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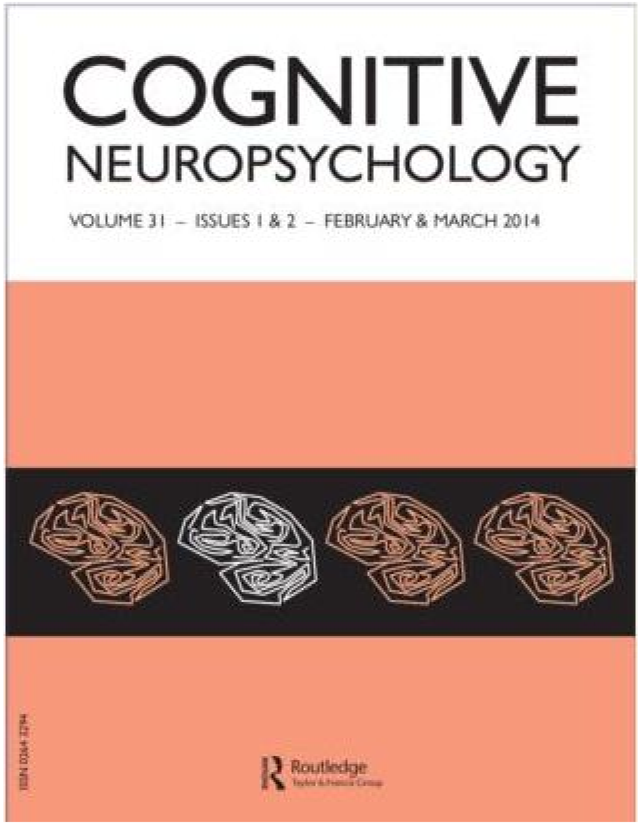

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A case-study of language-specific executive disorder

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ABSTRACT

Executive control is recruited for language processing, particularly in complex linguistic tasks. Although the issue of the existence of an executive control specific to language is still an open issue, there is much evidence that executively-demanding language tasks rely on domain-general rather than language-specific executive resources. Here, we addressed this issue by assessing verbal and non-verbal executive capacities in LG, an aphasic patient after a stroke. First, we showed that LG's performance was spared in all non-verbal tasks regardless of the executive demands. Second, by contrasting conditions of high and low executive demand in verbal tasks, we showed that LG was only impaired in verbal task with high executive demand. The performance dissociation between low and high executive demand conditions in the verbal domain, not observed in the non-verbal domain, shows that verbal executive control partly dissociates from non-verbal executive control. This language-specific executive disorder suggests that some executive processes might be language-specific.

Keywords: Language processing; Executive functions; Domain-specific process; Domain-general process; Performance dissociation; Aphasia

INTRODUCTION

Executive control includes a wide range of mechanisms such as sustained attention, inhibition, planning, flexibility, monitoring and initiation that provide resources for other cognitive functions (Diamond, 2012). Executive control is essential for regulating processes and resolving conflicts in order to orchestrate behavior according to our internal goals: It allows for monitoring and updating working memory information, for inhibiting irrelevant stimulus-driven responses and suppressing task-irrelevant information, and for shifting between processes or stimuli (Miller, 2000).

More specifically, in the language domain, executive control improves the efficiency and fluidity of language, enabling on-line processing of language components (phonology, lexicon, syntax, semantic…) (Baddeley, 2003; Hoffman et al., 2009; Nozari et al., 2016). The impact of executive control in language is limited when comprehending canonical sentences such as active sentences when naming familiar pictures, when producing automatized sequences such as the days of the week or even when producing lexically expected words in sentences; the latter being the basis of the Hayling sentence completion test (Burgess & Shallice, 1997) which provides an excellent illustration of the potential contribution of the executive control in language. In this task, the participant listens to a sentence in which the last word is missing. In section A, the patient has to simply complete the sentence such as "Before going to bed, we switch off the [light]". Whereas in section B, the patient is required to complete the sentence with a nonsense ending word, thus imposing inhibition of the spontaneous meaningful word. Executive control is higher in section B, where in addition to word production and initiation, inhibition processes are required to perform the task. This supports the view that the executive control of language is modulated by task complexity and that language may involve monitoring, inhibition, switching or re-analysing of complex structures. Indeed, in speech comprehension, whereas canonical sentences elicit an automatic response, non-canonical sentences conflict with the automatic response and, hence, require a high-order executive control response (Kotz et al., 2003; Mestres-Misse et al., 2012). Executive control also plays a substantial role in disambiguation and reanalysis of semantic content or syntactic structure, when the communicative context requires selecting an appropriate interpretation among multiple alternatives (topic, speaker, etc) (Jacquemot et al., 2006; Kotz et al., 2003; Novick et al., 2005; Ye & Zhou, 2009). In speech production, executive control allows for selecting the correct lexical items from semantic memory according to both the communicative intention and the context, as well as to plan and monitor the speech output (Indefrey & Levelt, 2004; E Jefferies, 2013; Shao et al., 2012).

An important issue is determining how language and executive control interact. Prior research has argued for a distinction between two separable systems: language and executive control, where domain-general executive resources apply in the language system similarly to other cognitive domains such as arithmetic, music, etc. According to this common view, even if domain-general executive resources are engaged during language processing and impact language performance, they are independent from language: language and executive resources can be selectively impaired and involved distinct networks. Indeed, there is much evidence from neuropsychological, brain imaging and behavioral studies indicating that even if executive control and language system interact, the two domains dissociate (Ye & Zhou, 2009). In patients with brain lesion, double dissociations between language and executive control demonstrate that two systems may be independently impaired (Fedorenko & Varley, 2016). Some severe aphasic patients perform flawlessly in executive tasks; conversely, patients without aphasia are impaired in executive tasks (Reverberi et al., 2009; Varley & Siegal, 2000). Brain imaging studies also show that executive control and language involve spatially and functionally different brain networks (Fedorenko, 2014). Whereas left-lateralized brain areas in frontal, temporal and parietal regions selectively and robustly respond to language processing, a bilateral fronto-parietal network responds to executively-demanding tasks regardless of the cognitive domain (language, memory, arithmetic, etc.) (Duncan & Owen, 2000), suggesting that domain-general executive control is modulated by task complexity regardless of the domain. In addition, domain-general executive control ability predicts performance in complex language tasks, suggesting that domain-general control processes support language tasks. Non-verbal executive control abilities such as was assessed with the go/no go task or the Wisconsin Card-Sorting Test correlate with performance in complex language tasks such as producing words under conditions of high lexical competition or speeded action-naming tasks (Shao et al., 2012; Taler et al., 2010). Evidence also comes from multilingualism in which multilingual individuals have to intensively control their speech input and output to select the target language (among the languages they master), while inhibiting the one(s) they are not using (Abutalebi et al., 2013; Hervais-Adelman et al., 2011). Bilingualism improves linguistic capacity – for example, multilingual individuals outperformed monolinguals in comprehending non-canonical sentences in the presence of linguistic interference (Bialystok & Feng, 2009; Filippi et al., 2012, 2015). Interestingly, monolingual and multilingual individuals perform at the same level with canonical sentences, suggesting that multilingual individuals show greater advantage in complex linguistic tasks when the executive demand is high. In parallel, being multilingual is associated with higher capacity in non-verbal executive control tasks which require rapid switching between rules, suppression of irrelevant information, monitoring and updating changes (Bialystok, 2017; Bialystok et al., 2012; Pelham & Abrams, 2014). Although these findings suggest that the enhanced executive control capacity observed in multilinguism is not specific to language but spreads to other cognitive domains, this multilinguism advantage has been recently questioned in a growing number of studies (Filippi et al., 2020; Lehtonen et al., 2018; Paap et al., 2014; Paap & Greenberg, 2013). Finally, impaired performance in children with specific language impairment (SLI), a developmental disorder affecting language acquisition when processing complex sentences, (Im-Bolter et al., 2006; van der Lely, 2005) correlates with their deficit in inhibition and working memory; this therefore suggests a link between general executive control ability and complex language tasks.

Altogether, this suggests that executive control in language is supported by domain-general resources and modulated by the complexity of the linguistic task (January et al., 2008; Novick et al., 2005). However, this hypothesis does not preclude that executive processes specifically dedicated to language may complement general executive functions (Hsu et al., 2017; Hamilton & Martin, 2005).

Here, by reporting the case of a patient with a dissociation between verbal and non-verbal executive tasks, we argue that there is a part of executive control specifically dedicated to language. This language-specific component of the executive network could be impaired independently of its non-verbal component. In tasks with high executive demand, the patient showed impaired performance in the verbal domain but spared performance in non-verbal domain. This language-specific executive disorder undermines the notion of domain-generality of executive control and suggests that some executive resources instead of being domain-general might be language-specific.

MATERIAL AND METHODS

Case report

Patient LG, right-handed and 50-years old, was working as a computer programmer (14 years of education) at the time of his stroke. He was admitted to the hospital for acute language difficulties. A CT scan showed a stroke encompassing the left anterior cingulate cortex (ACC) and the left caudate nucleus. LG was fluent but his spontaneous speech was sprinkled with semantic paraphasias and circumlocutions. The patient was tested from 3 to 9 months after the stroke. Healthy participants were included in this study to provide controls for the novel tasks. The study was carried out in accordance with the recommendations of the code of ethics in French law for observational studies and of the Declaration of Helsinki. All participants consented to this research.

General neuropsychological assessment

Neuropsychological examination included verbal and non-verbal tests to assess global intellectual function, language, executive functions, working memory, visual processing, and attention. Whereas the assessment of LG's intellectual functioning with the non-verbal test of the Wechsler Adult Intelligence Scale (WAIS III) (Wechsler, 1997) showed normal performance, LG's intellectual functioning assessed through verbal tests (WAIS III and Binois-Pichot Vocabulary Test) (Binois & Pichot, 1956) showed only low average performance (see Table 1). Intellectual assessment revealed a discrepancy between non-verbal and verbal performance. Because intellectual functioning assessment is highly dependent on executive functions and language, we further explored executive ability in non-verbal and verbal domains.

In order to evaluate LG's non-verbal executive ability, we assessed non-verbal tasks from previous studies and contrasted tasks requiring low and high executive demand (Calabria et al., 2014; Hoffman et al., 2009, 2011, 2012; Hoffman, Jefferies, et al., 2013; Jefferies et al., 2008; Jefferies & Lambon Ralph, 2006; Thompson & Jefferies, 2013). The digit cancellation task (Della Sala et al., 1992) is a three-step task which consists of cancelling a target digit, then two targets, and finally three target digits in a panel of numbers. It allows for assessing attention allocation. The Trail Making Test (TMT) consists of two parts (A and B) in which the participant is instructed to connect a set of dots as accurately and quickly as possible

(Tombaugh, 2004). Part A (TMT A) consists of digits and assesses both attention and motor speed while part B (TMT B), consisting of alternating digits and letters, assesses attention, motor speed and flexibility, thus requiring executive resources. The Raven progressive matrices task measures abstract reasoning (Raven, 1983). The participant is asked to identify the missing pattern within a series of geometrical patterns. In the Wisconsin Card-Sorting Test, which measures abstract reasoning, task switching and attention, the participant is asked to match cards with figures differing with respect to color, quantity, and shape (Heaton, 1981). The Rey figure is a complex figure that the participant is asked to copy (Fastenau et al., 1999). In the Ratcliff test, the participant is asked to decide in which hand human figures from the front, from the back or oriented upside down are holding a ball in order to assess spatial orientation (Ratcliff, 1979). The Protocole d'Evaluation des capacités Gnosiques Visuelles (PEGV) assesses visuospatial abilities, attention, working memory, planning, and monitoring to detect eventual visual agnosia. It comprises of several tasks (embedded pictures to recognize, intruder detection, functional matching, and categorical matching) (Agniel et al., 1992). Patient LG performed within the normal range of all these non-verbal tests regardless of the executive demand of the task.

In contrast, LG displayed a dissociation in performance among verbal tasks, showing low performance when the executive demand was high but spared when the executive demand was low. More precisely, LG's speech quality was normal in a free narrative and open-ended conversation. He performed normally at picture-naming in both the DO80 (Oral Naming 80) (Deloche & Hannequin, 1997) and the naming part of the French version of the Boston Diagnostic Aphasia Examination (BDAE) (Goodglass et al., 2007). Conversely, LG's performance was below the normal range in the Commands part of the BDAE, in which he was requested to carry out commands such as "place the watch on the other side of the pen and turn the card over", which imply subsequent embedded actions. He was also impaired in both categorical and letter fluency (Cardebat et al., 1990), tests where subjects are required to orally elicit as many animal names (categorical) or words beginning with a specific letter (letter) in two minutes. In contrast to picture naming, fluency tasks require higher executive resources for monitoring and inhibiting the numerous competitors. Likewise, LG was impaired in the similarities subtest of the WAIS, a verbal task in which the participant has to describe how two auditory words or concepts are similar. This task assesses language conceptualization, verbal abstraction, and analogical verbal reasoning. It examines the ability to think abstractly and to find similarities among words or ideas that may not appear to be similar on the surface. LG was also impaired in section B of the Hayling sentence completion test (Burgess & Shallice, 1997) but not in section A. Consistently, LG was performed flawlessly in the forward digit span, which is mostly an attentional and immediate memory task, but was impaired in the backward span (Jacquemot et al., 2019; Wechsler, 1997) which involves the executive control component of the verbal working memory (Baddeley, 2003b).

In summary, the general assessment demonstrated impaired performance in verbal tasks with high executive demand, but spared performance in verbal tasks with low executive demand and in all non-verbal tasks regardless of their executive demand. In order to directly assess the role of executive control in the patient's verbal deficit, we assessed language tasks in which the executive demand was modulated within-task.

Language assessment

Statistical methods

We performed case-control comparisons using the Crawford modified t-test (Crawford et al., 2010) which calculates the probability that a single case comes from the distribution of a control sample. In addition, to demonstrate the existence of a dissociation between performance across two conditions, we compared the difference between LG's scores with the analogous difference in controls using the Revised Standardized Difference Test (RSDT, Crawford et al., 2010). Two-tailed p values are reported. For each task, the percent of correct response and standard deviation are reported. The correlation coefficient (r) among conditions in the control sample is also reported.

Language comprehension

Word comprehension was evaluated with an auditory word-picture matching task (Jacquemot et al., 2007). A total of 64 pictures of common concrete nouns were selected and were visually presented with an auditory word. The word was either the correct name of the picture (e.g., “bureau” /byro/ desk for a picture of a desk), an unrelated distractor (e.g., “pomme” /pom/ apple), a semantic distractor (e.g., “armoire” /armwar/ wardrobe), or a phonological distractor. There were two types of phonological distractors: words and pseudowords, which were phonologically equidistant from the target word (e.g., the word /bylo/ whelk and the pseudoword /byfo/). Every picture was presented once with each auditory item (the identity and the four types of distractor) with a total of 320 trials. LG was asked to decide whether the auditory word matched the picture. His performance was compared to that of matched controls (N=5; mean age: 52.2 ±2.16, $p > 0.1$; mean age of education: 14 ±3.9, $p > 0.1$).

Sentence comprehension was evaluated with a sentence-picture matching task. The patient was asked to decide whether an auditory sentence matched a picture (Teichmann et al., 2005). We contrasted two syntactic conditions: sentences followed either the French canonical syntactic order (active and subject relative sentences, e.g. “The girl waters the flower that is white”, N=16) or a non-canonical syntactic order (passive and object-relative sentences, e.g. “The flower that is white is watered by the girl”, N=16) (Supplementary material, Table 1). The two conditions were matched for sentence length and word frequency. LG’s performance was compared to that of matched controls (N=20; mean age: 46.1 ±6.6, p > 0.1; mean education age: 13.2 ±4.3, p > 0.1).

Language production

Speech production was assessed through a word production task, using an oral definition (Bachoud-Lévi & Dupoux, 2003). We contrasted two conditions: “concrete” and “abstract” in which the expected responses were respectively, concrete and abstract words as rated by control participants from 1 to 5. Since the definition of abstract and concrete is debated, the scale was rated arbitrarily between two examples tomato (1) and freedom (5) (Bachoud-Lévi & Dupoux, 2003). The two conditions were matched for syllable length and word frequency. For each word, concrete (N=20) or abstract (N=20), a definition was constructed and presented orally to LG who was asked to produce the word corresponding to the definition (Supplementary material, Table 2). LG’s performance was compared to that of matched controls (N=17; mean age: 56.8 ±3.6, p > 0.1; mean education age: 14.2 ±2.6, p > 0.1).

We designed the CATEX® (CATegory / EXemplar) (Jacquemot & Bachoud-Lévi, 2019), a picture-naming task in which the executive demand is modulated independently of linguistic factors. We contrasted two conditions: “exemplar” and “category”, in which the expected responses were respectively, exemplar and category words. In this task, LG and matched controls (N=37; mean age: 50.8 ±20.6, p > 0.1; mean education age: 11.4 ±4.95, p > 0.1) were asked to produce a single word describing two pictures either of the same item (“exemplar” condition, e.g. a banana and a peeled banana, with “banana” as the expected response) or of two different items from the same category (“category” condition, e.g. a banana and an apple, with “fruit” as the expected response). The production of category words is more demanding of executive resources than the production of exemplar words, but conditions were equalised for linguistic demand. We selected exemplar (N=31) and category (N=31) items with a mean accuracy above 90% (data from a naming agreement pilot study with 40 participants), matched for syllable length (mean syllable number of Exemplar: 1.87 ±0.72; Category: 1.87 ±0.56; p = 1), phonemes number (mean phoneme number of Exemplar: 4.6 ±1.12; Category: 4.44 ±1.32; p = 0.6) and word frequency (mean word frequency[1] of Exemplar: 65.2 ±112.1; Category: 52.2 ±54.2; p = 0.6) (Supplementary material, Table 3).

Semantic cognition

Lambon Ralph et al., (2017) refers to semantic cognition as the ability to use, manipulate and generalize knowledge acquired over a lifespan to support verbal and non-verbal behaviours. It combines semantic memory, referring to acquired knowledge and its executive control component regulating and organising both retrieval and access to semantic memory. To assess semantic cognition, we constructed non-verbal picture tasks such as anomalous picture detection, picture completion, categorical intruder detection and functional matching (N=140). In addition, we assessed LG's capacity to retrieve semantic information related to pictures of artefacts, animals, vegetables and tools (N=66). LG had to answer yes/no questions with respect to pictures (e.g. "Is it edible?", "Does it fit in a shoe box?", "Is it from inside or outside the house?", N=308) (Jacquemot et al., 2012). Finally, we assessed whether LG understood the concept of "category" by asking him to produce a word from the same category of a given auditory word (N=28).

[1] Lemma frequency from movies, www.lexique.org.

For instance, on hearing the word "fork", the patient was expected to reply "knife", "spoon", etc.

RESULTS

Language comprehension

Word comprehension

In word comprehension, LG performed as well as controls (percent of correct responses, LG: 99.4%; controls: 99.8±0.3%; Z-score: -1.43; $t = -1.4$, $df = 4$, $p = 0.16$).

Sentence comprehension

In sentence comprehension, LG comprehended canonical sentences as well as controls, but his comprehension of non-canonical sentences was poorer than controls (percent of correct responses for canonical sentences, LG: 93,7%; controls: 99±9.6%; Z-score: -0.5; $t = -0.52$, $df = 19$, $p > 0.1$; percent of correct responses for non-canonical sentences, LG: 81.3%; controls: 90.3±2.2%; Z-score: -3.8; $t = -3.7$, $df = 19$, $p < 0.001$; $r = 0.59$). The difference between LG's performance on canonical and non-canonical sentences differs significantly from the distribution of differences in controls (RSDT $t = 3.3$, $p = 0.004$, $ES = 3.5$) (Table 2).

Language production

Concrete and abstract word production

LG's production was flawless for concrete words, but impaired for abstract words compared to controls (correct responses for concrete words, LG: 95%; controls: 94±4%; Z-score: 0.22; $t = 0.2$, $df = 16$, $p = 0.8$; correct responses for abstract words, LG: 65%; controls: 90.6±5%; Z-score: -5.17; $t = -5.0$, $df = 16$, $p < 0.001$; $r = 0.21$). The difference between LG's performance in concrete and abstract words differs significantly from the distribution of differences in controls[2] (RSDT $t = 3.9$, $p = 0.001$, ES = 4.3), (Table 2). The distribution of LG's errors is reported Table 3.

Exemplar and category word production (CATEX)

In the CATEX, LG performed similarly to controls for the exemplar condition (correct responses, LG: 90.3%; controls: 94±5%; Z-score: -0.76; $t = -0.75$, $df = 36$, $p = 0.45$) but lower than controls for the category condition (correct responses, LG: 51.6%; controls: 89.1±8%; Z-score: -4.93; $t = -4.9$, $df = 36$, $p < 0.001$; $r = 0.5$). The difference between LG's performance in exemplar and category conditions differs significantly from the distribution of differences in controls (RSDT $t = 4.1$, $p < 0.001$, ES = -4.2), (Table 2).

Semantic cognition

LG's semantic cognition was intact. LG was unimpaired in non-verbal picture tasks: anomalous picture detection, picture completion, categorical intruder detection and functional matching (97.1% of correct responses). LG's capacity to retrieve semantic information related to pictures of artefacts, animals, vegetables and tools was flawless (100% of correct responses). LG performance in yes/no questions about semantic information related to depicted items on picture was spared too (98.8% of correct responses). He performed flawlessly in naming exemplars from the same category of pictures of items (96.4% of correct responses), indicating a spared understanding of the concept of category.

[2] Note that in controls, the absence of performance difference between concrete and abstract words, and exemplar and category words is not due to a ceiling effect, since their performance with abstract and category words are not at ceiling.

DISCUSSION

LG displayed a language disorder with normal intellectual abilities following a left ACC and left caudate nucleus lesion. He showed normal performance in executively-undemanding verbal tasks (i.e. section A of the Hayling test, automatic speech, forward digit span, picture naming, repetition, word comprehension) but impaired performance in executively-demanding verbal tasks requiring executive control (i.e. section B of the Hayling test, verbal fluency, backward digit span, similarities subtest of the WAIS, comprehension of commands and complex sentences). In contrast, his performance was unaffected in non-verbal tasks regardless of the executive demand: LG succeeded in both executively-undemanding tasks such as the TMT A and the digit cancellation test, as well as in executively-demanding tasks such as the Raven progressive matrices, the Wisconsin card-sorting test, the TMT B and tasks assessing visual, spatial and mental rotation skills, i.e. the Ratcliff test, the Rey figure copying test and the PEGV (Table 1). The results of the language assessment in which conditions of high and low executive demand were contrasted within each verbal task confirmed that LG was specifically impaired in conditions requiring high executive demand.

Unlike previous cases displaying a domain-general executive deficit affecting verbal and non-verbal tasks indiscriminately (Calabria et al., 2014; Hoffman et al., 2012; Thompson & Jefferies, 2013; Vuong & Martin, 2015), LG displayed an impairment specific to verbal tasks requiring executive control to be performed while sparing capacities in non-verbal tasks. Acknowledging that comparison between tasks might mask uncontrolled biases, we further assessed language through speech comprehension and production tasks in which we contrasted two conditions within tasks: low executive control demand versus high executive control demand while keeping constant linguistic parameters. Sentence length, syllable length and word frequency were matched between conditions in the sentence picture matching task, in the concrete/abstract word production task and in the CATEX® task, suggesting that LG's lower performance in high executive conditions was not due to linguistic parameters. In addition, we ensured that LG had no semantic cognition impairment as demonstrated by LG's excellent performance in semantic cognition and category concept assessments.

One could argue that LG suffers from a disorder of semantic cognition in which semantic control processes interact with semantic memory to ensure that the information accessed at any given moment is appropriate for the current task and context (Jefferies & Lambon Ralph, 2006). Indeed, two kinds of deficits affect semantic cognition: semantic dementia and semantic aphasia. Semantic dementia is characterized by an impairment of semantic memory affecting all tasks regardless of the modality (spoken and written words, pictures, environmental sounds, object use…) and lower performance for specific concept and unique features (Patterson et al., 2007). For instance, patients with semantic dementia will forget the zebra stripes before forgetting a common feature in animals like its tail. Semantic dementia occurs after bilateral anterior temporal lobe damage. In contrast, semantic aphasia is due to an executive control deficit of semantic memory and associated with prefrontal or temporo-parietal infarcts. Patients' performance with semantic aphasia is consistent across the different modalities but inconsistent across tasks since it depends of the executive control requirement of the tasks (Jefferies & Lambon Ralph, 2006; Noonan et al., 2010). Patients show deficits in executively demanding semantic tasks in both verbal and non-verbal domains (Corbett et al., 2008, 2009; Jefferies & Lambon Ralph, 2006; Thompson & Jefferies, 2013). In addition, their performance in language tasks is highly influenced by the degree of competition between concepts and the extent to which the task constrains semantic processing (Krieger-Redwood et al., 2015). We can easily rule out semantic dementia in LG because the behavioural and anatomical data are not consistent with the etiology of this neurodegenerative disease: LG's performance in semantic cognition tasks is not impaired and the anterior parts of his temporal lobe are not damaged. It is also unlikely that LG had semantic aphasia for several reasons. First, when assessing semantic cognition, LG showed no impairment even in tasks requiring the control of semantic memory such as categorical intruder detection or functional matching. Second, contrary to patients with semantic aphasia who perform poorly on a variety of executive measures such as the WCST, the Raven matrices, the TMT B (Jefferies et al., 2008; Thompson & Jefferies, 2013), LG was not impaired in non-verbal executive tasks. Third, in semantic aphasia, we would expect some difficulties in the auditory word-picture matching task, especially with semantic distractors and in the exemplar naming task, which was not the case with LG (Jefferies & Lambon Ralph, 2006).

LG was impaired in speech production tasks in conditions that involve executive control (abstract and category words) in comparison to exemplar and concrete words production. This dissociation between performance in abstract and category words compared to concrete and exemplar words deserves special interest. What factors make abstract and category words special compared to concrete and exemplar words? Concrete words are associated to richer perceptual experiences and a higher number of active semantic features, than abstract words (Gao et al., 2019; Jones, 1985; Paivio, 1990). As the meaning of abstract words does not refer to an object that may be perceived directly in the world (e.g. peace) and relates to intangible experiences or properties (Paivio, 1990), their context is highly variable (Hoffman, 2016). For example, "peace" combines different contextual frameworks. It may refer to a state of mind or to the status of two countries after a war. Similarly, a category refers to the relationships between several exemplars that may differ considerably (e.g., cats and lions are very different, but both are from the same category of felines). The meaning of abstract and category words is heavily dependent on the context -the so-called semantic diversity- in which they are being used (Hoffman et al., 2010, 2015; Hoffman, Jones, et al., 2013; Jefferies, 2013; Jefferies & Lambon Ralph, 2006). In contrast to exemplar and concrete words, abstract and category words can occur in many different contexts: they refer to many meanings, less tangible items with lower sensory-perceptual content and lower number of active semantic features. Hence, processing them requires greater demands on executive control of semantic knowledge to provide access to competing aspects of semantic cognition not dependent on any particular perceptual experience for retrieving the correct meaning in speech comprehension and selecting the correct word in production. This suggests that LG's verbal performance depends on the executive demand of the task (Table 2). Consistently, LG was also impaired in the sentence comprehension task, but only for non-canonical sentences, the condition that involves executive control in comparison to canonical sentences. LG's verbal performance is modulated by executive demand whereas non-verbal performance is unaffected by executive demand (Table 1).

This dissociation between verbal and non-verbal domains suggests that executively-demanding language tasks rely at least partly on mechanisms different from those used in the non-verbal domain. This effect might be the result of an impaired interaction between language processing and a general executive system, where language modality would be specifically affected, or the result of an impaired language-specific executive component (Jacquemot & Bachoud-Lévi, in revision). It has been recently proposed that executive control involved in language tasks, instead of being considered as a domain general "central controller" may be an emergent property of distributed systems (Eisenreich et al., 2017). A similar proposal has been made in the domain of short-term memory, where short-term memory capacity is an emergent property of the language system relying on the links between the speech comprehension and speech production modalities rather than a separate system (Jacquemot & Scott, 2006; Majerus, 2013). Another view is that rather than being domain-general, some mechanisms can become duplicated over evolution, with independent copies in different domains wrongly suggesting there are domain-general mechanisms (Endress, 2019). Whereas our study does not specifically address these hypotheses, LG's dissociation between executive verbal and non-verbal tasks supports the view that verbal executively-demanding tasks rely on processes different from those involved in non-verbal executively-demanding tasks which may specifically be impaired.

The location of LG lesions in the left ACC and caudate nucleus enhance their role in the neuronal architecture underpinning executive functions dedicated to language. Previous literature showed that executive control is associated with a fronto-parietal network including the prefrontal cortex, the ACC, the temporo-parietal junction and basal ganglia (Duncan & Owen, 2000; Friederici, 2006; Monchi et al., 2006; Noonan et al., 2013; Pini et al., 2020; Ye & Zhou, 2009). Within this network, a key role is attributed to the ACC when effortful control is required (Bush et al., 2000). Functional and structural imaging studies on language showed that the caudate nucleus and putamen (dorsal striatum) played a critical role in language control and flexibility, notably in tasks involving selection among linguistic alternatives switching between languages (Abutalebi et al., 2013; Crinion et al., 2006; Giavazzi et al., 2018; Hervais-Adelman et al., 2015). Because they focused on the modulation of executive control in verbal tasks, these studies did not indicate whether some parts of the network would be specific to executive control in language or rather be involved in domain-general executive control. In contrast, LG's case allowed us to dissociate language-specific executive processes from non-verbal executive processes. A potential candidate for the language-specific executive network may involve the ACC and the caudate nucleus.

This patient case study shows that contrary to the traditional view, some executive processes are language-specific and can be selectively impaired without affecting non-verbal executive performance. We refer to executive control as a whole without distinguishing between different executive processes (flexibility, monitoring, inhibition, etc.). A further step would be to determine how domain-general and language-specific executive resources interact by focusing on each type of executive process and assessing them separately. Finally, investigating their neural correlates within the fronto-striatal network may help in comprehending the language system.

Disclosure of interest

The authors report no conflict of interest.

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TABLES

Table 1

Test			Score	Z-score or cut-off[1]	LG's deficit[2]
VERBAL TESTS					
Intellectual function					
	Binois-Pichot Vocabulary Test[3]		13/44 IQ= 83	-1.33	Low Average
	WAIS-III	Information	8/19	-0.67	Average
Language					
	Hayling test	Section A	15/15	/	
	DO80	Picture naming	75/80	<73	
	BDAE				
	Comprehension	Word discrimination	60/72	-1.80	
		Body-part identification	18/20	-0.64	
		Commands	10/15	-3.38	**
		Logical reasoning	8/12	-0.73	
	Fluency	Articulatory agility	7/7	/	
		Phrase Length	7/7	/	
		Verbal production	12/14	-0.83	
	Automatic speech	Automizeted sequences	9/9	/	
		Reciting	2/2	/	
	Repetition	Words	10/10	/	
		Concrete sentences	8/8	/	
		Abstract sentences	8/8	/	
	Production	Confrontation naming	85/105	-1.30	
Executive functions					
	WAIS-III verbal tests	Similarities	6/19	-1.33	Low average
	Verbal fluency	Animal (2 min)	12	-2.86	**
		Letter P (2 min)	4	-2.58	**
		Letter R (2 min)	0	-2.32	*
		Letter V (2 min)	10	-1.32	
	Hayling test	Section B	6/15	-3.97	**
Working memory					
	WAIS III	Digit span	7/19	-1.00	Low average
	Forward digit span		6	-0.45	
	Backward digit pan		3	-2.14	*

Test		Score	Z-score or cut-off[1]	LG's deficit[2]
NON-VERBAL TESTS				
Intellectual function				
WAIS-III	Raven progressive matrices	54/60 IQ>135	+2.33	Very superior
Executive functions				
Trail Making Test B		24/25 (80 sec)	<21 (>151 sec)	
Wisconsin card-sorting test	Series	6/6	/	
	Criteria	3/3	/	
WAIS-III picture arrangement		12/19	+0.67	Average
Ratcliff Manikin test	Mental rotation	14/16	-0.21	
Attention				
Trail Making Test A		25/25 (27 sec)	<22 (>67 sec)	
Digit cancellation test	1 digit	10/10	/	
	2 digits	20/20	/	
	3 digits	24/30	0.19	
Visual process				
PEGV	Identical figures	10/10	/	
	Entangled figures	10/10	/	
	Functional matching	10/10	/	
	Category matching	10/10	/	
Rey figure		35/36	0	

Z-scores or published cut-offs are reported for LG's scores that are not at ceiling. A negative Z-score value indicates that LG had a lower score than healthy participants. Cut-offs are indicated with superior or inferior signs. For score cut-offs, the value is the score under which a score is considered as abnormal. For time cut-offs, the value is the time above which a duration is considered as abnormal.

LG's deficit with a Z-score below 1.96 (outside the 95% confidence interval) is indicated with * and below 2.58 (outside the 99% confidence interval) with **, except for LG's WAIS normative scores for which the WAIS score interpretation is reported (Wechsler, 1997).

Table 2

	Low executive condition	High executive condition	Dissociation between low and high executive load compared to controls (RSDT)
Language comprehension	Canonical sentences: 93.7% Z-score: -0.5	Non-canonical sentences: 81.2% Z-score: -3.8	p = 0.004 ES = 3.5, 95% CI = [2.2 to 5.1]
Language production	Concrete words: 95% Z-score: 0.22	Abstract words: 65% Z-score: -5.17	p = 0.001 ES = 4.3, 95% CI = [2.6 to 6.2]
	Exemplar words: 90.3% Z-score: -0.76	Category words: 51.6% Z-score: -4.93	p < 0.001 ES = -4.2, 95% CI = [-5.5 to -2.9]

Table 2: Dissociation of LG's performance in language as a function of executive load. Conditions of the language comprehension and production tasks are classified according to the executive resources they require to be performed (low or high executive load). We reported LG's score, as well as a Z-score of LG's performance in each condition and the statistical difference (two tailed probability) between LG's standardized scores for low and high executive language conditions compared to controls using the Revised Standardized Difference Test (RSDT, Crawford et al., 2010). Effect sizes (ES) for the difference between LG and controls (Z-DCC) and 95% Bayesian Credible Interval (CI) are also reported. LG's pattern of performance fulfils the criteria of dissociation between low and high executive conditions for each of the language tasks.

Table 3

	Picture Naming		CATEX		Word finding from definition	
	DO80	BDAE	Category	Exemplar	Concrete	Abstract
Superordinate			5	1		
Semantic paraphasia	5	15	3	2		6
Phonological paraphasia					1	1
Circumlocution		5	5			
Single exemplar			2			

Table 3: Type of errors by LG in speech production tasks. The number of errors in each task is reported according to the error type. Superordinate error means that LG produced a word of a superordinate category instead of the correct word (i.e., animal instead of feline). Circumlocution error means that LG produced a phrase that circles around the target item (i.e., an item that can be found in a room instead of furniture). Single exemplar is an error that can only be produced in the Category condition of the CATEX task and where LG produced a word that corresponds to only one of the two exemplars he was presented with.

Supplementary material

Table 1: Sentence comprehension task. Items of the Canonical and Non-canonical conditions.

Canonical sentences	
la fille qui arrose la fleur est noire	*the girl who waters the flower is black*
le cheval qui attrape le garcon est noir	*the horse that catches the boy is black*
le garcon qui attrappe le cheval est noir	*the boy who catches the horse is black*
le pompier qui a des bottes noires arrose la valise	*the fireman who has black boots water the suitcase*
la fleur qui arrose la fille est blanche	*the flower that waters the girl is white*
le facteur qui a des chaussures noires mord le chien	*the postman with black shoes bites the dog*
le fleur qui arrose la fille est blanche	*the flower that waters the girl is white*
le cheval qui attrape le garcon est noir	*the horse that catches the boy is black*
le garcon qui attrape le cheval est noir	*the boy who catches the horse is black*
le pompier qui a des bottes noires arrose la valise	*the fireman who has black boots water the suitcase*
la fille qui arrose la fleur est blanche	*the girl who waters the flower is white*
le facteur qui a des chaussures noires mord le chien	*the postman with black shoes bites the dog*
le chien mord le facteur qui a des chaussures noires	*the dog bites the postman who has black shoes*
la valise arrose le pompier qui a des bottes noires	*the suitcase waters the fireman who has black boots*
le chien mord le facteur qui a des chaussures noires	*the dog bites the postman who has black shoes*
la valise arrose le pompier qui a des bottes noires	*the suitcase waters the fireman who has black boots*
Non-canonical sentences	
le garcon qu'attrape le cheval est blanc	*the boy the horse catches is white*
le cheval qu'attrape le garcon est noir	*the horse the boy catches is black*
le garcon qu'attrappe le cheval est noir	*the boy caught by the horse is black*
la fille qu'arrose la fleur est blanche	*the girl who waters the flower is white*
la fille qu'arrose la fleurs est blanche	*the girl who waters the flowers is white*
la fleur qu'arrose la fille est blanche	*the flower the girl waters is white*
le cheval qu'attrape le garcon est noir	*the horse the boy catches is black*
la fleur qu'arrose la fille est blanche	*the flower the girl waters is white*
la facteur qui a des chaussures noires est mordu par le chien	*the postman who has black shoes is bitten by the dog*

la pompier qui a des bottes noires est arrosé par la valise	*the fireman who has black boots is hosed down by the suitcase*
le pompier qui a des bottes noires est arrosé par la valise	*the fireman who has black boots is hosed down by the suitcase*
le facteur qui a des chaussures noires est mordu par le chien	*the postman who has black shoes is bitten by the dog*
la valise est arrosé par le pompier qui a des bottes noires	*the suitcase is hosed down by the fireman who has black boots*
le chien est mordu par le facteur qui a de chaussures noires	*the dog is bitten by the postman who has black shoes*
le chien est mordu par le facteur qui a de chaussures noires	*the dog is bitten by the postman who has black shoes*
la valise est arrosé par le pompier qui a des bottes noires	*the suitcase is hosed down by the fireman who has black boots*

Table 2: Word finding from definitions. Items of the Abstract and Concrete conditions

Concrete		Abstract	
lit	*bed*	paix	*peace*
chaise	*chair*	tante	*aunt*
chaine	*chain*	messe	*mass*
bague	*Ring*	paire	*pair*
beurre	*Butter*	dette	*debt*
delle	*delle*	panne	*breakdown*
hanche	*hip*	honte	*shame*
feuille	*leaf*	deuil	*mourning*
quille	*keel*	bail	*lease*
barbe	*beard*	perte	*loss*
forêt	*forest*	santé	*health*
rideau	*curtain*	salut	*salvation*
cheval	*horse*	retard	*delay*
montagne	*Mountain*	semaine	*week*
journal	*newspaper*	vertige	*vertigo*
casquette	*cap*	discours	*speech*
serpent	*snake*	serment	*oath*
jardin	*garden*	respect	*respect*
horloge	*clock*	organe	*organ*
éponge	*sponge*	usure	*wear*

Table 3: Picture naming task (CATEX). Items of the Exemplar and Category conditions.

Exemplar		Category	
piano	*piano*	reptiles	*reptiles*
couteau	*knife*	vêtements	*clothing*
marteau	*hammer*	couverts	*cutlery*
table	*table*	outils	*tools*
artichaut	*artichoke*	meubles	*furniture*
banane	*banana*	animaux	*animals*
cerveau	*brain*	oiseaux	*birds*
fourmi	*ant*	fleurs	*flowers*
collier	*necklace*	arbres	*trees*
canon	*cannon*	légumes	*vegetables*
requin	*shark*	fruits	*fruits*
terre	*Earth*	végétaux	*plants*
cerises	*cherries*	organes	*organs*
voiture	*car*	insectes	*insects*
jambe	*leg*	bijoux	*jewelry*
un	*one*	armes	*weapons*
serpent	*snake*	nourriture	*food*
manteau	*coat*	félins	*felines*
perroquet	*parrot*	jeux	*games*
aigle	*eagle*	poissons	*fishes*
rose	*pink*	rongeur	*rodent*
palmier	*palm*	pièces	*rooms*
cactus	*cactus*	bagages	*luggage*
cœur	*heart*	planètes	*planets*
gâteau	*cake*	desserts	*desserts*
castor	*beaver*	vivants	*Living being*
valise	*suitcase*	véhicules	*vehicles*
commode	*dresser*	singes	*monkeys*
chimpanzé	*chimpanzee*	membres	*limb*
trompette	*trumpet*	instruments	*instruments*
trois	*three*	chiffres	*numbers*