HIGHLIGHTS

Degeneration of basal and limbic networks is a core feature of behavioural variant frontotemporal dementia

Vesna Vuksanović[1,2], Roger T Staff[3], Suzannah Morson[4,5], Trevor Ahearn[3], Luc Bracoud[6], Alison D Murray[1,2], Peter Bentham[4], Christopher M Kipps[7], Charles R Harrington[2,4] and Claude M Wischik[2,4]

[1]Aberdeen Biomedical Imaging Centre, University of Aberdeen, Aberdeen, UK

[2]School of Medicine, Medical Sciences and Nutrition, University of Aberdeen, Aberdeen, UK

[3]Medical Physics, NHS Grampian, Aberdeen, UK

[4]TauRx, Therapeutics, Aberdeen, UK

[5]School of Psychology, University of Aberdeen, Aberdeen, UK

[6]Bioclinica, Lyon, France

[7]University Hospital Southampton and University of Southampton, UK

- bvFTD patients can be classified on the basis of distinct patterns of cortical atrophy.
- The anatomically distinct subtypes all share a common pattern of atrophy in basal, limbic and frontal highly connected networks.
- Atrophy in these core regions drives cognitive and functional impairment in bvFTD.

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[1]Aberdeen Biomedical Imaging Centre, University of Aberdeen, Aberdeen, UK

[2]School of Medicine, Medical Sciences and Nutrition, University of Aberdeen, Aberdeen, UK

[3]Medical Physics, NHS Grampian, Aberdeen, UK

[4]TauRx, Therapeutics, Aberdeen, UK

[5]School of Psychology, University of Aberdeen, Aberdeen, UK

[6]Bioclinica, Lyon, France

[7]University Hospital Southampton and University of Southampton, UK

*Corresponding author: cmw@taurx.com; Claude Wischik, TauRx Therapeutics Ltd., 395 King Street, Aberdeen AB24 5RP, United Kingdom.

Keywords: behavioural variant frontotemporal dementia, brain networks, rich club, neurodegeneration, anatomical subtypes

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Abstract

Behavioural variant of frontotemporal dementia (bvFTD) is a clinical syndrome characterised by changes in behaviour, cognition and functional ability. Although atrophy in frontal and temporal regions would appear to be a defining feature, neuroimaging studies have identified volumetric differences distributed across large parts of the cortex, giving rise to a classification into distinct neuroanatomical sub-types. Here, we extended these neuroimaging studies to examine how these distributed patterns of atrophy map onto brain network hubs. We used baseline structural magnetic resonance imaging data collected from 213 bvFTD patients meeting consensus diagnostic criteria and having definite evidence of frontal and/or temporal lobe atrophy from a global clinical trial conducted in 70 sites in Canada, US, Australia, Asia and EU. These were compared with data from 244 healthy elderly subjects from a well-characterised cohort study. We have used statistical methods of hierarchical agglomerative clustering of 68 regional cortical and subcortical volumes (34 in each hemisphere) to determine the reproducibility of previously described neuroanatomical subtypes in a global study. We have also attempted to link the structural findings to clinical features defined systematically using well-validated clinical scales (Addenbrooke's Cognitive Examination Revised, the Mini-Mental Status Examination, the Frontotemporal Dementia Rating Scale and the Functional Assessment Questionnaire) and subscales derived from them. Whilst we can confirm that the subtypes are robust, they have limited value in explaining the clinical heterogeneity of the syndrome. We have found that a common pattern of degeneration affecting a small number of subcortical, limbic and frontal nodes within highly connected networks (most previously identified as rich club members or functional binding nodes) is shared by all the anatomical subtypes. Degeneration in these core regions is correlated with cognitive and functional impairment, but less so with behavioural impairment. These findings suggest that degeneration in highly connected basal, limbic and frontal networks is a core feature of the bvFTD phenotype irrespective of neuroanatomical and clinical heterogeneity, and may underly the disorder of integration of cognition, function and behaviour that characterises the syndrome.

Introduction

Frontotemporal Dementia (FTD) is a heterogeneous disorder with distinct clinical phenotypes associated with multiple neuropathologic entities (Olney, Spina, and Miller 2017). The core FTD disorders are behavioural variant frontotemporal dementia (bvFTD), semantic variant primary progressive aphasia, and non-fluent variant primary progressive aphasia, but there are other disorders within the FTD spectrum that include frontotemporal dementia with motor neurone disease, progressive supranuclear palsy and corticobasal syndrome. Most cases of FTD have underlying tau, TDP-43 or FET protein neuropathology (Mackenzie and Neumann 2016).

The behavioural variant of frontotemporal dementia (bvFTD) is a clinical syndrome characterised by insidious onset and progressive deterioration in behaviour, cognition and functional ability, the core symptoms being: disinhibition, apathy, lack of empathy, compulsions, hyperorality and impairment of executive function (Rascovsky et al. 2011). Recently, higher levels of socially inappropriate behaviour and criminality in bvFTD compared with Alzheimer's disease (Liljegren et al. 2019) have been recognised, due to a dissociation between factual and evaluative understanding of actions and their consequences (Mendez 2010; Sfera et al. 2014). Some patients may display the core clinical symptoms as a phenocopy syndrome that is not associated with brain atrophy (Devenney et al. 2018; Kipps et al. 2009; Valente et al. 2019). The revised diagnostic criteria for bvFTD therefore additionally require imaging evidence of a frontotemporal abnormality for a diagnosis of probable bvFTD. Although atrophy in frontal and temporal regions would appear to be a defining feature, neuroimaging studies have identified volumetric differences distributed across large parts of the cortex, giving rise to a classification into distinct neuroanatomical sub-types (Josephs et al. 2009; Ranasinghe et al. 2016; Rohrer et al. 2011; Whitwell et al. 2009, 2013). Different patterns of atrophy have also been associated with different types of FTLD pathology and mutations (Perry et al. 2017; Rohrer et al. 2009). However, all pathological subgroups appear to share atrophy in the anterior cingulate, fronto-insula region, striatum, and amygdala. Studies of genetic frontotemporal dementia have also shown that structural brain changes occur in insula at least ten years before expected symptom onset (Rohrer et al. 2015). These vulnerable connected regions, which are affected early in bvFTD, are part of what has been termed the

'salience' network which is thought to be responsible for processing of behaviourally salient stimuli in the normal brain (Perry et al. 2017; Seeley, Menon, et al. 2007; Seeley et al. 2008, 2009). However, resting state network functional abnormalities may also extend to the default mode, fronto-parietal and semantic appraisal networks resulting in other symptoms affecting attention, working memory and semantics (Filippi et al. 2013; Ranasinghe et al. 2016).

We have previously reported the results of a voxel-based morphometric (VBM) comparison of baseline MRI scans of patients in a large randomised controlled clinical trial in bvFTD (TRx-237-007, NCT01626378) with those randomised to a comparable study of mild AD (TRx-237-005). This showed that the bvFTD group was clearly distinguishable from the mild AD group with a similar overall level of cognitive impairment (Shiells et al. 2020; Vuksanović et al. 2019). As expected, the bvFTD patients had significantly more atrophy in frontal cortex and anterior temporal cortex, and significantly less atrophy in hippocampus, middle temporal gyrus, cuneus and insula.

Here, we have extended these studies to examine how distributed patterns of atrophy in bvFTD map onto brain network hubs. For this purposes, we used baseline structural magnetic resonance imaging data collected from 213 bvFTD patients meeting consensus diagnostic criteria (Rascovsky et al. 2011) and having definite evidence of frontal and/or temporal lobe atrophy (Kipps et al. 2008) and compared this with data from 244 healthy elderly subjects from a well-characterised cohort study (Murray et al. 2011). In addition, the availability of systematically collected clinical baseline scores using validated cognitive and functional scales provided the opportunity to determine how neuroanatomical subtypes and atrophy in brain networks relate to distinctive clinical profiles.

Methods

Study participants

Study TRx-237-007 was designed as a 52-week Phase three, randomised, controlled, double-blind, parallel-group trial conducted at 70 sites in Canada, United States, Australia, Asia and Europe. Eligible patients had to be younger than 80 years of age

with a diagnosis of bvFTD according to criteria revised by the International bvFTD Criteria Consortium (Rascovsky et al. 2011), with Mini-mental Status Examination (MMSE; (Folstein, Folstein, and McHugh 1975)) score greater than or equal to 20 at screening. There was an additional requirement that patients had to meet the criterion of having definite brain atrophy in frontal and/or temporal lobes scoring two or more on a scale proposed by Kipps et al. (Kipps et al. 2008). Concomitant use of acetylcholinesterase inhibitors or memantine (or both) was permitted provided this was at a stable dose for at least 18 weeks before randomisation. Concomitant use of serotonergic antidepressant, antipsychotic (except clozapine or olanzapine) and sedative medications was also permitted at stable doses where clinically feasible. Each patient had one or more study partners participate with them in the trial as informants. Patients were excluded from the study if they had a significant CNS disorder other than bvFTD. A detailed list of inclusion and exclusion criteria in the protocol is available in the Supplementary Materials in Shiells *et al.* (Shiells et al. 2020). Baseline MRI scans were evaluated by a single independent neuroradiologist out of a pool of trained neuroradiologists to determine eligibility (RadMD, NY).

In addition, MRI scans were obtained from 244 age-matched healthy controls from the well characterised Aberdeen 1936 Birth Cohort (ABC36) brain imaging database held in the Aberdeen Biomedical Imaging Centre at the University of Aberdeen. The ABC36 project has been described elsewhere (Murray et al. 2011; Whalley et al. 2011). Demographics and clinical characteristics of the study groups are given in Table 1.

RI data collection and analysis

The acquisition protocol was standardised across sites using 1.5T and 3T scanners manufactured by General Electric, Philips or Siemens. All data were centrally collected, quality-controlled and analysed by the imaging core laboratory (Bioclinica). MRI data acquisition included a 3D sagittal T1-weighted sequence which we used in our analysis here. 3DT1 images were acquired using a 3D MPRAGE sequence (Siemens) or the specific manufacturer equivalent sequence (General Electric 3D IR-

prepped Fast SPGR, Philips 3D TFE), covering the whole brain with a resolution of $1.25\times1.25\times1.2$ mm^3.

FreeSurfer version 5.3.0 (http://freesurfer.net/) was used to extract regional volumes for the clustering analysis. FreeSurfer automated segmentation parcelates the brain into 76 regions according to the Desikan-Killiany Atlas (Desikan et al. 2006). For the purpose of this study, we selected 68 regional volumes (34 from each hemisphere) of the frontal, temporal or parietal lobe and additional sub-lobar regions (limbic lobes, basal ganglia, amygdala and thalamus) previously identified as locations of atrophy in bvFTD and/or as anatomical correlates of clinical symptoms. A full list of regions is given in the Supplementary Information (SI) Table 1 SI.

Hierarchical agglomerative clustering, implemented in SPSS v.23.0, was used to classify differences/similarities in the 68 regional volumes. The bottom-up hierarchical agglomerative clustering is based on similarities and linkages between data points (subject-wise region of interest [ROI] volumes on MRI), with successive agglomeration of pairs of clusters until all clusters are merged into a single cluster containing all subjects. Similarity was measured by Euclidean distance between pairs of data points and linkage was measured by Ward's linkage method (Ward 1963). This approach does not require the number of clusters to be specified in advance, making it possible to derive multiple clustering solutions depending on the resolution required.

Voxel-based morphometry (VBM) was used in parallel with ROI-based approaches. The VBM processing procedure employed for this study followed the steps described in by Ashburner (Ashburner 2015). In short, the images were first segmented into grey matter, white matter and cerebrospinal fluid mask images (Ashburner 2015; Ashburner and Friston 2005). Each class of the segmented images were then warped together and non-linearly registered so that they matched each other (Ashburner and Friston 2011). A custom template was created from a data set of all participants in the study. Finally, images were normalized to the Montreal Neurological Institute space and smoothed with a Gaussian kernel (8 mm FWHM). Each group identified by the clustering technique was compared to the healthy control group. Regions showing atrophy in the bvFTD group were identified from the MNI coordinates of the voxels within the areas that were significantly different using maximum difference t-test statistics. All image processing steps and statistical analysis

were implemented in the Statistical Parametric Mapping (SPM12) software package available at http://www.fil.ion.ucl.ac.uk/spm/. The t-tests were performed on each pair of voxels/volumes corrected for age, gender and either estimated total intracranial volume (Whitwell et al. 2009) or total brain volume (Bigler and Tate 2001) to correct for global atrophy/severity. To correct for the false discoveries of significant differences due to multiple tests, the t-test statistics were corrected at the significance level $p < 0.05$ using the family-wise-error correction available in the VBM statistical package.

Clinical assessments

Baseline clinical assessments included the Addenbrooke's Cognitive Examination Revised (ACE-R) (Mioshi et al. 2006), the Mini-Mental State Examination (Folstein et al. 1975), the Frontotemporal Dementia Rating Scale (FRS) (Mioshi et al. 2010) and the Functional Assessment Questionnaire (FAQ)(Pfeffer et al. 1982). The bvFTD subtypes were compared using these scales and using subscales derived from the ACE-R and FRS prior to identification of the bvFTD subtypes. A total of 18 subscales were created: 11 cognitive subscales (from the ACE-R) and seven behavioural subscales (from the FRS). The FAQ scale was used in its entirety as an independent measure of activities of daily living. The primary scales and derived subscales are described in greater detail in the Supplementary Information.

Statistical analysis

Statistical analyses were performed using SPSS v.23.0, employing paired samples t-tests to compare males and females in Table 1. One-way ANOVA was used to test differences between bvFTD subtypes in cognitive and behavioural sub-scores given in Table 2. A significance level of $p < 0.05$ was used. In addition, post hoc analysis employed data reduction techniques, within SPSS, such as principal component and factor analysis to reduce the volumetric measurements into a manageable number of factors.

Data Availability

Data supporting the findings of this study are available from the corresponding author, upon reasonable request.

Results

Demographic and clinical features of the populations studied

A total of 213 bvFTD patients of 220 randomised to the trial were included in the present study based on baseline MRI scan quality and the complete clinical data required for the present study at baseline. Baseline demographic and clinical data are provided in Table 1. Mean (± SD) age was 63 ± 7 years for both males (136) and females (77). Total years in education were 15.4 ± 0.5, with no difference between males and females. The estimated total intracranial volume (eTIV) was significantly larger in males (1600 ± 220 cm^3) than in females (1400 ± 150 cm^3), although there was no difference in brain parenchymal fraction (BF, 0.67 ± 0.06). The MMSE score was significantly higher in males (25.4 ± 3.5) than in females (22.9 ± 4.0), as was the total ACE-R score (males: 72 ± 16; females: 62 ± 14). Males performed better on most of the ACE-R subscales apart from phonemics, language structure, episodic memory and perceptual abilities. By contrast, there was no overall difference on either the FRS or the FAQ score between males and females. The only FRS subscales showing a gender difference were ADL (where males performed better) and disinhibition (where males performed worse). There were no demographic differences between patients prescribed symptomatic treatments approved for AD (but not bvFTD) and those not receiving these treatments.

There were 133 males and 111 females in the healthy elderly group. There were no sex differences in age, years of education or MMSE score. The healthy elderly group was significantly older (69 ± 2 years), had less education (11 ± 2 years), and had a higher MMSE score (28.9 ± 1.2) than the bvFTD group.

Classification of bvFTD subjects by agglomerative clustering based on regional brain volumes

We applied a hierarchical agglomerative clustering algorithm using Euclidean distance and Ward linkage to provide measures of differences/similarities in the 68 regional volumes of the Desikan-Killiany Atlas (Desikan et al. 2006). The tree/dendrogram is shown in SI Figure 1. It is possible to classify bvFTD groups into either three or four clusters depending on the cluster distance. We used the 4-group clustering in further analyses for consistency

with previous studies (Ranasinghe et al. 2016; Whitwell et al. 2009). Each of these groups was then treated as a single group and compared to the healthy elderly subject group using VBM. Figure 1 shows the 3D surface rendering of the voxel-wise differences between each of the bvFTD groups and the healthy elderly group after correction for total intra-cranial volume. A similar result was found when the correction was based on estimated brain volume (SI Figure 3). Following Whitwell and colleagues (Whitwell et al. 2013), we designated the four anatomical sub-types: fronto/temporo/parietal (FTP), frontal-dominant (FD), temporal-dominant (TD) and sub-lobar (SL). The differences in cortical atrophy across bvFTD subtypes are shown in Figure 2.

Degeneration of central basal and limbic nodes as a core feature of bvFTD

Having confirmed the classification of the bvFTD subtypes based on distinct patterns of cortical atrophy, we determined how these are linked to atrophy in subcortical and limbic regions (Figure 3 and Table 2). As shown in Tables 2A and 2B, we found that it is possible to distinguish regions that are common to the four subtypes from those that are not. The limbic structures found to be common to all subtypes in terms of atrophy included anterior cingulate gyrus, hippocampal and parahippocampal gyri, insula and temporal pole (superior temporal gyrus). The subcortical grey nuclei affected in all subtypes included amygdala, caudate nucleus, pallidum and thalamus. The cortical regions common to the subtypes were the orbital surface areas of the frontal cortex (inferior frontal gyrus, olfactory cortex and gyrus rectus) and the medial surface areas of the frontal cortex (superior frontal gyrus and supplementary motor area). Only the middle temporal gyrus of the temporal lobe was shared between the subtypes. In all cases, the involvement of the common regions was bilateral.

A striking feature of the regions of atrophy shared across subtypes was that all have been identified previously as either members of the rich club (van den Heuvel et al. 2012) or functional binding nodes (Deco et al. 2017), or as regions having higher than average connectivity. As shown in Figure 3 and in Table 2A, the rich club members identified as undergoing atrophy in all four bvFTD sub-types were superior frontal gyrus, thalamus, pallidum, putamen and hippocampus. The functional ‘binding’ regions (Deco et al. 2017) common to the four subtypes include anterior cingulate and

insula. In addition, parahippocampal gyrus, amygdala and caudate have been identified as highly connected nodes.

By contrast with these subtype-independent regions, the regions listed in Table 2B had more limited subtype overlap and were generally unilateral. Atrophy in the superior temporal gyrus was unique to the TD subtype. The FTP subtype showed atrophy in middle occipital gyrus and precuneus, and the latter is also seen in the FT subtype. There was no overlap between atrophy and any of the rich club or linker regions that was unique to the SL subtype. Degeneration in the superior occipital lobe was unique to the frontal-dominant subtype. Atrophy in the superior temporal gyrus, although a functional binding node, was unique to the temporal-dominant subtype.

Cognitive, functional and behavioural performance across bvFTD subtypes

The principal cognitive scales, ACE-R and MMSE, showed no significant differences according to the bvFTD subtypes (Table 3). By contrast, the functional and behavioural scales, FAQ and FRS, showed significant differences (Table 3 and Figure 4), with the FD subtype showing greater overall impairment than the others. To examine this further, we used FRS subscales to determine whether behavioural elements of the bvFTD syndrome could be differentiated according to subtype. As shown in Table 3 and Figure 4, a picture like that seen with the full scales emerged, namely that the FD subtype was generally more impaired than the others. This could be seen for Behavioural Symptoms (characterised predominantly by lack of appropriate behaviours), Apathy/Disinterest and Disinhibition. The only significant exception was that both the FD and TD subtypes were characterised by significantly greater impairment on the subscales measuring Problematic Behaviours than the FTL and SL subtypes. Although it was possible to map functional and behavioural deficits to specific cortical regions (SI Figure 4), these features did not discriminate between the bvFTD subtypes identified by structural criteria, apart from greater general impairment largely restricted to the FD subtype (see also SI Figure 5).

Since overall cognitive impairment did not provide a basis for discriminating between the subtypes, we next tested whether cognitive subdomains possessed greater discriminatory capacity. Here a more complex picture emerged, as shown in Table 3

and Figure 5 (and SI Figure 7). As expected, the TD subtype was characterised more specifically by greater impairment in semantic memory and language semantics, but not in episodic memory. The FD subtype was differentiated by more prominent deficits in letter fluency. The FTP subtype showed somewhat greater impairment in language phonemics and perceptual abilities. There were no cognitive deficits that could be linked more specifically to the SL subtype. Although the FTD subtype might appear to be more AD-like, there were no differences in likelihood of being prescribed symptomatic treatments approved for AD.

The relationship between core features and cognitive, behaviour and functional performance in bvFTD.

It is clear from the foregoing analysis that atrophy patterns in bvFTD can be split into those atrophy patterns which are common to all subtypes and those that are associated with specific subtypes. Using the core regions, we performed a data reduction technique and extracted the first unrotated factor which explained 40% of the variance found across all core regions. There were significant correlations between this extracted factor and cognitive, behaviour and functional scores (Table 4). We next used a GLM approach to determine whether these associations depend on unique features of the subtype. In this analysis, the cognitive, behaviour and functional scores were considered separately as the dependent variable, and sex and subtype were included as fixed factors, while age, the summary core factor and head size were included as covariates (Table 5). The GLM analysis showed that the summary core feature drives the association with the cognitive scores and the functional activity score. By contrast, the behavioural score is associated with the cortical subtype, but not with the summary core feature.

Discussion

We have analysed a large clinical cohort of 213 well characterised bvFTD patients from a global, multicentre study. We aimed to examine how common and heterogeneous patterns of atrophy account for clinical diversity in this syndrome. Whilst confirming the existence of four anatomically distinct subtypes at the cortical level, our study has identified sub-lobar and limbic brain atrophy as a core feature of bvFTD that is common to the anatomically distinct subtypes that have been described.

A summary metric based on core region atrophy was found to associate significantly with cognitive and functional performance across all subtypes. Conversely, cortical heterogeneity was associated with behavioural performance independent of the variance explained by the core features. Therefore, the bvFTD syndrome can be understood as comprising a core disturbance in highly connected subcortical and limbic brain structures that is closely linked to cognitive and functional impairment.

Common and distinct atrophy patterns

Despite the existence of four anatomically distinct patterns of cortical surface atrophy in the population we have analysed, there is a homogenous pattern of atrophy across sub-cortical and limbic regions that is common to the anatomical subtypes. Of 39 brain regions showing atrophy when compared to heathy elderly subjects, 16 regions were found to be common to all four subtypes, whereas 23 had selective subtype associations. Of the 16 subtype-independent regions of atrophy, 10 regions have been characterised previously as brain hubs, i.e., brain regions with higher than average connectivity. These 10 regions map either to the so-called "rich club" of highly connected nodes (van den Heuvel et al. 2012), to highly connected functional binding nodes (Deco et al. 2017) or nodes known to have higher than average connectivity in either functional or structural MRI studies (Robinson et al. 2012; Ward et al. 2014). These network hubs are central to communication and functional integration of the brain and represent potential hotspots for loss of connectivity across multiple brain networks (Gollo et al. 2015). It is known from previous studies that the sub-networks of highly connected nodes play an important role in efficient information processing between segregated brain areas (Bullmore and Sporns 2012) and have been found to be associated with cognitive performance (Baggio et al. 2015) in healthy brain. Meta-analysis of MRI studies has suggested that there is a high vulnerability of the structural brain hubs and their connections in AD (Crossley et al. 2014; Sha et al. 2018) although the hubs implicated in bvFTD and AD differ (Daianu et al. 2016). Of the 23 regions where atrophy is not shared across the subtypes, two were found to be either subcortical or limbic, and five are members of the rich club or functional binding group. We therefore conclude that degeneration in basal, limbic and frontal networks that have

high levels of connectivity represents a core feature of the bvFTD syndrome irrespective of the anatomically distinct subtypes that have been described.

Degeneration of brain network hubs is not unique to bvFTD. It has been noted that neurodegeneration targets brain hubs in most of the neurodegenerative disorders (van den Heuvel and Sporns 2019; Stam 2014; Stam and van Straaten 2012). As noted above, the anatomical sites of atrophy differ between different neurodegenerative disorders. For example, the central brain regions affected in AD are more likely to be the medial temporal and parietal regions, although thalamus and hippocampus are consistently atrophied in both bvFTD and AD. It has been proposed that the increased traffic that hubs are required to support may help to explain why these regions have preferentially greater vulnerability to neurological disorders in general (van den Heuvel and Sporns 2013a; de Lange et al. 2019; Stam 2014). The vulnerability of the central networks of the human brain to neurodegeneration (Stam 2014) may explain the involvement of some rich club network nodes (insula, anterior cingulate, hippocampus, superior temporal pole, pallidum and thalamus), but not all (putamen and a number of cortical regions). A high degree of connectivity may also make certain regions more vulnerable to prion-like spread of pathology arising stochastically in linked subregions. These need not be mutually exclusive, since a chronically high level of activity may itself lead to high demands on turnover of vulnerable protein systems and predispose to pathological aggregation and transmission.

In an admittedly simplified model, Seeley and colleagues have proposed that neurodegeneration in bvFTD targets primarily the salience network (Seeley, Zhou, and Kim 2012). It is hypothesised that this would be responsible for social-emotional-autonomic processing (Seeley, Allman, et al. 2007) and affect some other functional brain networks via its afferent/efferent interactions. The salience network is closely allied with the ventral valuation/context appraisal network also known as the semantic appraisal network (Guo et al. 2013), default mode network and task-control or executive network (Cole and Schneider 2007; Possin et al. 2013), all reported as being disrupted in bvFTD. The trans-modal areas of the default mode and salience network also overlap with the rich club network regions (van den Heuvel and Sporns 2013b; Uddin et al. 2011). Our results support the existence of a common underlying pattern of degeneration which is not restricted to the salience network. Different subtypes of

bvFTD, which can be distinguished at the cortical level, ranging from absence of cortical lobar atrophy, to lobe-specific dominance, to multi-lobar atrophy, all share degeneration in the basal, limbic and frontal networks we have described.

In our cohort, the fronto-temporo-parietal subtype had the highest frequency (39%) and the frontal-dominant (19%), the temporal-dominant (24%) and the sub-lobar subtypes (18%) had comparable lower frequencies. Therefore, the syndrome as defined by consensus clinical criteria and by the requirement for a significant degree of frontal and/or temporal lobe atrophy remains neuroanatomically heterogeneous in the population we have studied. Our results align with two smaller studies reporting consistent differences in patterns of degeneration across cortical areas in patients diagnosed as having bvFTD by consensus criteria (Ranasinghe et al. 2016; Whitwell et al. 2009). This consistency between studies is preserved despite sampling of different subsets of regional volumes and utilisation of different statistical classifications. The frontal-dominant, temporal-dominant and fronto-temporo-parietal groups are comparable with the same anatomical sub-types identified by Whitwell and colleagues (2009). Ranasinghe and colleagues (2016). designate essentially the same anatomical subtypes in terms of a theoretical construct as the salience-network-frontal subtype (i.e., frontal-dominant), the semantic appraisal-network sub-type (i.e., temporal dominant) and salience-network-frontotemporal (i.e., fronto-temporo-parietal) subtype. Their sub-cortical subtype parallels our sub-lobar subtype. Although it is possible that the sub-lobar subtype might represent an earlier stage of the disease, Ranasinghe and colleagues have argued that it represents a true bvFTD subtype which progresses more slowly. We found no global cognitive, functional or behaviour differences which might have been expected if it represented an earlier stage of the disease. Our data therefore support the suggestion of Ranasinghe and colleagues that this is indeed a distinct subtype, and that its prevalence is comparable to that of the frontal- and temporal-dominant subtypes.

Heterogeneity at the cortical level is associated to only a limited extent with distinct behavioural, functional and cognitive features. The frontal-dominant subtype is characterised by greater global impairment on both the FRS and FAQ scales. It is notable that the frontal-dominant subtype is the most severely affected in terms of behavioural symptoms such as lack of appropriate social response, apathy and

disinterest, as well as disinhibition and problematic positive behaviours. In other words, in contrast to the overall importance of highly connected networks in defining the bvFTD syndrome, the frontal lobe remains particularly important for regulation of behaviour. By contrast, cognitive deficits segregate as expected, with the temporal-dominant form associated particularly with semantic memory and language semantics, and a stronger association between frontal-dominant atrophy and impairment in letter fluency.

Independently of the sub-type, a summary metric variable for the core features (the first unrotated factor), was found to have a highly significant statistical association with cognitive impairment, particularly with ACE-R, and with functional impairment as measured by the FAQ scale. After adjusting for the core factor, there was no residual association with subtype. On the other hand, the behavioural subscale derived from the FRS retained a significant association with anatomical subtype after taking account of the core factor variable. This may explain the possible latent nature of the pure sub-lobar subtype (Ranasinghe et al. 2016) in which prominent behavioural deficits may not be demonstrated.

This mapping of imaging features to clinical features should be viewed in the context of the inclusion criteria of this study, namely the requirement for presence of brain atrophy in frontal and/or temporal lobes scoring two or more on a scale proposed by Kipps et al. (Kipps et al. 2008). That is subjects with little or no frontal and/or temporal atrophy and who fulfilled all other criteria for bvFTD were not included. The results of the present analysis suggest that the diagnostic utility of MRI in the differentiation of bvFTD from healthy controls and other dementias may be best served by examining the core features with or without the frontal and temporal lobes. A recent study reports that a data driven approach for discriminating between bvFTD patients and controls showed good discriminatory performance without a priori knowledge of any potential structure within the data (Manera et al. 2019). It remains to be determined how a prior knowledge of the core features we have described could improve the discrimination. More importantly, it remains to be determined how incorporating a core feature metric assists with the more pertinent clinical question which is to discriminate between bvFTD and other dementias.

Limitations and conclusions

There are limitations to the inferences which can be drawn from the present study. Although it is based on a large sample, it is possible that still greater power is required to define the subtle clinical features of the subtypes. Similarly, the clinical scales we have used to interrogate the bvFTD phenotype may not be sufficiently discriminatory, and more refined neuropsychological measures may characterise the clinical features of the subtypes with greater subtlety. A further limitation is that we have used patterns of atrophy on MRI as the sole investigative tool for analysing the brain abnormalities of bvFTD. Although this has the advantages of a wide applicability and standardisation, metrics based on functional MRI that may be able to define abnormalities in the underlying connectome were not available in the present study. Again, there is a trade-off between the feasibility of more refined approaches and study size/cost considerations.

Notwithstanding these limitations, a useful general picture that emerges from our study is that the MRI abnormalities in the bvFTD syndrome can be characterised at two neuroanatomical levels. The core of the syndrome appears to depend on a common pattern of degeneration in which basal and limbic lobes are disproportionately represented. Some, but not all of these, have been identified previously as brain structural and functional network hubs. In addition, the neuroanatomical heterogeneity at the cortical level, which is robust and reproducible across studies, appears to have limited explanatory power in accounting for cognitive, functional and behavioural heterogeneity. Our results are consistent with the idea that bvFTD is characterised by a core disturbance within basal, limbic and frontal networks required for integration of cognition, function and behaviour. This core disturbance at the level of integration may help to understand both the inappropriate conduct that families find distressing and the higher rates of socially inappropriate behaviour and criminality in bvFTD than in other comparable neurodegenerative disorders (Liljegren et al. 2019).

There appears to be a dissociation between the cognitive understanding of actions and their consequences as matters of fact, and the capacity for an appropriate evaluation of their personal and societal implications (Mendez 2010; Sfera et al. 2014). This dissociation could be viewed as resulting from pathology affecting particularly

the central integrative systems that enable segregated functional regions of the brain to interact and communicate.

Acknowledgment

We would like to acknowledge the support of the Maxwell Computer Cluster funded by the University of Aberdeen. We also gratefully acknowledge study investigators and the generosity of study participants.

Supplementary material

Supplementary material is available at Brain online

Figure legends

Figure 1. bvFTD individuals clustered based on differences in the 68 regional volumes. Yellow areas represent significant volume loss in each bvFTD cluster/sub-group (sagittal and medial views) based on pair-wise comparisons with the healthy control group. Abbreviations: FTP = frontotemporoparietal; TD = temporal-dominant; FD = frontal-dominant; SL = sub-lobar.

Figure 2. Pair-wise differences between the four identified bvFTD clusters/groups mapped onto the cortical surface. Hot/cold colours indicate t-test statistics used for the voxel-wise comparisons. Hot colours indicate 'more' atrophy (as indicated in each panel by an inequality sign). Abbreviations: FTP = frontotemporoparietal; TD = temporal-dominant; FD = frontal-dominant; SL = sub-lobar.

Figure 3. Brain views (sagittal and middle) of the common-to-all (grey) and distinct (magenta) regional atrophy in the four bvFTD sub-groups. Atrophied regions were labelled using Automated Anatomical Labelling (AAL). Abbreviations: FTP = frontotemporoparietal; TD = temporal-dominant; FD = frontal-dominant; SL = sub-lobar.

Figure 4. Box-plots with individual data points superimposed for behavioural and functional sub-scores in bvFTD sub-groups. Abbreviations: FTP = frontotemporoparietal;

TD = temporal-dominant; FD = frontal-dominant; SL = sub-lobar; FRS = Frontotemporal Dementia Rating Scale; FAQ = Functional Activities Questionnaire.

Figure 5. Box-plots with individual data points superimposed for cognitive sub-scores in bvFTD sub-groups. FTP = frontotemporoparietal; TD = temporal-dominant; FD = frontal-dominant; SL = sub-lobar.

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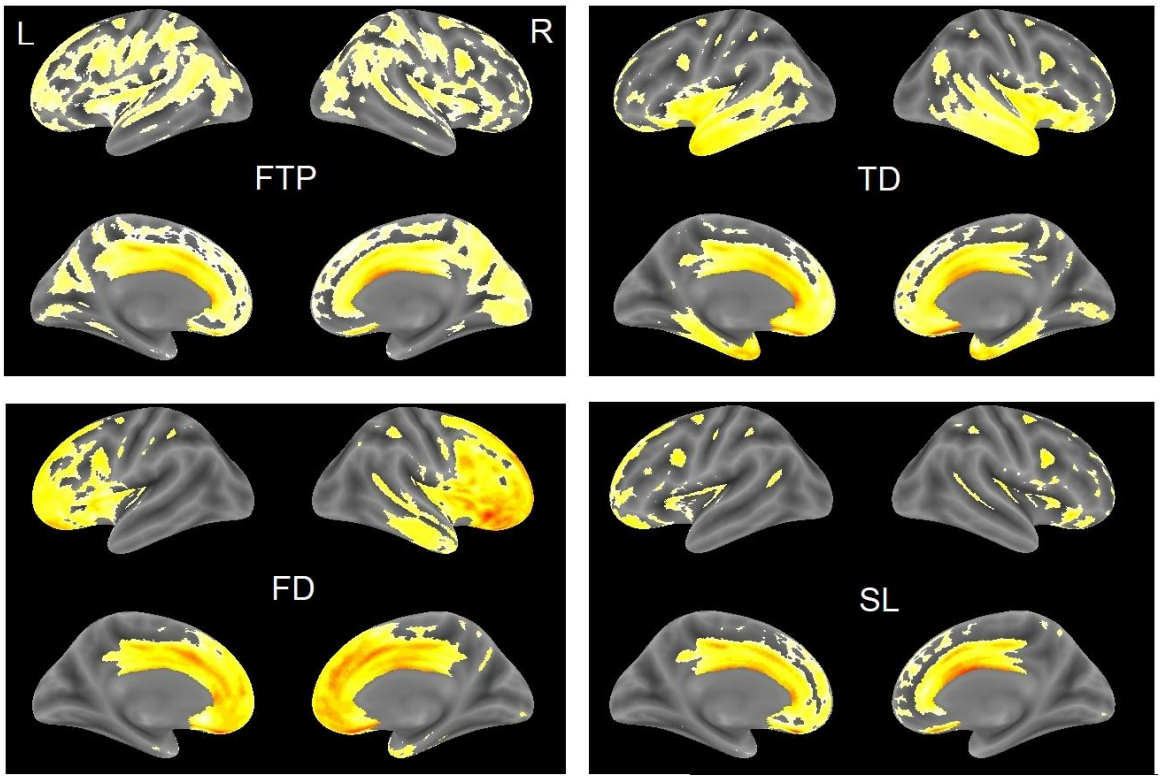
Figure 1:



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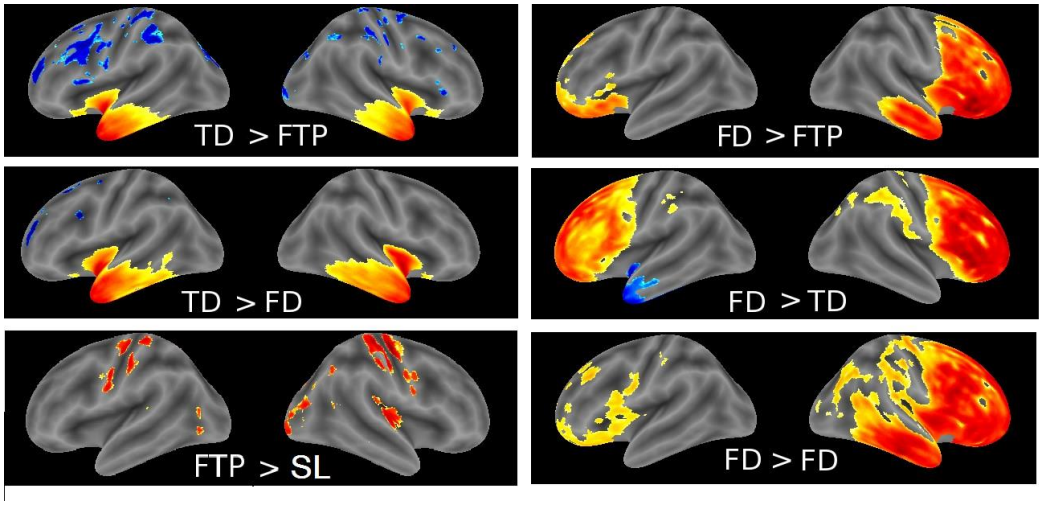

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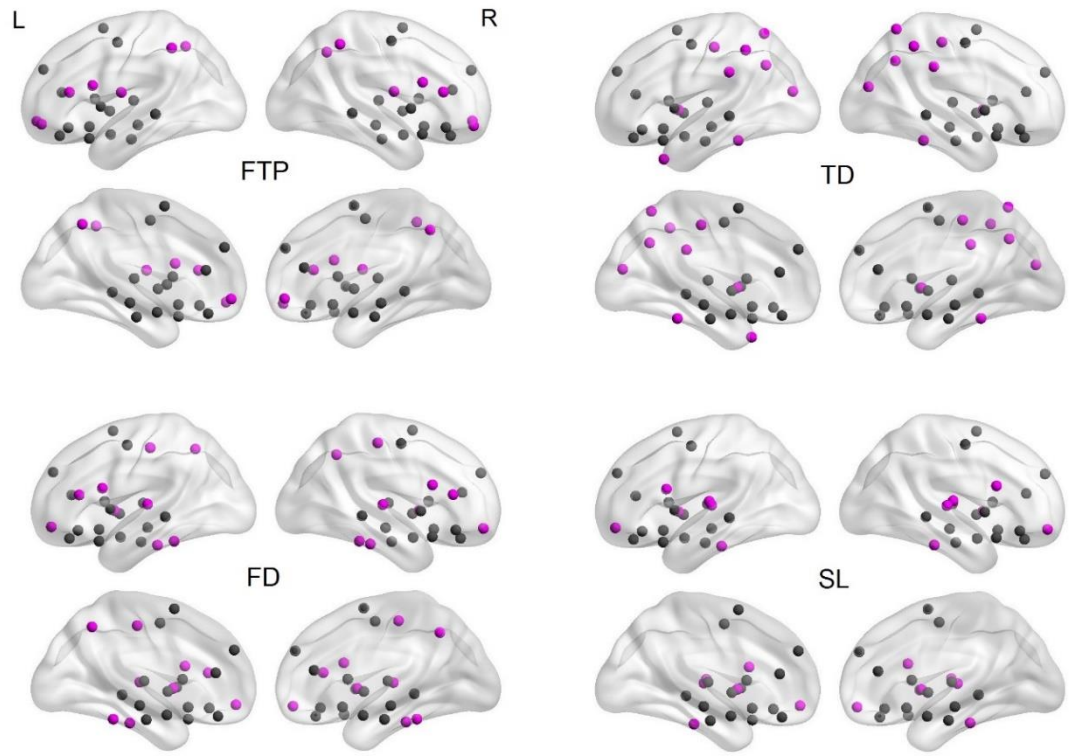

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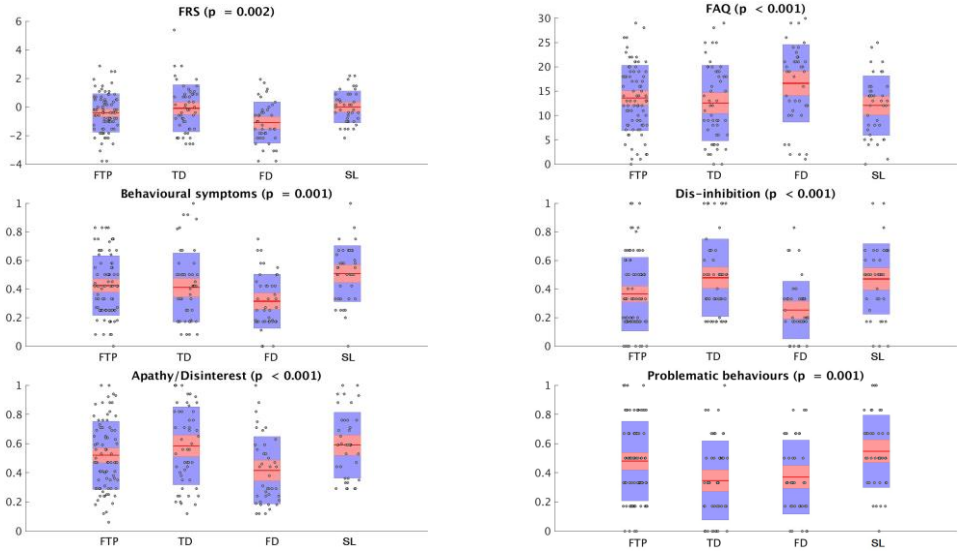
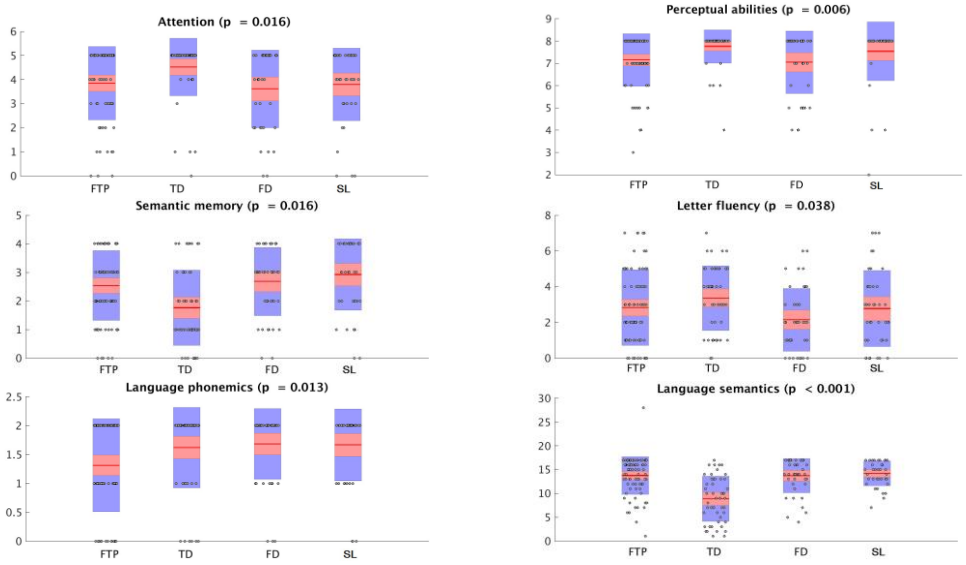

FRS (p = 0.002)
FAQ (p < 0.001)
Behavioural symptoms (p = 0.001)
Dis-inhibition (p < 0.001)
Apathy/Disinterest (p < 0.001)
Problematic behaviours (p = 0.001)
FTP
TD
FD
SL

Figure 5:


Attention (p = 0.016)
Perceptual abilities (p = 0.006)
Semantic memory (p = 0.016)
Letter fluency (p = 0.038)
Language phonemics (p = 0.013)
Language semantics (p < 0.001)
FTP
TD
FD
SL