967) suggest a role of parietal structures, in particular the right parietal lobe, in verbal numerosity estimation. This makes sense, as mere perception of or perceptual comparative judgments of numerosity (without a verbal output; e.g., comparing the quantity of two sets of dots) have been linked to parietal structures through imaging studies (e.g. Cantlon, Brannon, Carter, & Pelphrey, 2006; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Piazza, Pinel, Le Bihan, & Dehaene, 2007). Unlike cognitive estimation, verbal numerosity estimation does not rely on general semantic knowledge (sub-served by temporal structures), but rather on the intact processing of domain specific numerical representations, that is representation of numerosity (semantic representation of numbers) sub-served by parietal structures, as these studies suggest (for a review on numerical processing and the parietal lobes, see Dehaene, Piazza, Pinel, & Cohen, 2003). Thus, investigating verbal numerosity estimation in a patient with perfect processing of numerosities would allow specifically studying estimation processes without confounding deficits in semantic knowledge or number representation.

Could verbal numerosity estimation be impaired following focal frontal lobe damage, as is the case for cognitive estimation? To our knowledge, this question has not been specifically studied in controlled conditions. Similarly to the results of studies pertaining to cognitive estimation (Della Sala et al., 2004; Shallice & Evans, 1978; Smith & Milner, 1984, Experiment 1), one could expect impairments in verbal numerosity estimation in patients with frontal lobe damage, as it also represents a task in which no exact answer is readily available (in contrast to counting), and calls upon the selection of a response among a theoretically infinite range of possibilities. Here we report a study in which we tested this hypothesis by administering a verbal numerosity estimation test to a patient with focal frontal lesions, a cognitive estimation deficit and executive impairments.

If a verbal numerosity estimation deficit should arise, it would be of importance to determine whether it is linked to impairment at the level of the semantic representation of numbers. Although the semantic representation of numbers has been linked to parietal structures as discussed above, some studies suggest a possible additional involvement of the fronto-lateral cortex (in monkeys: Nieder, Freedman, & Miller, 2002; Nieder & Miller, 2004, for a review, see Nieder, 2005; in human healthy adults: e.g. Piazza, Mechelli, Price, & Butterworth, 2006). However, we did not aim to test this hypothesis, and, importantly, the patient investigated in this study presented frontal lesions which did not extend to the fronto-lateral cortex. Thus, we hypothesized that the semantic representation of numbers should be spared in such a patient. We tested this by administering tasks known to recruit the semantic representation of numbers, and which do not require a verbal output: dots comparison, dots addition and comparison, digit comparison, and number-size Stroop digit comparison.

Another level which should be investigated, should a verbal numerosity estimation deficit arise, is external calibration. Calibration characterizes the spontaneous mapping from the approximate semantic representation of numbers to a verbal response grid during verbal numerosity estimation. Healthy subjects have been shown to be poorly calibrated, that is, they present coherent estimates (estimates which increase as numerosity increases) but systematically under- or overestimate the presented numerosities (Izard & Dehaene, 2008; Minturn & Reese, 1951). External calibration (showing an example of a numerosity concurrently to the correct verbal response) has been shown to improve estimates such that under- or overestimation is significantly reduced (Izard & Dehaene, 2008; Minturn & Reese, 1951). It was suggested that this external calibration process was probably a mix between strategic and automatic adjustment of verbal responses to the semantic representation of numbers (Izard & Dehaene, 2008). Would a patient presenting a verbal numerosity estimation deficit benefit from external calibration, similarly to healthy subjects? We wished to also address this question and therefore also tested verbal numerosity estimation with external calibration. We hypothesized that a patient with frontal lesions and executive deficits would improve less following external calibration, considering that this process might involve a strategic (executive) component.

Finally, it would be important to rule out the possibility that a verbal numerosity estimation deficit might occur in relation to a specific impairment at the verbal output level. If the deficit persists with different output modalities, and if the semantic representation of numbers is intact, this would suggest that the impairment is situated at the level of translation from representation to output. We investigated this first by testing numerosity estimation with a forced-choice paradigm presenting symbolic output other than number words (forced-choice estimation "from dots to digits"); and secondly, with a forced-choice paradigm presenting non-symbolic output (forced-choice estimation "from digits to dots"). We hypothesized that the estimation deficit should extend to these other outputs, reasoning that the impairment should be situated at the level of translation from semantic representation to output, as cognitive estimation deficits following frontal lobe damage seem linked to impairments at this level (selective and regulative deficits).

2. Methods and results

2.1. Case description

The patient we examined was a 28-year old right-handed native German speaking man who had completed polytechnic studies and trained as an engines fitter. He was the beneficiary of an incapacity pension, following a car accident about 8 years prior to testing, that had caused left frontal substance defect. About 2 years prior to testing, the patient had suffered a second accident (a fall down some stairs), causing right cerebral contusions. A computed tomography (CT) scan taken during the testing period showed left fronto-polar to fronto-basal damage (see Fig. 1).

Because of the recent occurrence of epileptic Grand Mal seizures, he underwent routine neuropsychological testing. Following the testing, he was asked if he wished to participate in this study. The patient agreed and gave his informed written consent prior to his inclusion in the study.

2.2. Healthy participants

An initial group of 15 healthy unpaid volunteers (five men) was used as a comparison of the patient's results on most tasks. The volunteers were 21–43 years of age (mean age = 26.87 years). For one task (see Section 2.9), data were collected from a second group of 15 healthy participants (10 men), 5 of which were participants from the first group. Participants of this second group were 24–37 years of age (mean = 28.00 years). Participants of both groups were all native German speakers. Finally, for one other task (see Section 2.6.1) we used control data collected from 18 healthy French-speaking paid volunteers (8 men; mean age = 24.94 years, ranging from 18 to 38), participating in another study. We used these data even though they had been collected from French speakers, because the task did not call for verbal responses. Participants from all three groups were right-handed and of similar educational level (all university students or graduates), and gave their informed consent prior to their inclusion in the study.

2.3. Neuropsychological examination

A neuropsychological evaluation of the patient was carried out two days before numerical testing began (all results are reported in Table 1).

The patient presented a slight deficit in verbal long-term memory (learning and recall difficulties, consolidation and recognition being intact), in verbal production