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Dissociating nouns and verbs in temporal and perisylvian networks: Evidence from neurodegenerative diseases

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Abstract

Naming of nouns and verbs can be selectively impaired in neurological disorders, but the specificity of the neural and cognitive correlates of such dissociation remains unclear. Functional imaging and stroke research sought to identify cortical regions selectively recruited for nouns versus verbs, yet findings are inconsistent.

The present study investigated this issue in neurodegenerative diseases known to selectively affect different brain networks, thus providing new critical evidence of network specificity. We examined naming performances on nouns and verbs in 146 patients with different neurodegenerative syndromes (Primary Progressive Aphasia – PPA, Alzheimer's disease – AD, and behavioral variant Frontotemporal Dementia – FTD) and 30 healthy adults. We then correlated naming scores with MRI-derived cortical thickness values as well as with performances in semantic and syntactic tasks, across all subjects.

Results indicated that patients with the semantic variant PPA named significantly fewer nouns than verbs. Instead, nonfluent/agrammatic PPA patients named fewer verbs than nouns. Across all subjects, performance on nouns (adjusted for verbs) specifically correlated with cortical atrophy in left anterior temporal regions, and performance on verbs (adjusted for nouns) with atrophy in left

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Sladjana Lukic: Conceptualization, Methodology, Writing-Original Draft, Writing-Review & Editing, Data curation, Formal behavioral and imaging analysis, Visualization. **Valentina Borghesani:** Conceptualization, Methodology, Visualization, Editing. **Elizabeth Weis:** Investigation. **Ariane Welch:** Investigation. **Rian Bogley:** MR Data quality check. **John Neuhaus:** Statistical behavioral analyses, Supervision. **Jessica Deleon**: Investigation. **Zachary A. Miller**: Investigation. **Joel H. Kramer**: Investigation, Resources. **Bruce L. Miller:** Funding acquisition, Resources. **Nina F. Dronkers**: Conceptualization, Funding acquisition, Writing-Original Draft, Writing-Review & Editing, Supervision. **Maria Luisa Gorno-Tempini**: Conceptualization, Investigation, Resources, Funding acquisition, Writing-Original Draft, Writing-Review & Editing, Supervision.

Open practices

The study in this article earned an Open Materials badge for transparent practices. Materials for this study can be found at http://dbm.neuro.uni-jena.de/cat.

Supplementary data

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inferior and middle frontal, inferior parietal and posterior temporal regions. Furthermore, lower lexical-semantic abilities correlated with deficits in naming both nouns and verbs, while lower syntactic abilities only correlated with naming verbs.

Our results show that different neural and cognitive mechanisms underlie naming of specific grammatical categories in neurodegenerative diseases. Importantly, our findings showed that verb processing depends on a widespread perisylvian networks, suggesting that some regions might be involved in processing different types of action knowledge. These findings have important implications for early differential diagnosis of neurodegenerative disorders.

Keywords

Neurodegenerative diseases; Nouns; Verbs; Cortical atrophy; Lexical-semantics; Syntax

1. Introduction

A frequent feature across neurodegenerative disorders is impaired naming, or anomia, which can differentially affect classes of words such as nouns (e.g., while naming pictures of objects) and/or verbs (e.g., while naming pictures of actions) (Cotelli et al., 2006; Grossman et al., 2004; Hardy et al., 2016; Hillis et al., 2006; Thompson, Cho, et al., 2012). Different patterns of impairment in naming nouns and verbs have been identified, suggesting that successful naming relies on a number of different processes and the coordination of multiple brain regions. However, little is known about how noun and verb processing relate to atrophy and processing mechanisms in neurodegenerative disorders.

Most neurocognitive models link naming abilities to the interactive activation of word's conceptual/semantic, syntactic, and phonological representations stored in different brain regions (e.g., Carreiras, Armstrong, Perea, & Frost, 2014; Gaskell & Marslen-Wilson, 1997; Hickok & Poeppel, 2007; Indefrey & Levelt, 2004; Levelt, Roelofs, & Meyer, 1999; Matchin & Hickok, 2019; Seidenberg & McClelland, 1989). For instance, naming a picture of 'cat' or 'kick' requires first the selection of the appropriate concept: an entity (e.g., animal) with prototypical perceptual features (e.g., four legs and a tail) or an action with prototypical motor/functional features (e.g., leg/foot action). Next, syntactic properties of the lexical item are accessed (e.g., gender of nouns or argument structure of verbs). For many verbs – for example *kick* – a complex argument structure is selected, incorporating in its meaning two thematic roles (an agent that initiates the action and a theme), but for others – such as *run* – a simple argument structure is involved (an agent). Finally, the speaker retrieves the appropriate phonological word form. The identification of brain regions specific to nouns versus verbs in healthy subjects or neurological patients would hence inform on the neural correlates of multiple cognitive processes and representations.

Combining topographical and temporal information from fMRI and electromagnetic studies in healthy individuals, Indefrey and Levelt (2004) proposed a neuroanatomical framework for word production in which phonological and semantic networks interface via the syntactic system. Accordingly, conceptual preparation is linked to the anterior middle temporal gyrus (MTG) and phonological encoding is linked to the mid-to-posterior superior temporal

gyrus (STG). Moreover, two conceptual networks are identified: an entity (taxonomic) knowledge hub in the anterior temporal lobe (ATL) and an event (thematic) knowledge hub in the inferior parietal lobe (IPL) (Binder & Desai, 2011; Binder, Desai, Graves, & Conant, 2009; Hodges, Patterson, Oxbury, & Funnell, 1992; Rogers et al., 2004; Wilson, Bautista, & McCarron, 2018). What is less clear is the functional neuroanatomy of lexical-syntactic encoding (e.g., access to verb argument structure properties). The lexical-syntactic selection seems to begin at about the same time as relevant conceptual information (e.g., animacy/animal) becomes available, and is subserved by the left middle and posterior MTG (Binder & Desai, 2011; Binney et al., 2016; Matchin & Hickok, 2019; Thompson & Meltzer-Asscher, 2014), the ventral bank of superior temporal sulcus (STS) (Wilson et al., 2018) as well as by the frontoparietal areas (Bornkessel-Schlesewsky & Schlesewsky, 2013; den Ouden, Fix, Parrish, & Thompson, 2009; de Zubicaray, Fraser, Ramajoo, & McMahon, 2017; Meltzer-Asscher, Schuchard, den Ouden, & Thompson, 2012; Thompson et al., 2007). While the functional neuroanatomy of these processes and representations continues to be evaluated, the neural networks associated with impaired naming of nouns and verbs remains particularly controversial.

For decades, neuropsychological studies of patients with aphasia secondary to stroke addressed the neural processes underpinning different word classes, however, research findings diverged widely (see Crepaldi, Berlingeri, Paulesu, & Luzzatti, 2011; Crepaldi et al., 2013; Vigliocco, Vinson, Druks, Barber, & Cappa, 2011 for reviews). While some lesion-symptom mapping studies revealed the typical posterior-anterior dissociation for naming nouns and verbs, with nouns relying more on temporal cortex and verbs on frontal regions (e.g., Damasio & Tranel, 1993; Daniele, Giustolisi, Silveri, Colosimo, & Gainotti, 1994), others revealed overlapping neural correlates of noun and verb processing along left perisylvian regions (e.g., Aggujaro, Crepaldi, Pistarini, Taricco, & Luzzatti, 2006; Alyahya, Halai, Conroy, & Ralph, 2018; Kemmerer, Rudrauf, Manzel, & Tranel, 2012; Luzzatti, Aggujaro, & Crepaldi, 2006; Tranel, Adolphs, Damasio, & Damasio, 2001).

Confrontation naming is commonly used for the diagnosis of neurodegenerative diseases. However, most of the findings stem from the description of single cases or comparisons of few clinical groups, and assessed naming abilities using object nouns, with only few including action verbs (see Table 1 for a comprehensive summary). Overall naming impairments have been consistently observed in primary progressive aphasia (PPA), the behavioral variant Frontotemporal Dementia (bvFTD) and Alzheimer's disease (AD) (Hodges, Patterson, Graham, & Dawson, 1996; Ralph, Patterson, & Hodges, 1997; Tippett & Farah, 1994). In PPA, some studies found relatively impaired naming abilities across grammatical categories (e.g., Hardy et al., 2016; Marcotte et al., 2014), while others showed disproportionate impairment of naming nouns versus verbs (e.g., Hillis, Oh, & Ken, 2004; Hillis et al., 2006; Thompson, Cho, et al., 2012). For instance, semantic variant PPA (svPPA) showed impaired naming of nouns compare to verbs. Non-fluent/agrammatic variant PPA (nfvPPA) showed the opposite naming pattern, impaired verb naming, yet spared noun naming (see Table 1 for conflicting findings). It is matter of debate whether these naming deficit patterns may stem from impaired lexical-semantic or lexical-syntactic representations.

In bvFTD, inconsistent results emerge regarding the degree of naming impairments suggesting that language deficits may go unrecognized in this population. Recent evidence showed relatively spared naming ability for nouns (Blair, Marczinski, Davis-Faroque, & Kertesz, 2007; Kertesz, Jesso, Harciarek, Blair, & McMonagle, 2010; Libon et al., 2009; Rhee, Antiquena, & Grossman, 2001), while previous studies reported impairment across both nouns and verbs (Almor et al., 2009; Cotelli et al., 2006; Hardy et al., 2016; Silveri, Salvigni, Cappa, Della Vedova, & Puopolo, 2003). Finally, in AD, naming (noun) difficulty was reported, and has been associated with impairments in a heterogeneous range of processes: lexical retrieval (Cronin-Golomb, Keane, Kokodis, Corkin, & Growdon, 1992; Hodges, Salmon, & Butters, 1992; Lambon, Graham, Ellis, & Hodges, 1998; Thompson, Ballard, Tait, Weintraub, & Mesulam, 1997; Weintraub, Rubin, & Mesulam, 1990), and semantic components of naming (Hodges, Graham, & Patterson, 1995; Hodges et al., 1996; Huff, Corkin, & Growdon, 1986; Ralph et al., 1997, 2001), partially overlapping with the basis for naming difficulty in FTD.

Different patterns of performance are likely associated with different neural bases. To our knowledge, only a few studies correlated grey matter volume with naming performance across FTD. Migliaccio et al. (2016) found that noun naming was correlated with grey matter volume in the left lateral temporal cortex across PPA variants, while Grossman et al. (2004) found that noun naming was correlated with volume in the bilateral anterior temporal and frontal regions in FTD. Although relatively little is known about the neuroanatomical basis of noun and verb specific deficits, one previous study found that the left inferior temporal and to a lesser extent, inferior frontal areas, explained 36% and 20% of the total variance in noun and verb performance, respectively (Riello et al., 2018). To date, there have been no attempts to systematically review naming studies in neurodegenerative disorders, which hinders our ability to delineate syndrome-specific naming deficit patterns, and to provide insight into their neuro-cognitive correlates.

Here, we examined naming abilities in the largest well-defined cohort of PPA, bvFTD, and AD patients based on performances on a confrontation naming test of nouns and verbs matched for all relevant lexical variables (*Northwestern Naming Battery* – NNB; Thompson & Weintraub, 2014). Across participants, we used structural neuroimaging to determine cortical areas whose damage selectively affect naming nouns versus verbs. Lastly, we correlated participants' naming performances with measures of their lexical-semantic and syntactic abilities thus providing insight into the dynamic interaction of the corresponding neural correlates. Compared to healthy controls, all clinical groups were expected to show a generalized naming impairment. However, we expected specific disproportional naming deficits in two PPA variants: patients with svPPA and nfvPPA would name fewer nouns and verbs, respectively. We predicted noun and verb naming deficits to be associated with the anterior and inferior temporal and perisylvian areas, respectively. Finally, we expected noun and verb naming deficits to correlate with lower lexical-semantic and syntactic abilities, respectively.

2. Material and methods

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures included in the present study.

2.1. Participants

One hundred and forty-six individuals with neurodegenerative diseases, and thirty age-matched healthy controls (HC) participated in the present study. The clinical cohort included 90 individuals with PPA (33 nfvPPA, 21 lvPPA, 36 svPPA), 40 individuals with bvFTD, and 16 individuals with AD. Patients were diagnosed with FTD at the Memory and Aging Center at University of California San Francisco (UCSF) and were classified into one of the three language variants using Mesulam (2001) and Gorno Tempini et al. criteria (2011). Behavioral variant FTD patients were diagnosed using the current criteria by Rascovsky et al. (2011). AD patients were diagnosed according to current established research criteria (McKhann et al., 2011). Participants selection criteria were: patients who meet research criteria for one of those syndromes, Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) scores ≥ 15 and Clinical Dementia Rating (CDR; Morris, 1997) scores ≤ 2, an assessment of confrontation naming performance, and the availability of an MRI scan. Also, structural neuroimaging (MRI) was conducted for all participants but was not considered for diagnosis (see Supplementary Fig. 1 for cortical atrophy distribution across the patients).

All HC had a CDR Total score of zero and MMSE score 25 or higher, and received the same battery of behavioral tests and neuroimaging procedures as the patients, performing within normal limits. All participants provided written informed consent approved by the UCSF Institutional Review Board. Demographics, speech-language, and cognitive scores, and expected significant group differences are provided in Table 2. No part of the study procedures was pre-registered prior to the research being conducted. However, participants selection criteria were established prior to data analysis.

2.2. Language measures

2.2.1. Confrontation naming test—Participants completed a *confrontation naming subtest* (NNB; Thompson & Weintraub, 2014), provided within the Unified Data Set (UDS) FTLD module, a battery of standard neuropsychological tests and research measures developed specifically to assess the clinical symptoms of FTLD-related disorders (Weintraub et al., 2018). For the FTLD module documentation, visit: https://www.alz.washington.edu.

The NNB subtest includes 16 pictures of objects (from the categories of animals, fruits/vegetables, tools, and clothing) for testing noun production and 16 pictures of actions for testing verb production (from the types of intransitive one-argument verbs and transitive two- and three-argument verbs). Participants were asked to produce either a noun or a verb, and responses were scored as correct if they were recognizable verbal productions of target items. Any verb form (morphological inflection) is accepted as correct (e.g., for laugh, correct responses are laughs, laughed, and laughing). See Appendix in Thompson, Lukic,

King, Mesulam and Weintraub (2012b) for a complete list of stimuli used to test naming of both nouns and verbs.

2.2.2. Semantic and syntactic tests—To assess *lexical-semantic performance*, participants performed the Peabody Picture Vocabulary Test (PPVT; Dunn, 1959), a word-picture matching test of receptive vocabulary, assessing the auditory comprehension of single words. For each item, the clinician would say a word aloud, while participants viewed four full-color pictures. The participants were instructed to select one picture out of the four that best illustrated the word's meaning.

To access *syntactic performance*, participants were given the Northwestern Anagram Test (NAT Short Form; Thompson, Weintraub & Mesulam, 2012) through the UDS FTLD module (https://www.alz.washington.edu). This test is designed to test word order in sentence production in patients who present with speech production, word comprehension and/or word-finding difficulties or reduced working memory capacity (Weintraub et al., 2009). Participants were presented with a target drawing depicting two actors and an action, and printed words and arrows labeling each actor and the action in the picture. For each target sentence, the individual words constituting the correct sentence were printed on small cards. The anagram method requires the assembly of individual word cards presented in scrambled order into meaningful complete sentences (e.g., Actives: *The girl is tickling the boy*. Passives: *The boy is tickled by the girl*.).

2.3. MRI data acquisition and pre-processing

A 3T Trio (Siemens) scanner was used to obtain structural 3D T1-weighted images at UCSF. The T1-weighted images were acquired using an MP-RAGE sequence with the following parameters: repetition time (TR) = 2300 msec, echo time (TE) = 2.98 msec, inversion time = 900 msec, flip angle 9°, matrix size = 256 × 240, voxel size 1 mm^3 isotropic.

Pre-processing of neuroimaging data was performed using the Computational Anatomy Toolbox (CAT12; http://dbm.neuro.uni-jena.de/cat) in Statistical Parametric Mapping software (SPM12; http://www.fil.ion.ucl.ac.uk/spm/software/spm12) in Matlab 2019b. The T1-weighted images were bias-field corrected, skull-stripped, aligned to the Montreal Neurological Institute (MNI) standard space, and segmented into gray matter (GM), white matter (WM) and cerebrospinal fluid (CSF). Cortical thickness was measured with the Projection-based Thickness Method as described in Dahnke, Yotter, & Gaser, 2013. This method uses tissue segmentation to estimate the WM distance, then projects to the local maxima (which is equal to the cortical thickness) to other GM voxels using a neighbor relationship. The local maps were resampled and smoothed using a 15-mm Gaussian heat kernel (Yotter, Nenadic, Ziegler, Thompson, & Gaser, 2011).

2.4. Data analyses

2.4.1. Noun and verb naming performances and cognitive correlates—We calculated the mean percent accuracy of correct productions of nouns and verbs for 5 clinical groups and a group of healthy controls. Naming accuracy served as dependent variable and was analyzed using mixed-effects linear regression models, with fixed factors *Group*

(5 clinical groups and a group of healthy controls) and *Category* (nouns and verbs), and random intercepts for subjects. The category variable was coded in the direction of noun being 0 and verb being 1, and the svPPA group served as a baseline group. We tested the statistical significance of the Group by Category interaction effect using the likelihood ratio test and applied Fisher Least Significant Differences to identify specific statistically significant effects and control for multiple comparisons ($p < .05$). Similarly, we examined category effects for each group using multiple mixed-effects regression models. Age, gender, handedness, and severity (measured by the CDR Box Score) were entered as covariates in the regression models.

We further examined the underlying cognitive processing mechanisms of noun and verb naming deficits. We conducted multiple linear regressions and tested whether naming performances on nouns or verbs were associated with measures of lexical-semantic (word comprehension) and syntactic (sentence production) processes (controlling for age, gender, handedness, and severity). In addition, the measure of visuospatial ability as measured by Benson Figure Copy was used as a control measure to assess the specificity of the above-mentioned correlations.

2.4.2. Noun and verb naming performances and cortical thickness—Prior to the imaging analyses, quality control was performed on both MRI and unsmoothed segmented data which provides more anatomical details to ensure high quality data. As recommended (https://neuroimage.usc.edu/brainstorm/Tutorials/SegCAT12) to identify the outliers, the quality parameters were generated for each subject under the module "Check homogeneity for surface data" in the CAT12, such as the *weighted overall image quality*, which combines measurements of noise and spatial resolution of the image before preprocessing. Out of 176 participants, four participants were excluded for extensive white matter disease or significant motion artifacts upon visual inspections, and eight participants were excluded due to a lower weighted overall image quality (below 80%). In addition, there were two overall naming scores that were three standard deviations below the mean within a group, thus, these two subjects were considered outliers and excluded from the relevant analyses. The remaining 162 participants were included in the whole-brain surface-based morphometry analyses reported below.

Here, we examined the association between cortical thickness and noun and verb naming performances across patients and healthy controls using multiple linear regressions (controlling for age, gender, handedness, and severity). The mean naming accuracies of object-naming and action-naming served as dependent variables. To detect areas of cortical thinning (atrophy) associated with deficits of naming nouns (adjusted for verbs) or verbs (adjusted for nouns) across participants, we used the threshold-Free Cluster Enhancement function in CAT12 and set a significance threshold at $p < .05$ family-wise error (FWE) peak and cluster level corrections. Cluster p values were also corrected for multiple comparisons (with n being the number of regressions performed: nouns and verbs) using the Benjamini-Hochberg method (1995). All imaging analyses are performed following the CAT12 Manual which is publicly available (http://www.neuro.uni-jena.de/cat12/CAT12-Manual.pdf).

2.5. Data availability

The conditions of our ethics approval do not permit public archiving of anonymised study data. Data generated by the UCSF MAC are available upon request. Data requests can be submitted through the UCSF MAC Resource Request form: http://memory.ucsf.edu/resources/data. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. All requests will undergo UCSF regulated procedure thus require submission of a Material Transfer Agreement (MTA) which can be found at https://icd.ucsf.edu/material-transfer-and-data-agreements. No commercial use would be approved.

3. Results

3.1. Noun and verb naming performances and cognitive correlates

Percent correct productions of nouns and verbs for the PPA variants, bvFTD, AD, and healthy control participants are shown in Table 3 and Fig. 1. There were two overall naming scores (across nouns and verbs) that were three standard deviations below the mean within a group, thus, these two subjects (one HC and one bvFTD) were considered outliers and excluded from the relevant analyses.

Analysis of the naming data revealed a statistically significant Group by Category interaction effect ($p < .001$). To examine the interaction between Group and Category, we looked at category effects separately by Groups. A significant effect for grammatical category was found for the nfvPPA and svPPA groups: the nfvPPA participants produced verbs less accurately than nouns, $b = -8.52$, $SE = 2.74$, $p = .012$, whereas the svPPA participants produced nouns less accurately than verbs, $b = 11.28$, $SE = 3.67$, $p = .012$. No significant differences between categories were found for lvPPA, $b = -6.83$, $SE = 2.85$, $p = .052$, bvFTD, $b = -1.12$, $SE = .94$, $p = .288$, or AD group, $b = -4.70$, $SE = 3.49$, $p = .288$ (see Table 4).

In addition, post hoc analysis also revealed that svPPA group was overall less accurate compared to HC, $b = 29.33$, $SE = 4.86$, $p < .001$, nfvPPA, $b = 21.72$, $SE = 3.54$, $p < .001$, lvPPA, $b = 19.31$, $SE = 3.78$, $p = .001$, bvFTD, $b = 25.52$, $SE = 3.17$, $p < .001$, and AD, $b = 17.88$, $SE = 4.16$, $p < .001$. There were no significant differences in overall naming performances between the other groups.

As predicted, lower lexical-semantic abilities significantly correlated with the naming performances on nouns, $b = .77$, $SE = .05$, $p < .001$, and verbs, $b = .48$, $SE = .05$, $p < .001$. Lower syntactic abilities correlated with the naming performances on verbs, $b = .19$, $SE = .06$, $p = .001$, and did not correlate on nouns, $b = .06$, $SE = .07$, $p = .375$. However, visuospatial ability was not correlated with the naming performances on nouns, $b = -.08$, $SE = .60$, $p = .898$, or verbs, $b = .77$, $SE = .51$, $p = .135$. Table 3 also summarizes the performance of the clinical groups and healthy controls with regard to measures of each of the major language components thought to contribute to confrontation naming.

3.2. Associations between noun and verb naming performances and cortical atrophy

Across participants, nouns and verbs exhibited unique patterns of recruitment of left cortical regions: the poor noun performance was associated with lower cortical thickness in the left anterior ITG, and temporal pole, while poor verb performance was associated with lower cortical thickness in the left IPL (Supramarginal Gyrus – SMG), posterior MTG (also including banks of the STS), and inferior and middle frontal gyrus (IFG pars opercularis and MFG). The associations between cortical thickness and noun and verb specific performances on the confrontation naming test are depicted in Table 5 and Fig. 2.

4. Discussion

This study investigated the cognitive and neural correlates of noun and verb naming deficits in a large sample of well-characterized patients with FTD-spectrum and AD disorders. We found disproportional deficits in naming verbs and nouns in non-fluent/agrammatic and semantic variants of PPA (nfvPPA and svPPA), respectively. At the cognitive level, we demonstrated that lower lexical-semantic abilities correlated with deficits in naming both nouns and verbs, while lower syntactic abilities only correlated with naming verbs. The study also revealed distinct neuroanatomical correlates of naming nouns and verbs: noun performance was positively correlated with atrophy within the left anterior temporal lobe, while verb performance was correlated with atrophy within left inferior and middle frontal, inferior parietal and posterior temporal regions. We discuss these findings in relation to current neurocognitive models of language and previous literature on the neuroanatomical basis of noun and verb processing.

4.1. Distinct patterns of noun and verb naming deficits across neurodegenerative diseases

Previous research that examined confrontation naming tasks produced contradictory results with respect to whether certain categories of words, such as nouns and verbs, are differentially impaired in PPA, behavioral variant FTD, or AD. Our findings of lower naming accuracy for verbs in nfvPPA and for nouns in svPPA are consistent with previous studies in PPA (e.g., Cotelli et al., 2006; Hillis et al., 2004, 2006; Silveri & Ciccarelli, 2007; Thompson, Cho, et al., 2012) and stroke-induced agrammatic and anomic aphasia (e.g., Berndt, Mitchum, Haendiges, & Sandson, 1997; Kim & Thompson, 2000, 2004; McCarthy & Warrington, 1985; Miceli, Silveri, Villi, & Caramazza, 1984; Thompson, Cho, et al., 2012; Zingeser & Berndt, 1990).

Conversely, our results are inconsistent with studies showing no significant difference in accuracy between noun and verb naming in nfvPPA and svPPA (Marcotte et al., 2014; Riello et al., 2018). This inconsistency may stem from either participant selection (early versus late stage of the disease) and/or the use of stimuli that were not controlled for critical variables such as length, imageability and visual or linguistic complexity. Given that patients with neurodegenerative diseases tend to be tested during different stage of progression, it remains unclear whether disproportional noun-verb effects reflect a particular stage of the disease, or alternatively form a stable, consistent pattern over time. Moreover, a failure to detect early verb deficits could relate to the selection of verb type stimuli such as those not involving

more complex representations (e.g., verbs varying in number of arguments). Previous limited studies analyzed the verb production data for transitivity and showed that intransitive verbs were produced more accurately than transitive verbs in nfvPPA, and mixed findings were observed in lvPPA (Thompson, Cho, et al., 2012; Thompson et al., 2012b). Future studies are needed to directly evaluate category and transitivity effects over time in the language variants (PPA).

Our findings in bvFTD and AD indicate relatively spared and impaired naming abilities across nouns and verbs, respectively. Spared naming in the bvFTD cohort is consistent with the results of most studies (Blair et al., 2007; Kertesz et al., 2010; Libon et al., 2009; Rhee et al., 2001) and inconsistent with a few others (Cotelli et al., 2006; Hardy et al., 2016; Silveri et al., 2003). The inclusion in the sample of genetic variants of bvFTD could at least partially account for these discrepancies. For instance, bvFTD with mutations in microtubule-associated protein tau gene, demonstrated the greatest confrontation (noun) naming and single word comprehension decline (Poos et al., 2020). Lastly, the generalized nouns and verbs naming difficulty found in our AD cohort suggests, as previously argued, that this impairment relates to degradation of semantic features common to both (Almor et al., 2009; Grossman et al., 2007; Kim & Thompson, 2004).

To provide evidence regarding the cognitive processes underlying noun and verb selective naming deficits, we correlated noun and verb performances and measures of lexical-semantic (measured by word comprehension) and syntactic abilities (measured by sentence production) across participants. As predicted, the scores on nouns and verbs significantly correlated with lower semantic abilities, while verb naming only correlated with lower syntactic abilities, suggestive of distinct nature of naming impairments (semantic versus syntactic). Similarly, Marcotte et al. (2014) found that verb production is affected by lexical-semantic in svPPA, whereas both lexical-semantic and syntactic attributes affected verb production in nfvPPA. The neural correlates underlying the various patterns of noun and verb naming performance across FTD-spectrum and AD disorders have yet to be established. Our results provide important evidence on these topics.

4.2. Distinct patterns of cortical atrophy associated with noun and verb naming deficits

Despite the large body of research derived from stroke injury and functional imaging with healthy individuals, the question of whether the two grammatical categories are represented and/or processed separately or by overlapping brain system remains under debate (Alyahya et al., 2018; see Crepaldi et al., 2011, 2013; Vigliocco et al., 2011 for reviews). The two existing VBM studies that correlated noun naming with gray matter volume in FTD, reported rather different patterns: the left inferior and middle temporal gyri (ITG, MTG) across PPA variants ($n = 30$) in Migliaccio et al. study (2016), and the bilateral anterior temporal and inferior frontal regions in FTD ($n = 29$) in Grossman et al. study (2004). In a third more recent study which focused on both nouns and verbs in PPA variants ($n = 39$), Riello et al. (2018) found that the left ITG and to a lesser extent, left inferior frontal gyrus (IFG) orbitalis, were related to noun and verb performances, respectively. These limited naming-cortical correlations are consistent with the hypothesis that a large-scale neural network for naming is interrupted in unique ways for nouns versus verbs.

Our main finding indicates the existence of distinct neural networks associated with the two grammatical categories: left ATL and aITG appear to play a critical role in naming nouns, while the posterior middle temporal gyrus (pMTG; including banks of the STS), SMG, and IFG pars opercularis and MFG are involved in naming verbs. The anterior and middle temporal areas are known to be involved in tasks requiring lexical-semantic retrieval (Moore & Price, 1999; Race et al., 2013), and semantic compositions (Pylkkänen, 2019) in functional imaging studies, and have been involved in lesion studies with aphasic patients (Baldo, Arévalo, Patterson, & Dronkers, 2013; Damasio & Tranel, 1993; Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004; Hillis, Tuffiash, & Caramazza, 2002; Tranel et al., 2001) and patients with neurodegenerative disease (Binney et al., 2016; Daniele et al., 1994; Mesulam et al, 2009, 2013; 2015; Wilson et al., 2009).

The results of the present study underscore a greater involvement of the dorsal perisylvian network (e.g., SMG and IFG pars opercularis, and MFG) in verb production, likely reflects processing of event knowledge, thematic roles assignment (agent, theme), and phrase structure building processes associated primarily with verbs compared to nouns (Binder & Desai, 2011; Binder et al., 2009; den Ouden et al., 2019; Hodges, Patterson, et al., 1992; Meltzer-Asscher et al., 2012). The posterior temporal regions and SMG have been also implicated in the production of verbs with greater argument structure density (i.e., the number and type of arguments) during video and static picture naming (den Ouden et al., 2009). Similarly, increased neuronal activity associated with production of transitive (requiring a direct object) as compared to intransitive verbs (that do not require a direct object) were found not only in perisylvian regions, but also in the left IFG (den Ouden et al., 2009; see review by Thompson & Meltzer-Asscher, 2014). Moreover, naming actions that involve tools (generally transitive verbs like *write*) versus those not involving tools (generally intransitive like *run*) was associated with increased activity in the left SMG (Damasio et al., 2001). Our results corroborate previous evidence from lesion-symptom mapping studies showing an association between verb processing deficits and lesions to left inferior frontal regions (Akinina et al., 2019; Damasio & Tranel, 1993; Kemmerer et al., 2012; Tranel, Manzel, Asp, & Kemmerer, 2008), or posterior temporal ones (Aggujaro et al., 2006; Kalénine, Buxbaum, & Coslett, 2010; Kemmerer et al., 2012; Tranel et al., 2008).

The current study thus provides novel evidence supporting models that posit a division of labor between anterior temporal regions (involved in lexical-semantic processes) and posterior temporoparietal ones (recruited for both lexical-semantic and lexical-syntactic processes). However, future studies should tackle the following open questions. First, it is unclear whether noun and verb processing engages different brain areas because nouns and verbs constitute two distinct linguistic categories, or because they prototypically refer to different entities (i.e., objects and actions, respectively), loading on different cognitive and sensory processes.

There are several different views on these grammatical category deficits (for review see Vigliocco et al., 2011). Here, we are starting from neuroanatomical models motivated by neuropsychological data rather than psycholinguistic ones, with the three existing hypotheses: (1) nouns and verbs are lexically specified, and represented in partially separable temporal and frontal networks, respectively (*lexicalist views*), (2) morphosyntactic

processes, rather than nouns and verbs, are retrieved and represented in separable neural networks (*combinatorial views*), and (3) semantic processes (referring to objects and actions regardless of grammatic class) are retrieved and represented in partially separable temporal and frontal networks (*emergentist cognitive views*). Accordingly, Vigliocco et al. (2011) suggest that semantic distinctions are fundamental to grammatical class and that distinction between nouns and verbs would only become relevant to process of integration in sentence context, therefore, relying on a neural system different from the one used for simple lexical retrieval.

Like the vast majority of neuropsychological studies comparing patients' naming performances, our study is not designed to distinguish manipulations of grammatical class and semantics. Rather, we assume that semantic and/or grammatical distinctions such as concrete concepts (typically nouns) and concepts of actions (typically verbs) may fractionate in different ways, and hence would be associated with different atrophic neural patterns over-and-above the other category. The distinct neurocognitive systems associated with noun and verb deficits described in the current study imply distinct representations of lexical structures, in line with the neural models that assume different grammatical categories engage partially distinct representations or processes. Whether this represents an impairment of lexical retrieval or lexical integration into sentences remains to be explicitly tested.

Recent on-line sentence comprehension studies demonstrated abnormal thematic integration in nfvPPA, but not lvPPA using eye-tracking (Walenski, Mack, Mesulam, & Thompson, 2020), and abnormal ERP (reduced p600) to verb-argument structure violations in both subtypes, with nfvPPA also showing no evidence of morphosyntactic violation detection (Barbieri et al., 2021). Indeed, the strong association between sentence-processing impairments (as measured by sentence production on the NAT which included written labels for the agent, verb, and patient) and verb performance supported hypotheses of the neural separation of integration processes (e.g., thematic integration), engaging primarily left IFG/MFG and pSTS (in line with Bornkessel-Schlesewsky & Schlesewsky, 2013; Lukic et al., 2021; Shapiro, Moo, & Caramazza, 2006).

Considering our single word task, where a word's semantic content or its phonological form play a crucial role, accessing lexical-semantic information mediated by the temporal lobe (especially inferior and middle temporal gyri) and temporoparietal junction regions played a role across categories. According to the dual-hub theory (Rogers et al., 2004), accurate naming of objects relies on analyzing conceptual features (taxonomic knowledge; i.e., to respond *cat* to a picture of a *dog*) and ATL, whereas accurate naming of actions emphasizes thematic relations among concepts (thematic knowledge; to respond *leash* to the same picture) and relies more on IPL (see Boylan, Trueswell, & Thompson-Schill, 2015, 2017; Schwartz et al., 2011). Second, it has been suggested that the anterior and posterior temporal regions may contribute to naming independently, with the ATL playing a key role in lexical-semantic compositions (Pylkkänen, 2019), and the pMTG/STS in lexical-syntactic compositions (Indefrey & Levelt, 2004; Matchin & Hickok, 2019; Thompson & Meltzer-Asscher, 2014; Wilson et al., 2018). Lastly, these regions could reflect the processing of the actions performed, therefore being sensitive to various visual characteristics of the

performance (e.g., location and manipulation) (e.g., Arévalo et al., 2007; Saccuman et al., 2006).

Our imaging results provide key insights for neuroanatomical theories modeling the multiple processes involved in nouns and verbs production by elucidating the neural correlates underlying their deficits. Critically, this is possible because of key characteristics of our sample. The network-based nature of neurodegenerative diseases enables the association of specific naming deficits to distinct atrophy patterns. In these diseases, atrophy affects regions usually not involved in cerebral artery strokes, allowing a more broad and comprehensive investigation of braine–behavior relationships (see Supplementary Fig. 1 for atrophy distribution across patients). The patterns of atrophy versus ischemic brain lesions provide complementary information and greatly expand our understanding of the neural processes of language in the 20th century. The aphasia syndromes do not localize to small, discrete regions of the brain such as Broca's area, but rather involve neighboring tissue of the IFG, MFG, insula, basal ganglia, and surrounding white matter (Dronkers, Ivanova, & Baldo, 2017). On the other hand, frontotemporal spectrum disorders typically begin from the syndrome-specific epicenter and as the disorder progresses, the spread of neurodegeneration occurs by following specific neuronal network architectures. For instance, starting from the left IFG opercularis, atrophy progressed most significantly to the supplementary motor area through the aslant tract in nfvPPA (Mandelli et al., 2016). Similarly, svPPA has been associated with atrophy in the ATL, and lvPPA has been associated with atrophy in temporoparietal areas (Gorno-Tempini et al., 2004; Lukic et al., 2019).

Accordingly, the anterior portions of the temporal lobe may be recruited – together with posterior temporal regions – for naming nouns, but damage to either cortical tissue within the anterior temporal region (necrosed in the majority of our patients) or within posterior temporal region (usually necrosed in the stroke patients) may be sufficient to cause noun naming impairments. However, our data does not directly address this postulate, calling for further studies of the role of anterior and posterior temporal regions in noun naming.

6. Conclusion

Our findings provide key insights on the neural and cognitive mechanisms associated with impairments in different grammatical categories in neurological populations. Collectively, during word production, the ventral anterior temporal network might support a combination of semantic representations, while the dorsal perisylvian network subserves both syntactic processing and a linkage to action knowledge. The specific pattern of cognitive and anatomical impairment associated with verb processing deficits in PPA suggests new strategies for early diagnosis and treatment of naming difficulties expressed by patients with neurodegenerative disease of the dorsal language network.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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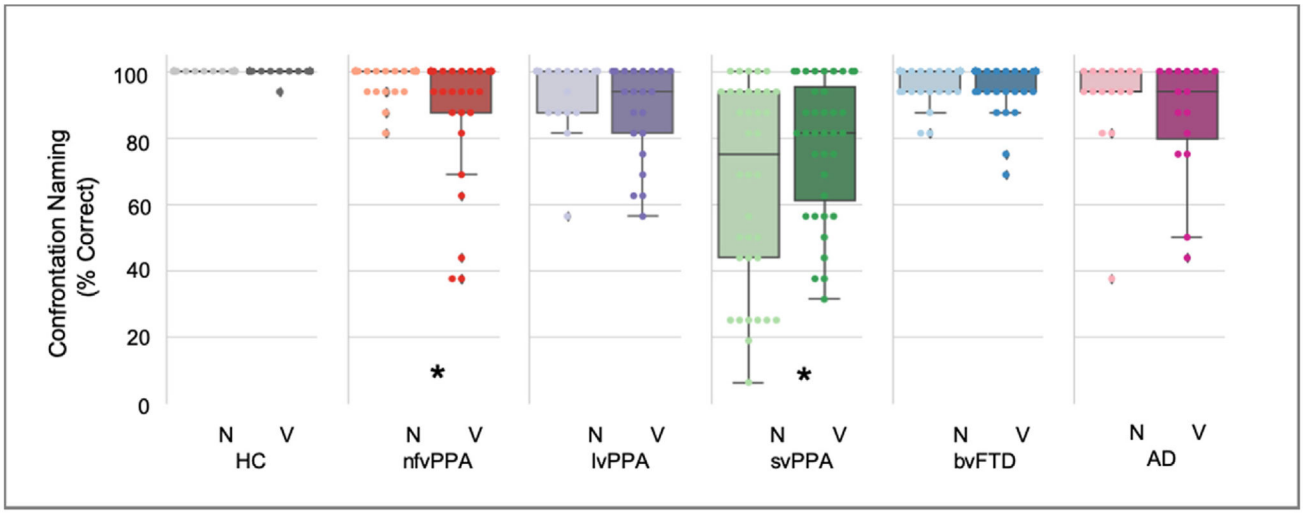

Fig. 1 –.

Noun and verb naming performances are presented for the healthy controls (HC), Primary Progressive Aphasia (PPA) variants, behavioral variant Frontotemporal Dementia (bvFTD), and Alzheimer's disease (AD). Bars illustrate means across participants, central lines show the medians and whiskers indicate the lower and upper quartiles; Asterisks indicate significantly impaired performances between grammatical category conditions (nouns versus verbs) at $p < .05$ (*).

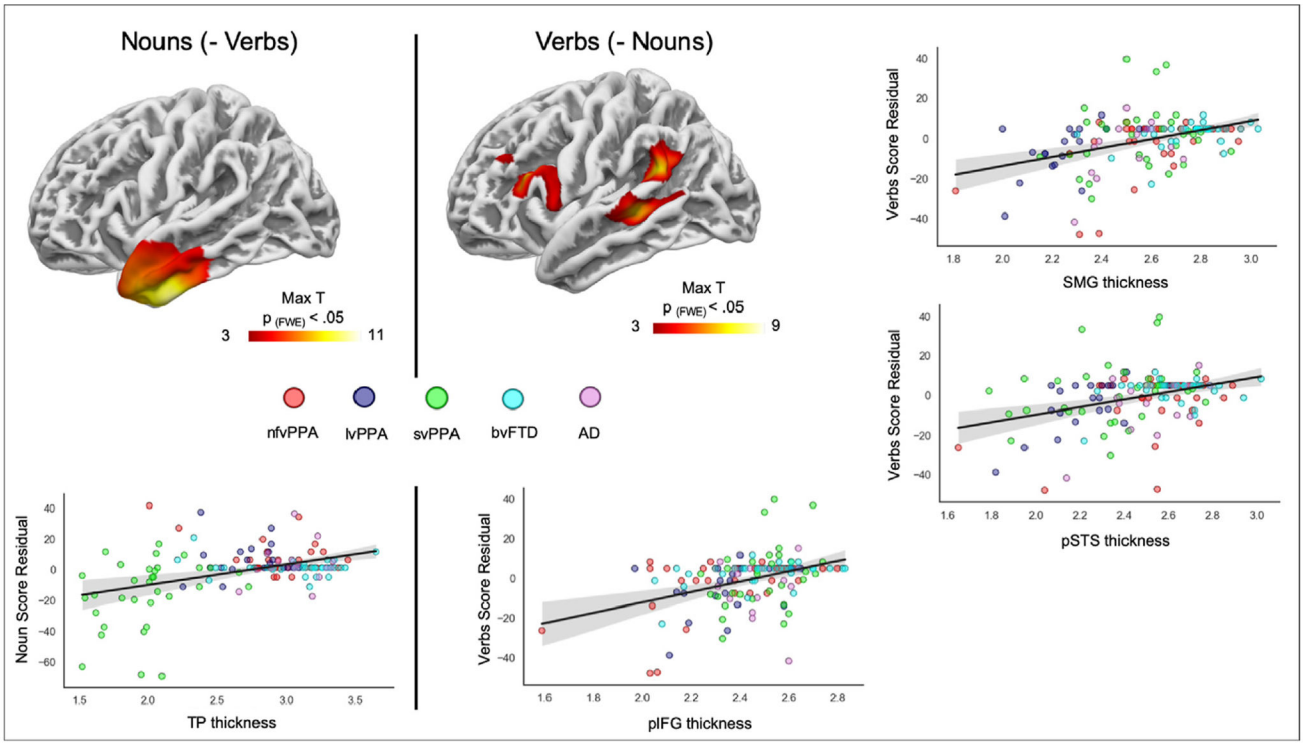

Fig. 2 –.

Neuroanatomical associations of naming nouns and verbs (adjusted for verb and noun naming ability, respectively) across participants. The presented maps are thresholded at $p < .05$ family-wise error (FWE) corrected both at peak-level and cluster extent-based thresholding ($k > 40$). The maps and scatterplots showed the peak areas of atrophy in the anterior temporal and perisylvian areas associated with naming nouns and verbs (noun-verb residuals presented), respectively.

Table 1 –

Summary of naming studies in neurodegenerative diseases; *Atrophy-naming correlation study; PNT = Picture Naming Test; BNT = Boston Naming Test; OANB = An Object and Action Naming Battery. Results are summarized as the average percent accuracy of the group in group studies, and average within subjects across items in case studies. Means; standard deviations in parentheses (if applicable).

Study	Year	No of cases, groups	Nouns (% correct)	Verbs (% correct)	Test
FTD					
Daniele et al.	1994	2 frontal cases, 1 temporal case	93.0, 94.0, & 7.0	81.0, 69.0, & 36.0	PNT
Cappa et al.	1998	10 FTD	80.75	58.5	OANB
Rhee et al.	2001	10 bvFTD, 7 nfvPPA, 4 svPPA	88.7 (11.7), 67.6 (25.3), 63.4 (24.6)	–	PNT
Silveri et al.	2003	17 bvFTD, 42 AD	69.9, 75.2	52.32, 62.57	PNT
Hillis et al.	2004	15 nfvPPA, 6 ALS-FTD, 7 fPPA	81.9 (22), 57.1 (41.5), 64.7 (26)	54.5 (30), 42.4 (41.5), 79.2 (24)	PNT
Clark et al.	2005	26 nfvPPA, 21 fPPA,	69.3, 44.0	–	15-item BNT
Cotelli et al.	2006	16 bvFTD, 6 svPPA; 2 nfvPPA cases	68.0, 40.0; 50.0 & 98.0	60.0, 38.0; 15.0 & 50.0	PNT
		10 PSP, 10 CBD, 10 AD	80.0, 85.0, 80.0	58.0, 62.0, 65.0	PNT
Hillis et al.	2006	27 nfvPPA, 13 ALS-FTD, 16 svPPA	80.0, 68.0, 55.0	65.0, 58.0, 68.0	PNT
Silveri & Ciccarelli	2007	5 cases of CBD	75.0, 66.0, 80.0, 68.0, & 74.0	36.0, 36.0, 30.0, 42.0, & 38.0	PNT
Blair et al.	2007	20 bvFTD, 54 PPA, 105 AD	85.3, 81.5, 90.5	–	WAB Naming
Libon et al.	2009	71 bvFTD, 26 nfvPPA, 21 svPPA	81.4, 77.9, 53.0	–	15-item BNT
Mesulam et al.	2009	4 nfvPPA, 7 lvPPA, 5 svPPA	87.5 (7.84), 93.3 (6.09), 10.6 (7.31)	–	15-item BNT
Kertesz et al.	2010	42 bvFTD, 52 nfvPPA, 48 svPPA	80.0, 90.0, 58.0	–	WAB Naming
Thompson et al.	2012	10 nfvPPA, 14 lvPPA, 4 svPPA	95.0 (11.71), 89.3 (26.68), 26.5 (38.32)	79.4 (18.17), 87.0 (22.12), 70.3 (27.66)	Northwestern Naming Battery
Marcotte et al.	2014	12 nfvPPA, 11 svPPA	79.0 (5.29), 59.3 (21.50)	75.0 (5.57), 62.6 (18.01)	OANB
Hardy et al.	2016	24 bvFTD, 18 nfvPPA, 14 svPPA	36.6, 36.6, .0	64.0, 24.0, .0	Graded & Verb Naming
Migliaccio et al.*	2016	7 nfvPPA, 12 lvPPA, 11 svPPA	75.9 (5.0), 60.8 (14.4), 38.1 (20.1)	–	PNT
Riello et al.*	2018	18 nfvPPA, 13 lvPPA, 8 svPPA	69.4 (36.0), 47.7 (33.2), 18.3 (26)	63.6 (34.2), 42.6 (35.2), 18.6 (21.3)	BNT; Naming Actions
svPPA					
Hodges et al.	1992	5 svPPA	.0, 14.6, 10.4, 35.4 & 29.2	–	Naming
Breedin et al.	1994	1 svPPA	50.0	46.4	PNT
Hodges et al.	1995	1 svPPA	16.6	–	60-item BNT
Ralph et al.	1997	9 svPPA	23.7 (20.92)	–	PNT
Ralph et al.	2001	2 svPPA-left; 2 svPPA-right	14.6 & 72.9; 35.4 & 66.6	–	PNT

Study	Year	No of cases, groups	Nouns (% correct)	Verbs (% correct)	Test
nfvPPA					
McCarthy & Warrington	1985	1 nfvPPA	–	57.0	Mimes/pictures
Weintraub et al.	1990	3 nfvPPA	80.0, 81.6 & 95.0	–	60-item BNT
Hodges & Patterson	1996	2 nfvPPA cases	30.0 & 6.6	–	Graded Naming Test
			81.2 & 56.2	–	Semantic Battery Naming Test
			68.3 & 40.0	–	60-item BNT
Croot et al.	1998	2 nfvPPA cases	36.2 & 6.9	–	PNT
Hillis et al.	2002	3 nfvPPA	88.0, 100.0 & 100.0	60.0, 80.0 & 50.0	PNT
Knibb et al.	2009	15 nfvPPA	30.6	–	Graded Naming Test
Beber et al.	2019	12 nfvPPA	80.2	67.2	PNT
AD					
Huff et al.	1986	23 AD	72.5	–	PNT
Hodges et al.	1992	22 AD	73.5	–	PNT
Hodges et al.	1996	16 minimal, 17 mild, 18 moderate AD	79.8, 77.7, 55.4	–	PNT
Ralph et al.	1997	10 AD	76.5 (19.02)	–	PNT
Cappa et al.	1998	19 AD	72.5	64.3	OANB
Kim & Thompson	2004	14 AD	96.6	87.1	PNT
Almor et al.	2009	14 AD	64.0 (20.12)	35.4 (10.67)	PNT

Table 2 –

Demographics, speech and language and neuropsychological data for the healthy controls (HC), Primary Progressive Aphasia (PPA) variants, behavioral variant Frontotemporal Dementia (bvFTD), and Alzheimer's disease (AD). Mini-Mental State Examination (MMSE); Clinical Dementia Rating (CDR); California Verbal Learning Test- UCSF version (CVLT-SF); Western Aphasia Battery (WAB; Kertesz, 1982); Uniform Data Set Frontotemporal Lobar Degeneration (UDS FTLD). Group differences ($p < .05$; one-way ANOVA and Tukey HSD Test); means with the same letter are not significantly different; bolded letter = most impaired group (s).

	HC	**nfvPPA**	**lvPPA**	**svPPA**	**bvFTD**	**AD**
Demographics						
N	30	33	21	36	40	16
Age, mean (SD)	43.2 (12.2)a	68.2 (7.3)b	65.5 (9.4)b	66.9 (8.3)b	64.2 (7.8)b	66.6 (9.9)b
Education, mean (SD)	16.0 (2.6)	16.0 (2.5)	17.6 (1.8)	16.9 (2.6)	16.0 (3.3)	15.6 (2.8)
Gender, *n* (%) female	16 (53%)	24 (73%)	12 (57%)	16 (44%)	15 (37%)	8 (50%)
Handedness, *n* (%) right	25 (83%)	29 (87%)	17 (81%)	35 (97%)	36 (90%)	14 (88%)
MMSE (max 30)	28.4 (1.6)a	26.2 (2.8)b	23.3 (4.4)c	24.9 (3.2)b	26.9 (2.3)ab	22.8 (4.2)c
CDR Box score	.0 (.0)a	1.4 (2.1)b	2.6 (1.5)bc	3.7 (1.9)c	4.5 (1.8)d	5.3 (2.1)d
Working memory/Executive functions						
Digit Span backwards	5.5 (1.3)a	3.6 (1.2)c	3.4 (1.1)c	5.0 (1.3)ab	4.3 (1.3)b	3.1 (1.3)c
Modified Trials (total time in seconds)	22.6 (8.0)a	60.1 (35.7)b	84.8 (38.9)c	43.5 (26.9)b	46.9 (34.1)b	105.3 (49.4)c
Modified Trials (# of correct lines)	13.5 (2.6)a	11.7 (4.6)ab	10.3 (4.9)bc	12.3 (4.3)ab	13.4 (3.0)a	8.1 (6.1)c
Visuospatial function/memory						
Benson figure copy (max 17)	15.7 (.7)a	14.2 (5.9)a	14.6 (1.5)a	15.5 (4.4)a	15.1 (2.6)a	11.3 (5.8)b
Benson figure recall (17)	13.6 (1.9)a	10.0 (4.6)b	8.2 (4.2)bc	7.7 (5.3)bc	10.0 (3.8)b	5.4 (4.3)c
Verbal memory						
CVLT-SF Trials 1–4 (40)	29.5 (6.6)a	23.7 (6.5)b	16.3 (7.3)c	17.7 (6.4)c	24.2 (7.4)b	17.9 (9.4)c
Digit Span forwards	7.2 (1.1)a	4.7 (1.2)d	4.6 (.8)d	6.2 (1.3)bc	5.6 (1.3)c	6.0 (2.0)bc
CVLT-SF 30 sec free recall (10)	7.9 (1.9)a	6.7 (2.2)ab	4.3 (2.8)c	3.1 (2.4)cd	6.0 (2.5)b	4.4 (2.6)c
CVLT-SF 10 min free recall (10)	7.6 (2.1)a	6.5 (2.3)a	4.0 (2.9)b	1.7 (2.1)c	4.8 (3.1)b	2.3 (2.4)c
Language production						
Boston (object) naming test (15)	14.2 (.8)a	13.6 (1.5)a	11.4 (2.7)b	5.7 (3.3)c	13.2 (2.3)ab	11.8 (3.2)b
Phonemic (D-letter) fluency	15.4 (4.8)a	6.7 (4.5)b	9.8 (4.2)b	8.6 (4.7)b	9.6 (5.4)b	8.4 (4.5)b
Semantic (animal) fluency	24.6 (5.3)a	12.9 (6.2)bc	10.9 (5.5)c	9.5 (4.8)c	15.1 (6.4)b	10.7 (5.5)b

	HC	nfvPPA	lvPPA	svPPA	bvFTD	AD
WAB Repetition (100)	–	84.2 (29.3)a	79.2 (19.8)a	91.9 (16.4)b	–	–
Language comprehension						
UDS FTLD Word-picture matching (20)	19.9 (.2)a	19.7 (3.8)a	19.8 (.5)a	18.9 (3.5)b	19.8 (.6)a	19.6 (1.0)a
UDS FTLD Semantic associates (16)	15.9 (.2)a	15.7 (3.1)a	15.8 (.4)a	13.8 (3.9)b	15.7 (1.1)a	15.4 (.9)a
WAB Auditory Word Recognition (60)	–	59.5 (17.4)a	59.4 (17.8)a	56.7 (4.8)b	–	–
WAB Sequential Command (100)	–	74.7 (23.1)a	65.0 (18.4)b	71.5 (12.7)a	–	–

Table 3 –

Mean (%) and standard deviation (SD) of the accuracy for each language measure for the healthy controls (HC), Primary Progressive Aphasia (PPA) variants, behavioral variant Frontotemporal Dementia (bvFTD), and Alzheimer's disease (AD).

	HC	nfvPPA	lvPPA	svPPA	bvFTD	AD
Overall naming	99.7 (1.3)	93.8 (10.8)	90.9 (10.9)	71.9 (23.4)	95.8 (8.2)	89.1 (15.3)
Noun naming	100 (.00)	98.1 (4.3)	94.3 (10.6)	66.3 (30.1)	97.4 (4.9)	91.4 (15.6)
Verb naming	99.4 (2.5)	89.6 (18.4)	87.5 (14.5)	77.6 (20.7)	96.3 (6.9)	86.7 (17.9)
Word-picture matching	96.8 (4.6)	90.7 (12.0)	91.1 (8.7)	57.9 (23.7)	91.4 (11.9)	90.6 (10.2)
Sentence production	94.0 (8.9)	74.5 (28.2)	70.0 (28.8)	85.2 (36.0)	86.2 (18.6)	76.7 (38.9)

Table 4 –

Linear mixed regression analyses of object-naming and action-naming performances: category effects within groups; Significance codes: .001 '**' .01 '*' .05; *p* values were also corrected for multiple comparisons using the Benjamini-Hochberg (BH) method (1995).

	Naming accuracy: Nouns versus Verbs					
	Estimate	**SE**	**df**	**t-value**	**Pr(>|t|)**	**BH-adjusted *p*-values**
HC	−.21	.20	53	−1.046	.300	.300
nfvPPA	−8.52	2.74	32	−3.103	.003**	.012*
lvPPA	−6.83	2.85	20	−2.393	.026*	.052
svPPA	11.28	3.67	35	3.070	.004**	.012*
bvFTD	−1.12	.94	38	−1.193	.240	.288
AD	−4.70	3.49	15	−1.345	.198	.288

Table 5 –

Brain regions (Desikan-Killiany Atlas) in which cortical thickness was significantly associated with performance on naming nouns and verbs, thresholded at $p < .05$ family-wise error (FWE) peak-level corrected, based on minimum cluster size ($k > 30$); Cluster p values were also corrected for multiple comparisons using the Benjamini-Hochberg (BH) method (1995).

	Region	Cluster size	MNI coordinates			t-value	*p*-value
			x	y	z		
Nouns (- Verbs)	L ITG, MTG	1930	−42	−14	−32	8.04	.000
Verbs (- Nouns)	L SMG	1005	−59	−48	23	5.78	.000
	L Bank STS/pMTG		−52	−36	0	5.62	.000
	L IFG Pars Opercularis	413	−48	25	16	5.53	.000
	L MFG	90	−36	38	30	4.56	.011

MTG = middle temporal gyrus, ITG = inferior temporal gyrus; SMG = supramarginal gyrus; STS = superior temporal sulcus; IFG = inferior frontal gyrus; MFG = middle frontal gyrus.