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A lesion model of envy and *Schadenfreude*: legal, deservingness and moral dimensions as revealed by neurodegeneration

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The study of moral emotions (i.e. *Schadenfreude* and envy) is critical to understand the ecological complexity of everyday interactions between cognitive, affective, and social cognition processes. Most previous studies in this area have used correlational imaging techniques and framed *Schadenfreude* and envy as unified and monolithic emotional domains. Here, we profit from a relevant neurodegeneration model to disentangle the brain regions engaged in three dimensions of *Schadenfreude* and envy: deservingness, morality, and legality. We tested a group of patients with behavioural variant frontotemporal dementia (bvFTD), patients with Alzheimer's disease, as a contrastive neurodegeneration model, and healthy controls on a novel task highlighting each of these dimensions in scenarios eliciting *Schadenfreude* and envy. Compared with the Alzheimer's disease and control groups, patients with bvFTD obtained significantly higher scores on all dimensions for both emotions. Correlational analyses revealed an association between envy and *Schadenfreude* scores and greater deficits in social cognition, inhibitory control, and behaviour disturbances in bvFTD patients. Brain anatomy findings (restricted to bvFTD and controls) confirmed the partially dissociable nature of the moral emotions' experiences and highlighted the importance of socio-moral brain areas in processing those emotions. In all subjects, an association emerged between *Schadenfreude* and the ventral striatum, and between envy and the anterior cingulate cortex. In addition, the results supported an association between scores for moral and legal transgression and the morphology of areas implicated in emotional appraisal, including the amygdala and the parahippocampus. By contrast, bvFTD patients exhibited a negative association between increased *Schadenfreude* and envy across dimensions and critical regions supporting social-value rewards and social-moral processes (dorsolateral prefrontal cortex, angular gyrus and precuneus). Together, this study provides lesion-based evidence for the multidimensional nature of the emotional experiences of envy and *Schadenfreude*. Our results offer new insights into the mechanisms subsuming complex emotions and moral cognition in neurodegeneration. Moreover, this study presents the exacerbation of envy and *Schadenfreude* as a new potential hallmark of bvFTD that could impact in diagnosis and progression.

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Introduction

The emerging cognitive neuroscience of moral emotions, such as *Schadenfreude* (a German word implying pleasure for others' misfortunes) and envy (Takahashi *et al.*, 2009; Jankowski and Takahashi, 2014) have opened a window for comprehending ecological affective processes (Fontenelle *et al.*, 2015). So far, this field has mainly relied on correlational imaging studies, largely neglecting the contributions of the lesion model approach, which helps to reveal direct links between brain regions and fine-grained cognitive functions. Active tasks in neuroimaging and electromagnetic studies provide only indirect evidence of brain-behaviour associations (Linden, 2012). The lesion model (Rorden and Karnath, 2004; Shahid *et al.*, 2017) and, in particular, the neurodegenerative lesion model (Irish *et al.*, 2012; García-Cordero *et al.*, 2016; Melloni *et al.*, 2016; O'Callaghan *et al.*, 2016; Ibanez *et al.*, 2017), reveals the critical areas, which directly relate to performance in a specific domain. Here we profit from this methodological strategy to shed new light on the neural correlates of both emotion types and their key dimensions.

Emotions constitute an adaptive mechanism supporting the regulation of one's own acts and the assessment of others' behaviours (Haidt, 2003; Adolfi *et al.*, 2016). Moral emotions, in particular, seem to be mediated by culturally defined conventions that are critical for group organization and cohesiveness (Haidt, 2003; Tangney *et al.*, 2007). Contrary to basic emotions, these are linked to the welfare of social groups (Moll *et al.*, 2003; Moll and de Oliveira-Souza, 2007), as they encourage or inhibit behaviours depending on their social acceptability (Ortony *et al.*, 1990). Moral emotions seem to modulate how humans assess which behaviours are social and morally acceptable. According to Haidt (2003), moral emotions are shaped under the influence of two factors: elicitors and action tendencies. Elicitors range from the behaviour of others to events affecting them and their evaluations of own actions. As regards social action tendencies, moral

emotions are experienced when we are motivated to deploy other-targeted actions, modulating social order and welfare. For Haidt (2003), envy and *Schadenfreude* appear to integrate another category as they involve no pro-social action tendencies (Haidt, 2003). Similar to the self-conscious family of emotions, which arise from a discrepancy between one's ideal self and current self (Ortony *et al.*, 1990), *Schadenfreude* and envy imply a discrepancy between one's current status and the status of another person (Ortony *et al.*, 1990). Thus, social comparison is crucial for describing all types of moral emotions. New approaches in the study of moral emotions have described *Schadenfreude* and envy as counter-empathy (Cikara and Fiske, 2013) or fortune of others' emotions (Shamay-Tsoory *et al.*, 2014).

Schadenfreude (to gloat), refers to the perceiver's experience of pleasure at another's misfortune (van Dijk *et al.*, 2006; Dvash *et al.*, 2010*b*; Jankowski and Takahashi, 2014). Envy, on the other hand, is defined as displeasure associated with another's success. These emotions have been shown to involve a critical interplay between social, moral, and affective processes (Takahashi *et al.*, 2009; Dvash *et al.*, 2010*b*; Jankowski and Takahashi, 2014), highlighting the complexity of their organization. At the neuroanatomical level, *Schadenfreude* has been associated with activity in ventral striatum, as assessed with functional MRI (Takahashi *et al.*, 2009; Cikara and Fiske, 2013; Jankowski and Takahashi, 2014). By contrast, envy has been associated with activation of temporal regions as well as the anterior and medial cingulate cortices (ACC and MCC, respectively) (Takahashi *et al.*, 2009; Cikara and Fiske, 2013; Jankowski and Takahashi, 2014). Despite the above advances, the literature on moral emotions still faces two caveats: the assumption of monolithic conceptions of the constructs and the lack of lesion studies to address the issue.

First, *Schadenfreude* and envy are most often treated as monolithic phenomena (van Dijk *et al.*, 2006; Takahashi *et al.*, 2009). However, research on various other emotion types have revealed partially dissociable dimensions

(Portmann, 2000; Chester *et al.*, 2013). Indeed, *Schadenfreude* or envy can be differently triggered by a broad spectrum of behaviours and affective scenarios (Portmann, 2000). Previous studies have shown that envy and *Schadenfreude* have different modulators, including (i) the inferred desirability of an outcome for a target (Haidt, 2003; Tangney *et al.*, 2007; Takahashi *et al.*, 2009; Jankowski and Takahashi, 2014); (ii) target likeability (Haidt, 2003; Tangney *et al.*, 2007; Takahashi *et al.*, 2009; Jankowski and Takahashi, 2014); (iii) inferred target deservedness (Feather and Sherman, 2002; van Dijk *et al.*, 2005; Smith and Kim, 2007; Dvash *et al.*, 2010*a*; Chester *et al.*, 2013; Ben-Ze'ev, 2014; van Dijk and Ouwerkerk, 2014; Zaki *et al.*, 2015); and (iv) subject's perception of justice and fairness in others' outcomes (Feather and Sherman, 2002; Smith, 2009; Dvash *et al.*, 2010*a*; Jankowski and Takahashi, 2014; Shamay-Tsoory *et al.*, 2014; van Dijk and Ouwerkerk, 2014; Yoder and Decety, 2014; Najle, 2015; Portmann, 2017). The situations used to trigger envy and *Schadenfreude* in our study are in part supported by some of these factors. In particular, deservingness situations trigger moral emotions with modulating factors such as target likeability and inferred target deservedness. In contrast, moral and legal situations evoke envy and *Schadenfreude* by modifying the subjects' perception of justice and fairness in outcomes reached by a receptor.

Deservingness, morality, and legality concepts are all intertwined notions able to modulate experiences of *Schadenfreude* (van Dijk and Ouwerkerk, 2014) and envy (Smith and Kim, 2007; Chester *et al.*, 2013). Considering that these emotions respond to the disagreement between one's current situation and that of another person, different sources and modulators can be identified for these emotions, including deduced target deservedness (Feather and Sherman, 2002; van Dijk *et al.*, 2005; Smith and Kim, 2007; Dvash *et al.*, 2010*a*; Chester *et al.*, 2013; Ben-Ze'ev, 2014; van Dijk and Ouwerkerk, 2014; Zaki *et al.*, 2015) and the perception of fairness in others' outcomes (Feather and Sherman, 2002; Smith, 2009; Dvash *et al.*, 2010*a*; Jankowski and Takahashi, 2014; Shamay-Tsoory *et al.*, 2014; van Dijk and Ouwerkerk, 2014; Yoder and Decety, 2014; Najle, 2015; Portmann, 2017). Along these lines, different approaches ranging from social psychology (Ortony *et al.*, 1990; Portmann, 2002; Ben-Ze'ev, 2014), to sociology (Plutchik, 1980; Fiske, 1992) and philosophy (de Spinoza, 1883) and, more recently, research in the field of social cognitive neuroscience (van Dijk *et al.*, 2005; Takahashi *et al.*, 2009; Dvash *et al.*, 2010*a*; Chester *et al.*, 2013; Cikara and Fiske, 2013; Fiske and Taylor, 2013), indicate that *Schadenfreude* and envy are complex and non-unified emotional experiences modulated by different factors, including the interplay between high and low order affective and cognitive mechanisms (Chester *et al.*, 2013; Jankowski and Takahashi, 2014).

Also, building on Schopenhauer's (1788–1860) account of *Schadenfreude* as a most obscure expression of human emotionality, this emotion can be considered to possess a component of maliciousness, even if the outcome is deserved. However, *Schadenfreude* may also rely on notions of justice (van Dijk *et al.*, 2006; Ben-Ze'ev, 2014), and moral or legal analyses can exonerate the pleasure experienced in presence of others' misfortunes. Enjoying the misfortune of someone who has violated a legal code or moral norm may be considered as a well-intentioned emotion, as it would reflect a reaction to fairness (van Dijk *et al.*, 2006; Ben-Ze'ev, 2014). Although both situations involve *Schadenfreude*, they clearly differ in their affective implications. Likewise, previous studies suggest that envy can be elicited either when someone gets an undeserved outcome or when someone is rewarded despite moral or legal transgressions (Portmann, 2000; Ben-Ze'ev, 2014; van Dijk and Ouwerkerk, 2014).

From a neurobiological perspective, abundant evidence indicates that morality is not a wholly unified faculty, but a collection of dissociable neurocognitive processes depending on the type of transgression being judged (Parkinson *et al.*, 2011; Hayashi *et al.*, 2014; Sinnott-Armstrong, 2016). Although different moral situations can share some neurocognitive mechanisms, they also exhibit dissociable neural pathways. For instance, processing of different moral situations, including disgust and moral transgressions, share neurocognitive processes as all of them are related to activity of the ACC, the medial prefrontal cortex, and the temporoparietal junction. However, these situations also have dissociable neural activations, as moral transgressions are more related to activity of the amygdala and the parahippocampus, whereas disgust is more associated to the activity of the posterior cingulate cortex and the dorsolateral prefrontal cortex (Parkinson *et al.*, 2011; Hayashi *et al.*, 2014; Sinnott-Armstrong, 2016). Our study aims to delve deeper into perspective by analysing the emotional responses associated with envy and *Schadenfreude* as dissociable experiences rather than as unified, monolithic constructs. We use the term 'monolithic' to refer to different situations than can elicit a same emotional response. For instance, although all dimensions of moral emotions can elicit pleasure or displeasure, each of them is typical of different situations (moral, legal or deservedness). This approach could offer new options in the study of envy and *Schadenfreude* by providing evidence on how they can be modulated by situations that differ in their nature.

Thus, at least three distinct dimensions of *Schadenfreude* and envy can be identified as more or less prominent depending on the situation: deservingness (the degree to which an actor deserves the outcome he experienced), morality (the degree to which an actor gets a different outcome than he/she could expected involving a moral precept violation), and legality (the degree to which an actor gets a different outcome than he/she could expected involving a legal precept violation). While each of these dimensions involves different cognitive and affective foundations and may thus rely on partially different neural mechanisms, such fine-grained associations have not yet been assessed.

Against this background, we conducted the first lesion-model study on the correlates of these dimensions for both *Schadenfreude* and envy. Specifically, we focused on the behavioural variant of frontotemporal dementia (bvFTD), a relevant neurodegenerative lesion model featuring selective atrophy of the main pathways associated with envy (the ACC and temporal areas) and *Schadenfreude* (the fronto-striatal network). This complex clinical syndrome is characterized by social cognition deficits and marked behavioural changes that impair social interaction (Piguet *et al.*, 2011; Ibañez and Manes, 2012; Seeley *et al.*, 2012; Ibanez *et al.*, 2014, 2017). More particularly, bvFTD have been associated with alterations in social and moral cognition, including reduced empathic concern for others' suffering (Eslinger *et al.*, 2011a; Baez *et al.*, 2014c, 2016b; Melloni *et al.*, 2014), diminished prosocial sentiments (Moll *et al.*, 2011), and reduced long-term cooperative behaviours (Melloni *et al.*, 2016; Ibanez *et al.*, 2017). Furthermore, patients with bvFTD show altered moral judgements, displaying more utilitarian judgements in the face of moral dilemmas (Baez *et al.*, 2014a, 2016a). A similar pattern has been also observed in extreme criminal terrorists (Baez *et al.*, 2017b). Finally, these patients have been shown to display increased antisocial and criminal behaviour (de Oliveira-Souza *et al.*, 2008; Liljegren *et al.*, 2015), as well as a relatively high incidence of legal violations (Mendez, 2010). In sum, bvFTD offers a relevant lesion model to assess the specific neural correlates of the different dimensions operative in the experience of *Schadenfreude* and envy.

To this end, we created a novel task tapping the dimensions of deservingness, morality, and legality in moral emotions, and administered it to patients with bvFTD, matched healthy controls, and patients with early stage Alzheimer's disease—another form of dementia offering a contrastive neurodegenerative model. Our task features situations whose characters are involved in fortunate and unfortunate events evoking envy and *Schadenfreude*, respectively. Crucially, each emotion type involved a subset of scenarios dominated by feelings of deservingness, morality, or legality. In addition, neutral situations were added to test task comprehension and attentional engagement.

We propose two sets of hypotheses at behavioural and neurocognitive levels. First, we expected a specific pattern of responses regarding the dimensions of moral emotions. Previous studies have shown that situations where justice notions are disrupted (and which feature severe violations of social codes) involve increased discomfort and heightened emotional responses (Tangney *et al.*, 2007; Yoder and Decety, 2014). Thus, for *Schadenfreude* and envy, healthy controls can be expected to show more emotional responses in situations with prominent moral and legal components compared to deservingness situations. Second, given that patients with bvFTD present disruptions of social skills, moral cognition, disinhibited behaviours, and altered affective states, they were expected to experience exacerbated degrees of envy and *Schadenfreude* relative to the other two groups. Also, since these patients usually exhibit low sensitivity to follow moral and legal codes (Mendez *et al.*, 2005; Mendez, 2010; Baez *et al.*, 2014a, 2016a), and usually present counter-empathy behaviours (Moll *et al.*, 2011), we expected bvFTD patients to exhibit higher scores across all dimensions (deservingness, moral or legal) in both emotion types. Thus, in those patients, a general (non-selective) increase of emotional responses can be predicted, irrespective of whether they are elicited by deservingness or moral-legal scenarios. Regarding neuroanatomy (assessed with voxel-based morphometry, VBM), we expected to find differential pathways implicated in *Schadenfreude* (striatum) and envy (ACC). In bvFTD patients, atrophy of frontotemporal regions subserving social cognition, cognitive control, and behavioural regulation (Ibañez and Manes, 2012; Seeley *et al.*, 2012; Sedeno *et al.*, 2017) should be associated with enhanced experiences of both emotion types. Furthermore, atrophy of regions involved in judging third-party and personal moral and legal situations (Buckholtz *et al.*, 2008), such as the ACC and angular gyrus, which are impaired in bvFTD and associated with moral deficits and illegal behaviour in this condition (Mendez, 2010; Baez *et al.*, 2016b), should also be associated with envy.

Materials and methods

Participants

We recruited 64 participants from an ongoing protocol (Couto *et al.*, 2013; Baez *et al.*, 2014c, 2016a, 2017c; García-Cordero *et al.*, 2016; Melloni *et al.*, 2016; Santamaria-Garcia *et al.*, 2016; Sedeno *et al.*, 2016), namely, 20 patients that met revised criteria for probable bvFTD (Rascovsky *et al.*, 2011), 24 patients diagnosed with early onset Alzheimer's disease (McKhann *et al.*, 2011), and 20 healthy control subjects. All patients were assessed by a multidisciplinary group of experts, including two neurologists (A.L., C.H.C.), three psychiatrists (J.M.S., G.O., H.S.), and two geriatricians (J.F.M., S.H.). Groups did not differ significantly in terms of age, gender, or years of education (Table 1). Patients and controls were included if they had no history of major neurological or psychiatric illnesses (other than bvFTD or Alzheimer's disease, in the case of patients) or alcohol/drug abuse. Patients and healthy controls were included in the study if they had no general language deficits, including semantic and comprehension alterations (see additional test below). All participants provided written informed consent in agreement with the Declaration of Helsinki. The study was approved by the Institution's Ethics and Research Committee.

Neuropsychological tests

General cognitive state

Participants' general cognitive state was assessed with the Montreal Cognitive Assessment (MOCA) (Nasreddine *et al.*, 2005), and their executive skills were evaluated with a frontal battery including the INECO Frontal Screening (IFS) test

Table 1 Demographic and neuropsychological data for all three groups

	Controls (n = 20) Mean /SD	BvFTD (n = 20) Mean /SD	Alzheimer's disease (n = 24) Mean /SD	P-value Controls versus bvFTD	P-value BvFTD versus Alzheimer's disease
Demographics					
Age (years)	61.1 (7.98)	58.9 (6.35)	63.1 (5.64)	N.S.	N.S.
Gender (F:M)	11:9	9:11	13:11	N.S.	N.S.
Education (years)	13.32 (4.9)	14.81 (4.3)	13.88 (5.6)	N.S.	N.S.
Years since disease onset	NA	3.1 (2.2)	3.9 (1.9)	NA	N.S.
MMSE	27.4 (2.1)	21.6 (4.5)**	20.7 (4.8)**	<0.01	N.S.
General cognitive assessment					
MoCA	26.2 (3.1)	19.2 (6.7)**	22.1 (6.1)**	<0.01	N.S.
Total IFS score	24.2 (2.9)	16.9 (5.4)	19.1 (5.9)	N.S	N.S.
Inhibitory cognitive control measure					
Hayling test	9.4 (2.1)	16.4 (2.8)	14.8 (3.1)	<0.01	<0.05
Behavioural changes					
FrSBE (Frontal System Behavioural Scale) total*	NA	48.4 (31.1)	37.9 (27.7)	NA	<0.01
Social cognitive measure					
RMET	0.88(0.10)	0.51 (0.16)**	0.69 (0.12)**	<0.01	<0.05

*To obtain an index of progression of Frontal System Behavioural Scale (FrSBE) scores, we subtracted the present score from the previous score.
**Differences compared to controls.
N.S = differences were not significant; NA = not assessed.

(Torralva *et al.*, 2009). The IFS is a 30-point scale that has been shown to successfully detect executive dysfunction in patients with neurological and psychiatric diseases (Torralva *et al.*, 2009; Baez *et al.*, 2014b). This test includes the following eight subtests: (i) motor programming (Luria series, 'fist, edge, palm'); (ii) conflicting instructions (hitting the table once when the administrator hits it twice, or hitting it twice when the administrator hits it only once); (iii) motor inhibitory control; (iv) numerical working memory (backward digit span); (v) verbal working memory (months backwards); (vi) spatial working memory (modified Corsi tapping test); (vii) abstraction capacity (inferring the meaning of proverbs); and (viii) verbal inhibitory control (modified Hayling test).

As a complementary measure of inhibitory control, we used the complete version of the Hayling test (Perez-Perez *et al.*, 2016). This scale tracks response initiation and response suppression (Hornberger *et al.*, 2010; Perez-Perez *et al.*, 2016) and has been largely used to assess disinhibition in patients with neurodegenerative diseases (Torralva *et al.*, 2009; Hornberger *et al.*, 2010). Higher scores on the Hayling test are thought to reflect difficulties in inhibitory control (Torralva *et al.*, 2009; Hornberger *et al.*, 2010).

Neuropsychiatric manifestations, including apathy and disinhibition, were assessed with the subjective subscales of apathy, executive functions, and disinhibition of the Frontal System Behavioural Scale, which tracks the degree of behavioural changes since disease onset (Carvalho *et al.*, 2013) and is usually reported as the percentage of changes of behavioural disturbances between free stages of disease and current stages (Carvalho *et al.*, 2013; Santamaria-Garcia *et al.*, 2016).

Theory of mind skills were assessed with the Reading the Mind in the Eyes Test (RMET) (Baron-Cohen *et al.*, 1997), which is also sensitive for the assessment of bvFTD and patients with Alzheimer's disease (Gregory *et al.*, 2002; Couto *et al.*, 2013;

Baez *et al.*, 2014a). This is a computerized and validated test consisting of 36 pictures of the eye region of a face. Participants are asked to choose which of four words best describes what the person in each photograph is thinking or feeling.

Language assessment

Language subscale in the Montreal Cognitive Assessment

We analysed the scores in the language subscale from the MoCA to assess general language performance among the groups. This subscale has a maximum possible score of 3 points out of a total of 30 in the MoCA. Results of this task revealed non-significant differences between groups [$F(2,82) = 1.76$, $P = 0.11$]. Mean values of the ratings for this subscale were 2 [standard deviation (SD) = 0.8] for bvFTD patients, 2.3 (SD = 0.6) for patients with Alzheimer's disease, and 2.6 (SD = 0.4) for healthy controls.

Picture naming task

To rule out semantic deficits, we administered a well-established picture-naming task (Snodgrass and Feenan, 1990; Sanfeliu and Fernandez, 1996) based on 60 black-and-white pictures depicting three categories of living things (animals, birds, and fruit) and three categories of artefacts (household items, tools, and vehicles). Subjects were required to name with a single spoken word a picture included in an array of other pictures within a same category. Results of this task revealed non-significant differences between groups [$F(2,82) = 2.16$, $P = 0.09$]. Mean values of the ratings for picture naming test in bvFTD group, Alzheimer's disease group and healthy controls were 53.7 (SD = 5.6), 56.4 (SD = 4.7), and 58.8 (SD = 2.8), respectively.

Experimental task

For the current study we created a novel task based on previous studies from our own group and others (Takahashi *et al.*, 2009; Baez *et al.*, 2016*c*, 2017*d*). We designed 40 situations to evoke different types of pleasant (*Schadenfreude*, *n* = 15) or unpleasant (envy, *n* = 15) emotional experiences, as well as emotionally neutral scenarios (*n* = 10) for control purposes. The situations eliciting each emotion type included five scenarios dominated by deservingness, five dominated by morality, and five dominated by legality. For *Schadenfreude*, we used situations that evoke pleasure due to feelings of deservingness (e.g. a liar is excluded from his or her group of friends), morality (e.g. a subject is found guilty and punished for faking a physical disability), and legality (e.g. a subject is punished for not paying for public transportation). Moreover, we included five neutral situations (e.g. a person turns on the light in the house when it gets dark). Likewise, for envy, we created situations evoking displeasure related to feelings of deservingness (e.g. a young man got a better test score for being the son of a professor), morality (e.g. someone avoids waiting at the bank by simulating a physical disability), and legality (e.g. a politician takes a vacation using taxpayers' money). As for the *Schadenfreude* situations, we also included five neutral situations for the envy condition.

Situations associated with each dimension in each type of emotion were validated through a survey completed by 81 subjects (39 females), with a mean age of 39 years, (SD = 4), and an average of 12.6 years of education (SD = 2.2). In this validation study, participants scored a group of deservingness situations, a group of moral situations, and a group of legal situations according to their degree of deservedness, morality, and legality. Results confirmed that each group of situations effectively tracked the expected dimension for each moral emotion (*Schadenfreude* and envy). The deservingness situations obtained the highest deservingness scores, the moral situations obtained the highest moral content scores, and the legal situations obtained the highest legality scores (Fig. 1 and Supplementary material).

In addition, an additional group of 39 extra subjects (details in the Supplementary material) validated the emotional profile of the situations of each dimension in each type of emotion (*Schadenfreude* and envy). Participants rated deservingness, moral, and legal situations according to their capacity to evoke different emotions. Mainly, we assessed the degree in which situations were able to evoke envy and *Schadenfreude* emotions, but also, as a control measure, we assessed to what extent the situations evoked other socio-moral emotions, such as pride and guilt. Thus, for *Schadenfreude*, the participants were required to score the situations according to how intensely they evoked (i) pleasure; (ii) *Schadenfreude* (as Spanish lacks a single word to name this experience, we translated it as: '*La satisfacción por lo que le ha ocurrido al sujeto de la situación*'; in English: 'How much satisfaction do you feel for the protagonist's outcome'); and (iii) pride. The participants also rated the envy situations in terms of how much these situations evoked (i) displeasure; (ii) envy; and (iii) guilt. Both pride and guilt emotions were used as control socio-moral emotions (Jankowski and Takahashi, 2014). Results confirmed that each group of situations effectively tracked the expected emotion (*Schadenfreude*/envy). Although the situations also evoked other socio-moral emotions, such as

pride/guilt, the scores for those emotions were significantly lower than for envy/*Schadenfreude* and for more general emotional responses, namely displeasure/pleasure (Supplementary material and Supplementary Fig. 1).
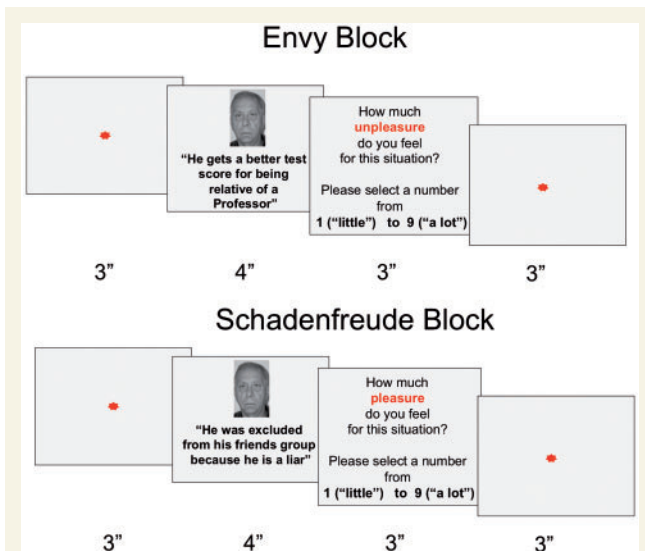
Task procedure

First, each participant was shown a real-life photograph and a description of two target characters matched to the participant in age and gender (based on data obtained in a brief interview before the task). The situations for each type of emotion occurred to the character presented before each block. Based on the results from the validation study, situations were organized in two blocks. In the first block (envy), participants evaluated situations that evoked dimensions of envy and, in the second block, they evaluated situations that evoked dimensions of *Schadenfreude*. Envy situations were presented first, in line with previous evidence suggesting that the degree of envy predicts *Schadenfreude* responses (Takahashi *et al.*, 2009; Jankowski and Takahashi, 2014). In each block, participants read five situations for each dimension. Within each block, we also included five situations describing five neutral events (e.g. a person washes clothes on weekends). Situations in each block were presented in pseudorandomized order.

Each situation was presented for 3 s. After reading each situation, participants reported the intensity of their 'displeasure' (for the envy block) or 'pleasure' (for the *Schadenfreude* block) regarding the character's situation. This stage lasted ~3 s (Fig. 2). All participants provided their responses using 9-point Likert scales, with 1 meaning 'low emotional intensity' and 9 meaning 'high emotional intensity'. In line with previous research on empathy and moral processing (Baez *et al.*, 2014*a*, *c*, 2016*c*; Patil and Silani, 2014; Carr *et al.*, 2015), the scales were always accompanied by simple words indicating low and high pleasure/unpleasantness, thus minimizing memory-related confounds while reducing attentional demands and improving comprehension. This procedure has been reported in multiple neuropsychiatric conditions (Brown and Cohen, 2010; Ibanez *et al.*, 2012; Baez *et al.*, 2015, 2016*a*, *c*), including neurodegenerative diseases such as bvFTD (Zamboni *et al.*, 2010; Eslinger *et al.*, 2012; Cohen *et al.*, 2016) and patients with Alzheimer's disease (Lai *et al.*, 2008; Tsoucalas *et al.*, 2015).

In our task, participants were asked to report their *Schadenfreude* and envy in terms of pleasure/displeasure given that these are the main overarching states elicited by each of those emotions. Previous studies have defined envy as: 'an *unpleasant*, often painful emotion characterized by feelings of inferiority, hostility, and resentment caused by an awareness of a desired attribute by another person or group of persons' (van Dijk *et al.*, 2006; Smith and Kim, 2007; Smith, 2009; Takahashi *et al.*, 2009; Dvash *et al.*, 2010*b*; Jankowski and Takahashi, 2014). Also, *Schadenfreude* has been formally defined as the pleasure derived from the misfortune of others, involving 'the expression of pleasure or self-satisfaction at another's failure' (van Dijk *et al.*, 2006; Dvash *et al.*, 2010*b*; Jankowski and Takahashi, 2014). Thus, we have used the terms 'pleasure' and 'displeasure' highlighting the critical emotional responses elicited by specific scenarios of envy and *Schadenfreude*. Also, explicit manifestations of envy and *Schadenfreude* are socially penalized (van Dijk *et al.*, 2006; Dvash *et al.*, 2010*b*; Jankowski and Takahashi, 2014) and,
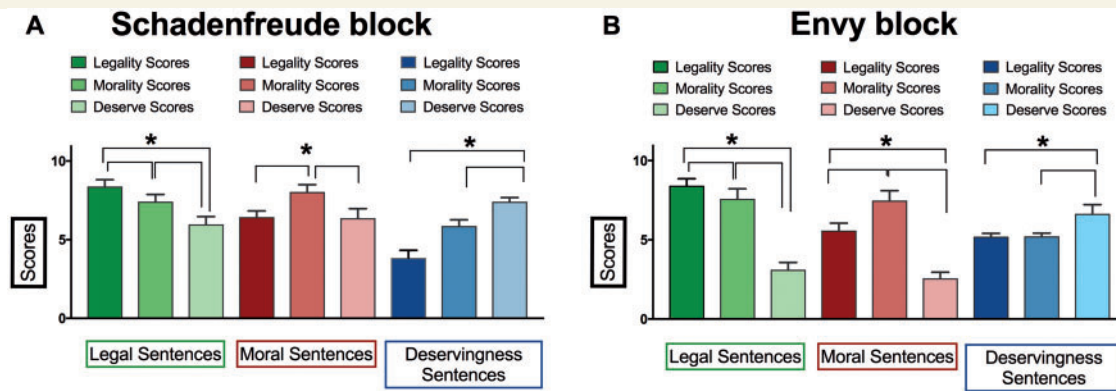
Figure 1 Scores for deservingness, morality, and legality for each group of situations (deservingness, moral, and legal) of each moral emotion (envy and *Schadenfreude*). Situations dominated by deservingness, morality, and legality are identified in green, red, and blue, respectively. (**A**) Scores for the *Schadenfreude* block; (**B**) scores for the envy block.

Figure 2 General task procedure. The *upper* panel shows a trial in the envy block and the bottom panel shows a trial in the *Schadenfreude* block. Participants first took part in the envy block and then performed the *Schadenfreude* block. In each block, participants read five situations (each lasting 3 s) in each dimension including a group of five neutral situations. In total, participants read 20 situations from each block, which were presented in randomized order. Next, participants reported the intensity of their 'displeasure' (for the envy block) or their 'pleasure' (for the *Schadenfreude* block) regarding the character's situation using a 9-point Likert scale with 1 meaning low, and 9 meaning high intensities.

hence, subjects might report lower levels of these emotions due to social desirability. Thus, our procedure circumvents such biases by avoiding explicit questions to explore social situations and inquiring into pleasure/displeasure, in line with previous methodological recommendations for exploring social and affective cognitive processes (Berkman *et al.*, 2014). In fact, asking about levels of pleasure/displeasure is the standard procedure reported in previous studies of envy and

Schadenfreude (Takahashi *et al.*, 2009; Baez *et al.*, 2016*c*, 2017*d*). We have adopted this design to make our results comparable with those of previous relevant literature. Note, also, that the terms 'pleasure' and 'displeasure' are easier to understand and thus more reliable than 'envy' and '*Schadenfreude*' as verbally cued measures. This is of critical relevance when assessing patients with such disorders as bvFTD and Alzheimer's disease.

Task comprehension assessment

Before the emotion task, bvFTD and Alzheimer's disease patients performed a pilot study involving situations with positive, negative, and neutral outcomes affecting a third person. Patients were asked to determine the type of valence (fortunate versus unfortunate) of each situation, which allowed us to assess general comprehension of situations while discarding potentially random response patterns. Relative to neutral situations, positive and negative situations were assigned higher and lower scores by both patient samples. These results suggest that patients discriminated the emotional valence of each situation type, showing that their performance was not biased by general comprehension difficulties (for details, see Supplementary material).

Data analysis

Demographic and cognitive state data were compared among groups using ANOVA and Tukey's honest significant difference *post hoc* tests. Chi square tests were applied to analyse categorical variables. Differences between types of emotion (envy, *Schadenfreude*, neutral) in each group (bvFTD patients, Alzheimer's disease patients, healthy controls) were first analysed using a 3×3 mixed repeated measures ANOVA. If any interaction among types of emotion and group was found, a second level of analysis was implemented for each emotion separately (*Schadenfreude*, envy, and neutral) and subsequently analysed with a one-way ANOVA using dimension (deservingness, morality, legality) as the within-subject factor and group (bvFTD patients, Alzheimer's disease patients, healthy controls) as the between-subjects factor. To control for the effect of general cognitive status on the experimental tasks, we applied ANCOVA tests independently adjusted for

total scores on the MoCA and the IFS batteries. In addition, we ran extra analyses controlling results on the experimental task for inhibitory control and theory of mind measures (Hayling test and RMET, respectively). As in other reports of neurodegenerative conditions from our group (Baez *et al.*, 2014c; García-Cordero *et al.*, 2016), we report only those effects that remained significant following covariation. Tukey's HSD *post hoc* tests were used when appropriate. Effect sizes were calculated through the partial eta squared (η^2) ratio.

Moreover, correlation analyses were used to explore the relationship between individual differences in disease presentation (regarding inhibitory control, theory of mind, and behavioural changes) and moral emotions (envy and *Schadenfreude*) in each group (bvFTD, Alzheimer's disease, healthy controls). A global score of envy (mean of deservingness, morality, and legality dimensions) and a global score of *Schadenfreude* were created to facilitate the analysis of the relationship between each moral emotion and the cognitive-behavioural measures. We also conducted correlational analyses with the scores for each dimension of both moral emotions.

Imaging recordings and voxel-based morphometry

Recordings were restricted to bvFTD and healthy control groups. Structural brain images were obtained using a Philips Achieva 3 T scanner with a 16-channel SENSE antenna. The anatomical and 3D T_1-weighted images had the following parameters: repetition time = 7.9 ms, echo time = 3.8 ms, ACQ matrix 220 × 220 pixels, voxel size 0.5 × 0.5 × 0.5 mm, 310 sections. Neuroanatomical correlates were analysed using VBM (Ashburner and Friston, 2000). Data processing and analysis were performed with VBM8 on the Statistical Parametric Mapping 8 package (SPM8; Wellcome Trust Centre for Neuroimaging, London, UK; http://www.fil.ion.ucl.ac.uk/spm), running under Matlab 2012 (MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, MA, USA). All imaging analysis steps were conducted as described in the VBM pipeline (http://www.fil.ion.ucl.ac.uk/~john/misc/VBM), as follows. The T_1-weighted images were normalized to the same stereotaxic space generated from the complete dataset using the DARTEL algorithm, which significantly reduces the imprecision of inter-subject recordings. The images were then segmented into white matter, and grey matter, and non-brain voxels (CSF). Subsequently, all images were modulated to correct volume changes by Jacobian determinants. Finally, images were smoothed by convolution with an isotropic 8-mm full-width Gaussian kernel at half maximum for statistical analyses.

First, we performed a whole-brain analysis using VBM to assess differences in brain atrophy between the group of patients with bvFTD and healthy controls (controlling for global intracranial volume, age, gender, and length of disease duration) (Supplementary Fig. 2). The statistical threshold for whole-brain analysis was defined as $P < 0.001$ (extent threshold = 50 voxels). In addition, to investigate potential, the association between brain areas and moral emotions, we performed a more restrictive analysis using a mask including the brain regions significantly associated with socio-moral cognitive processes and moral emotions (*Schadenfreude* and envy) (Supplementary Fig. 3). Then, using this mask, we performed

multiple regression analyses for each group using topological false discovery rate (FDR) for correction, at a threshold of $P < 0.05$ (Figs 5 and 6). The topological FDR was used following previous studies that suggest that this procedure is more sensitive than voxel-wise FDR (Chumbley *et al.*, 2010).

In assessing regions of atrophy as predictors of group performance in the experimental task, and following previous studies (Couto *et al.*, 2013; Baez *et al.*, 2016a), we restricted the data's multidimensionality using an extended mask that included the brain areas reported to be involved in social-moral cognition and moral emotions. The group of brain areas composing the mask was corroborated using the Neurosynth database (http://www.neurosynth.org). This meta-analytic database aggregates activation from thousands of previous functional MRI studies (Yarkoni *et al.*, 2011). This technique has been used to define main brain areas related to cognitive processes even in studies using imaging methods, including VBM (Vendetti and Bunge, 2014; Fermin *et al.*, 2016; Allen *et al.*, 2017). In Neurosynth online system we introduced as keywords: 'moral' and 'social cognition'. Afterwards, we downloaded the mask for both terms and integrated the brain areas selected in a single unified mask. This mask, following the Neurosynth database, includes a default correction for brain multiple comparisons using a FDR criterion of $P = 0.01$. In addition, we included basal ganglia in this mask considering its role in processing moral emotions, in particular *Shadenfreude* (Takahashi *et al.*, 2009). Furthermore, we also included bilateral frontal lobe as these brain areas are involved in inhibitory control (Collette *et al.*, 2001; Nathaniel-James and Frith, 2002; Roca *et al.*, 2010; Volle *et al.*, 2011) and are related to regulation of moral emotions (Koechlin, 2011; Rudebeck *et al.*, 2013). Therefore, we used an extended and unified mask including brain areas derived of two Neurosynth keywords (moral and social cognition), the basal ganglia, and frontal lobes. The final unified mask was smoothed with a standard $\sigma = 4$ mm isotropic Gaussian kernel (corresponding to full-width at half-maximum = 9.4 mm) following a procedure used in previous studies (Radua *et al.*, 2014; Scarpazza *et al.*, 2015).

In this study we used a mask that includes the ventromedial prefrontal cortex (VMPFC), the dorsolateral prefrontal cortex (DLPFC), the cingulate cortex (the anterior and posterior portions), the bilateral insula, the temporal lobes, bilateral angular gyrus, the superior and medial temporal gyri, the precuneus, the amygdala, the hippocampus, and the parahippocampus (socio-moral areas) (Moll *et al.*, 2008; Pievani *et al.*, 2011; Bzdok *et al.*, 2012; Ibañez and Manes, 2012; Chiong *et al.*, 2013; Baez *et al.*, 2016a; Santamaria-Garcia *et al.*, 2016; Sedeno *et al.*, 2016), areas involved in inhibitory control (in particular the frontal lobe) (Collette *et al.*, 2001; Nathaniel-James and Frith, 2002; Roca *et al.*, 2010; Eslinger *et al.*, 2011b; Volle *et al.*, 2011), and regions involved in moral emotions, including the anterior cingulate cortex and the ventral and dorsal striatum (Takahashi *et al.*, 2009; Dvash *et al.*, 2010a; Jankowski and Takahashi, 2014; Shamay-Tsoory *et al.*, 2014; van Dijk and Ouwerkerk, 2014; Baez *et al.*, 2016c, 2017d) (Supplementary Fig. 3). Considering that the different dimensions of *Schadenfreude* and envy (deservingness, moral and legal) could encompass different complex cognitive-affective and social constructs, we also analysed the brain-behaviour correlations using a whole-brain analysis to reveal other brain areas involved in processing specific dimensions of moral emotions (Supplementary Fig. 4).

Brain–behaviour associations

To detect distinctive neurocognitive correlates of moral emotions, we performed a two-step analysis based on regression models between moral emotion measures and brain volume. The VBM regression models were run for of each dimension of moral emotions independently. This procedure was applied to analyse which brain areas were exclusively associated to each dimension and which areas exhibited overlap between dimensions. We did not run all variables together in order to avoid collinearity.

First, both bvFTD patients and controls were included in a single set (all subjects) to increase behavioural variance and statistical power (Sollberger *et al.*, 2009; Irish *et al.*, 2014*a*; O'Callaghan *et al.*, 2016). This procedure has been also previously reported in studies exploring the structural correlates of social cognition in bvFTD (Melloni *et al.*, 2016; Sedeno *et al.*, 2016). In a second stage, aimed to assess the specific association between brain atrophy and potentially abnormal moral emotion performance, we conducted the same analysis only on bvFTD patients. Thus, we compared VBM findings first in a grouped set (all subjects) and later in the bvFTD group only. This two-step procedure addresses two critical requisites of the present study. First, as shown by previous studies (Irish *et al.*, 2012, 2014*b*; Kumfor *et al.*, 2013; Melloni *et al.*, 2016), the report of combined results between patients and healthy controls aims to tackle individual differences in VBM analyses while improving statistical power by increasing sample size, stability of VBM results, and consistency of the anatomical correlates of the cognitive measure analysed. Second, the study of a cognitive measure exclusively in bvFTD allows exploring which areas are critical for a particular cognitive process (Rorden and Karnath, 2004; García-Cordero *et al.*, 2016; Melloni *et al.*, 2016; Shahid *et al.*, 2017).

Results

General cognitive state and performance on cognitive control, behavioural, and social cognition measures

As expected, bvFTD patients were outperformed by controls on the IFS and the MoCA tests, but they did not differ significantly from patients with Alzheimer's disease (Table 1). BvFTD patients also obtained significantly lower scores than both other groups on the inhibitory control measure (Hayling B, Table 1). Furthermore, the Frontal System Behavioural Scale revealed that patients with bvFTD had significantly greater behavioural impairments than patients with Alzheimer's disease (Table 1). Finally, patients with bvFTD were also significantly more impaired than the other two groups on a social cognition measure (RMET), while patients with Alzheimer's disease performed worse than healthy controls (Table 1).

Moral emotions

An ANOVA between type of emotion (envy, *Schadenfreude*, neutral) and group (bvFTD, Alzheimer's disease, healthy

controls) revealed a main effect of type of emotion [$F(2,82) = 43.51$, $P < 0.0001$, $\eta^2 = 0.43$]. In all groups, *Schadenfreude* ($P < 0.01$) and envy ($P < 0.01$) situations were given higher scores than neutral situations. Also, we observed an interaction of group × type of emotion [$F(4,82) = 13.51$, $P < 0.001$, $\eta^2 = 0.19$]. This result allowed us to perform additional ANOVAs over each emotion type.

Schadenfreude

The ANOVA showed a main effect of dimension [$F(2,82) = 14.53$, $P < 0.001$, $\eta^2 = 0.13$], as deservingness showed lower scores than morality and legality. In addition analyses showed an interaction between dimension and group [$F(4,82) = 12.28$, $P < 0.01$, $\eta^2 = 0.22$]. *Post hoc* analyses (Tukey HSD, mean square = 12.5, *df* = 2) revealed higher scores across all three dimensions of *Schadenfreude* in bvFTD patients (Fig. 3A) than in patients with Alzheimer's disease (deservingness, $P = 0.001$; morality, $P = 0.03$; legality, $P = 0.004$) and healthy controls (deservingness, $P = 0.04$; morality, $P = 0.04$; legality, $P = 0.05$). No differences were observed between patients with Alzheimer's disease and healthy controls (deservingness, $P = 0.31$; morality, $P = 0.24$; legality, $P = 0.12$).
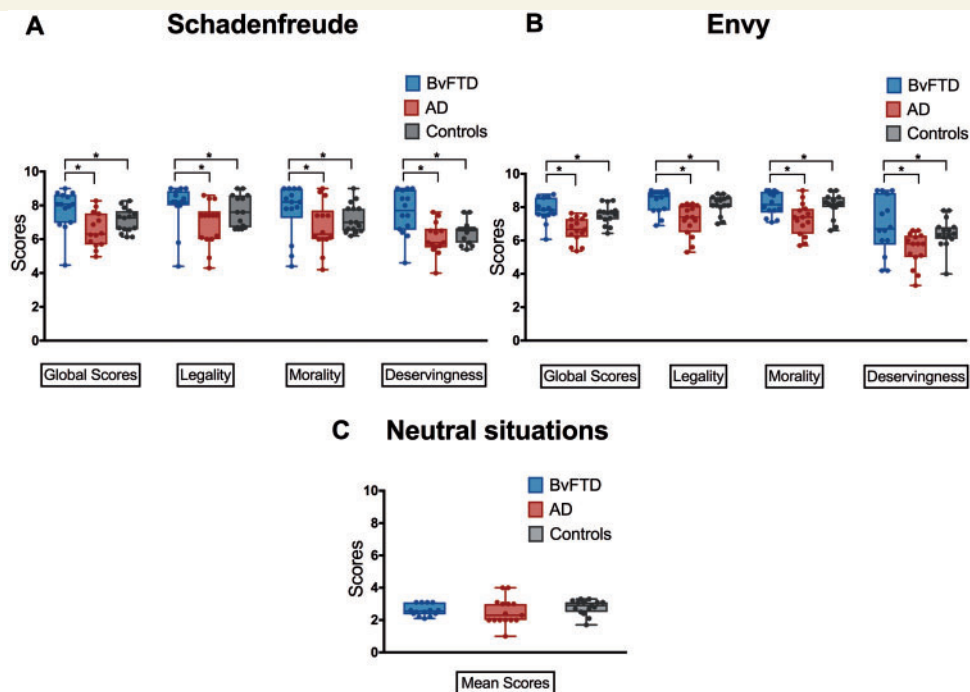
Envy

Envy scores were analysed using the same factors reported above for *Schadenfreude*. The analyses showed a main effect of dimension [$F(2,82) = 23.53$, $P < 0.0001$, $\eta^2 = 0.39$], as deservingness situations had lower scores than morality and legality; and an interaction between dimension and group [$F(4,82) = 22.38$, $P < 0.0001$, $\eta^2 = 0.52$]. *Post hoc* analyses of this last interaction (Tukey HSD, mean square = 12.5, *df* = 2) showed that bvFTD patients assigned higher scores for envy in the legal, moral and deservingness dimensions (Fig. 3B) than patients with Alzheimer's disease (deservingness, $P = 0.001$; morality, $P = 0.03$; legality, $P = 0.011$) and healthy controls (deservingness, $P = 0.05$; morality, $P = 0.043$; legality, $P = 0.031$). No differences were observed on any dimension between patients with Alzheimer's disease and healthy controls (deservingness, $P = 0.17$; morality, $P = 0.31$; legality, $P = 0.27$).

Neutral situations

No significant between-group differences emerged in the ratings for neutral situations [$F(2,82) = 0.89$, $P = 0.41$, $\eta^2 = 0.001$] (Fig. 3C).

Consistency of behavioural results among groups

Relative to controls, bvFTD and Alzheimer's disease patients evinced less consistent (i.e. more varied) scores across situations in both moral emotions (Supplementary

Figure 3 Dimensions of moral emotions in each group. (A) *Schadenfreude* results by group. **(B)** Envy results for each dimension by group. **(C)** Results for the neutral condition in each group. The whisker box plot depicts scores of each dimension in each group and the range of responses (depicted by dots) in each group. Each group was represented by different colours: bvFTD in blue; Alzheimer's disease (AD) in red, controls in grey. Asterisks depict significant differences at $P < 0.01$.

material). Nevertheless, no difference emerged between both patient groups.

Correlation analyses between moral emotions and cognitive-behavioural measures

Correlational analyses revealed that in bvFTD patients, the stronger experience of *Schadenfreude* (Fig. 4A), the least inhibitory control (Hayling test, $r^2 = 0.39$, $P < 0.05$), the greatest behavioural changes (Frontal System Behavioural Scale, $r^2 = 0.44$, $P < 0.01$), and the lowest theory of mind skills (RMET, $r^2 = -0.27$, $P < 0.05$). Similarly, higher envy was associated with reduced inhibitory control (Frontal System Behavioural Scale, $r^2 = 0.39$, $P < 0.05$; Fig. 4B) and theory of mind skills (RMET, $r^2 = -0.31$, $P < 0.05$). Correlational analyses for each specific dimension of *Schadenfreude* and envy did not reach significance (all P-values > 0.32). No associations were found in patients with Alzheimer's disease (all P-values > 0.24) or healthy controls (all P-values > 0.31).

Reanalysis of scores on the *Schadenfreude*, envy, and neutral situations with cognitive measures as covariates

Group differences in *Schadenfreude* [$F(2,82) = 5.34$, $P < 0.001$, $\eta^2 = 0.11$] and envy [$F(2,82) = 2.28$, $P < 0.05$, $\eta^2 = 0.07$] remained significant after adjusting for MoCA. Similarly, differences in *Schadenfreude* [$F(2,102) = 2.86$, $P < .05$, $\eta^2 = 0.06$], and envy [$F(2,102) = 3.18$, $P < 0.05$,

$\eta^2 = 0.07$] were preserved after covarying for Hayling scores. Finally, differences between groups in *Schadenfreude* [$F(1,59) < 7.1$, $P < 0.01$, $\eta^2 = 0.11$] and envy [$F(1,59) = 3.46$, $P < 0.05$, $\eta^2 = 0.04$] were also preserved after covarying for RMET scores.

## Atrophy in bvFTD patients: VBM results

Whole-brain analyses comparing the bvFTD group with healthy controls showed widespread bilateral atrophy predominantly involving the medial frontal cortex (MFC), the orbitofrontal cortex (OFC), the anteromedial temporal areas, the ACC, the bilateral insula, the basal ganglia, the right DLPFC, and bilateral medial frontal regions ($P = 0.001$, uncorrected) (Supplementary Fig. 1). Atrophy distribution was consistent with that reported in previous VBM studies (Rosen *et al.*, 2002; Kipps *et al.*, 2009; Seeley *et al.*, 2009; Whitwell *et al.*, 2009; Santamaria-Garcia *et al.*, 2016; Baez *et al.*, 2017c).

Structural neuroimaging of *Schadenfreude* and envy

Here we report the regression analyses ($P < 0.05$, FDR corrected) between each emotion (envy and *Schadenfreude*) for each dimension (deservingness, morality, and legality) and grey matter volume in all subjects (first step) and in bvFTD patients only (second step).
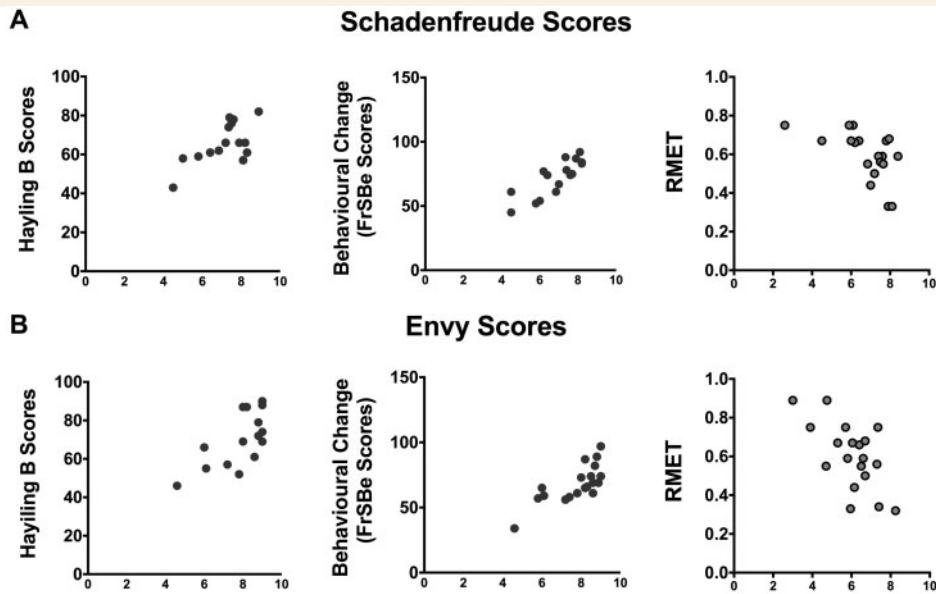
Figure 4 Correlations between moral emotions and individual bvFTD profiles. (**A**) Positive correlations between *Schadenfreude* scores and behavioural measures (behavioural changes tracked by FrSBE, inhibitory control tracked by the Hayling B test and social cognition tracked by RMET). (**B**) The same results are depicted for these behavioural scores and envy. FrSBe = Frontal System Behavioural Scale.
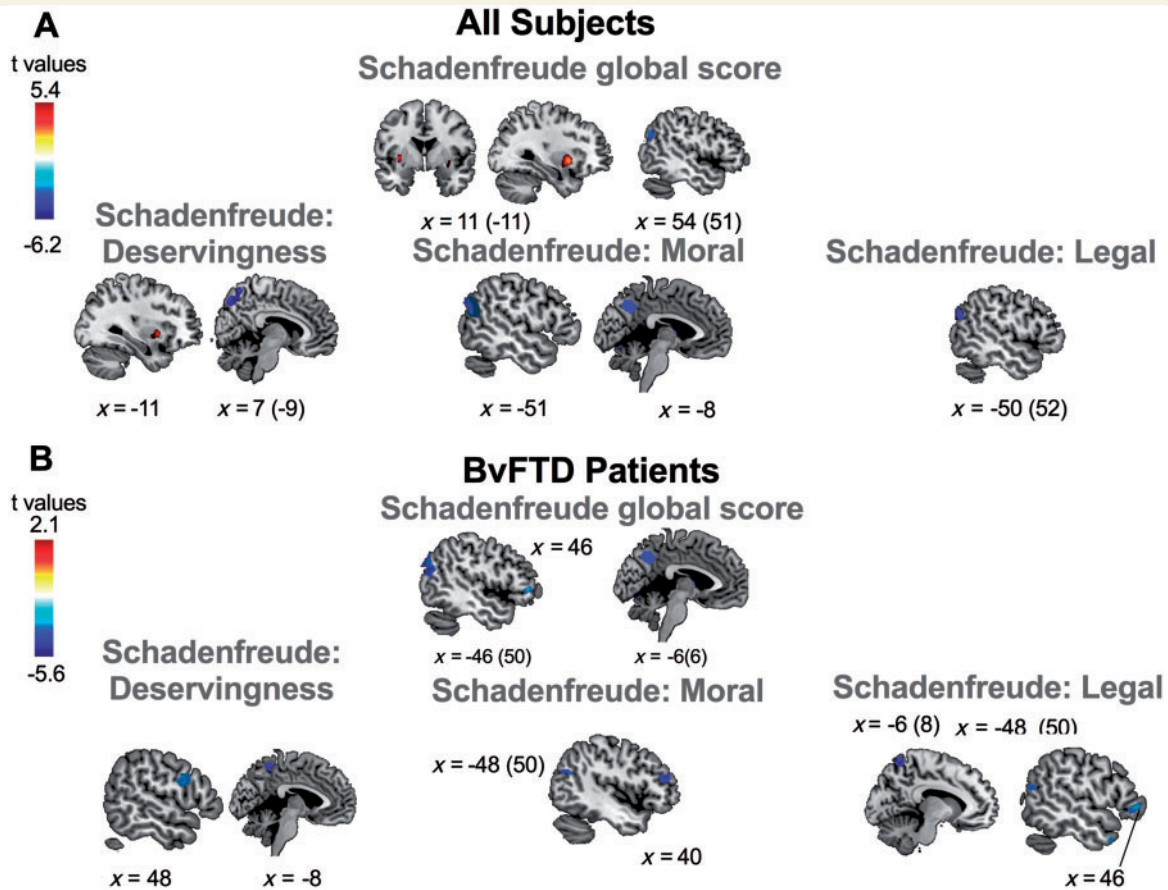
Figure 5 VBM analyses and *Schadenfreude* dimensions. VBM regression analyses within the brain areas associated with the social cognition network and moral emotion areas and the scores for each sub-dimension of *Schadenfreude*. (**A**) VBM analysis in all subjects. (**B**) VBM analysis in bvFTD patients only (in both cases, $P < 0.05$, FDR corrected).

Table 2 Association between grey matter volume and scores for each dimension of *Schadenfreude* and envy (FDR corrected at $P < 0.05$)

| Moral emotion by group analyses	Brain regions (+) (−)	Coordinates x, y, z {mm}	Cluster size	Peak T
Grouped *Schadenfreude*	Bilateral angular gyrus (−)	51 (−54)* 62 23	332	5.65
Mean	Right − left putamen (+)	28 (−27)* −6 −15	281	5.69
	Right − left Caudate (+)	10 −12 14 4	133	5.43
Grouped *Schadenfreude*	Bilateral precuneus	7 (−) 48 9	223	5.49
(deservingness dimension)	Right putamen (+)	28 −6 −15	281	5.39
	Right caudate (+)	10 14 4	133	5.43
	Bilateral angular gyrus (−)	−54 −64 24	382	5.43
Grouped *Schadenfreude*	Bilateral precuneus (−)	10 (−12)* 14 4	133	5.43
(moral dimension)	Bilateral angular gyrus (−)	52 (−54)* −64 24	822	6.16
Grouped *Schadenfreude*	Right frontal pole (−)	46 47 25	236	5.32
(legal dimension)				
BvFTD *Schadenfreude*	Bilateral precuneus (−)	6(−6) −63 47	510	5.13
Mean	Bilateral angular gyrus (−)	−46 (50)* −64 24	232	5.44
	Right DLPFC (−)	46 39 1	242	5.11
BvFTD *Schadenfreude*	Bilateral precuneus (−)	10 (−12) 14 4	222	4.38
(deservingness dimension)				
BvFTD *Schadenfreude*	Right frontal pole (−)	40 47 25	433	5.76
(deservingness dimension)	Bilateral angular gyrus (−)	50 (−48)* −64 24	394	5.23
	Right frontal pole (−)	46 42 2	638	5.33
BvFTD *Schadenfreude*	Bilateral precuneus (−)	8(−6) −48 9	523	5.44
(legal dimension)	Bilateral angular gyrus (−)	50 (−48)* −64 24	682	5.56
	Right ACC (+)	2 3 45	457	5.42
Grouped envy	Bilateral amygdala (+)	30 (−21)* −6 −15	134	5.43
Mean	Bilateral hippocampus (+)	16 (−19) −33 1	101	4.48
	Right ACC (+)	12 6 45	503	5.77
Grouped envy	Right DLPFC (−)	−51 39 1	346	5.66
(deservingness dimension)	Right ACC (+)	11 3 45	468	5.44
Grouped envy	Bilateral amygdala (+)	22 (−24)* −6 −15	381	5.88
(moral dimension)	Bilateral hippocampus (+)	16 (−19) −33 1	103	5.89
	Right ACC (+)	2 3 45	378	5.24
Grouped envy	Precuneus	−6 53 −30	328	4.32
(legal dimension)	Bilateral amygdala (+)	16 (−14)* −6 −15	317	4.12
	Bilateral hippocampus (+)	18 (−21) −33 1	564	4.09
BvFTD envy	Bilateral precuneus (−)	8 (−6) −56 39	127	4.57
Mean				
BvFTD envy	Right DLPFC (−)	−51 39 1	206	4.16
(deservingness dimension)				
BvFTD envy	Bilateral precuneus (−)	−5 (6) −48 9	323	3.94
(deservingness dimension)				
	Bilateral precuneus (−)	8 −6 −48 9	447	8.66
BvFTD envy (legal dimension)	Right ventromedial prefrontal cortex (−)	12 (−17)* −6 −15	210	4.43

*Left x-axis coordinates (MNI space).
(+) Positive associations between moral emotion scores and grey matter volume.
(−) Negative associations between moral emotion scores and grey matter volume.

The global score for *Schadenfreude* was positively associated with grey matter volume in the bilateral ventral striatum and negatively associated with the volume of the bilateral angular gyrus. *Schadenfreude* scores for the deservingness dimension were positively associated with grey matter in the dorsal striatum (left caudate and putamen) and negatively correlated to bilateral precuneus. Scores for moral *Schadenfreude* were negatively associated with the left angular gyrus and left precuneus. Legal *Schadenfreude* scores were negatively associated with bilateral angular gyrus (Fig. 5A and Table 2).

The global score for envy was positively associated with grey matter volume in the right ACC and with the volume of the bilateral amygdala and parahippocampus. Deservingness envy scores were positively associated with grey matter volume in the right ACC and negatively associated with the right DLPFC. In addition, moral and legal envy were positively associated with grey matter in the
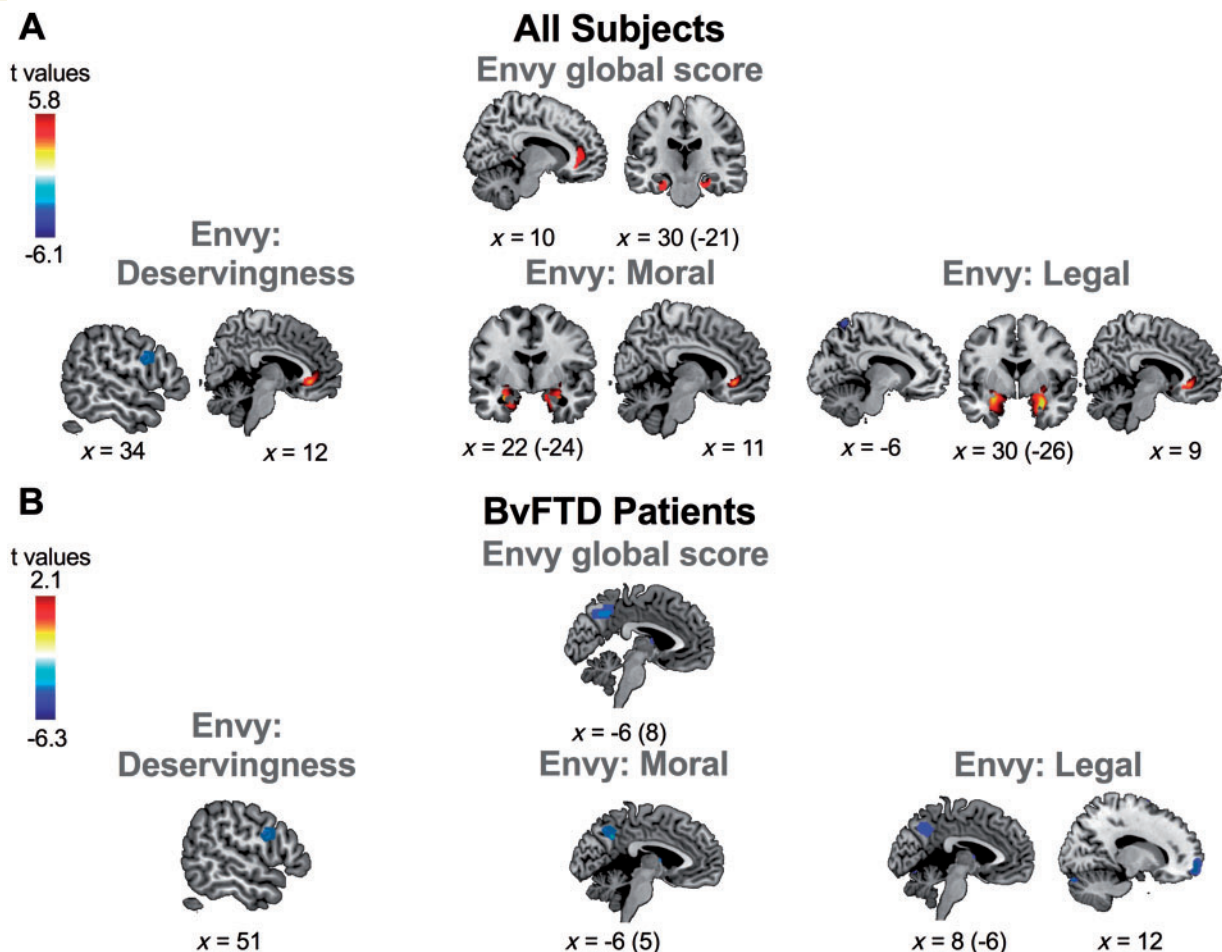
Figure 6 VBM analyses and envy. VBM regression analyses within the brain areas associated with the social cognition network and moral emotion areas and the scores for each sub-dimension of envy. (**A**) VBM analysis in all subjects. (**B**) VBM analysis in bvFTD patients only (in both cases, $P < 0.05$, FDR corrected).

right ACC and with the volume of the bilateral amygdala and parahippocampus (Fig. 6A and Table 2).

BvFTD patients

An exacerbated experience of *Schadenfreude* was associated with atrophy of the left angular gyrus and and precuneus. Increased *Schadenfreude* for the deservingness dimension was negatively associated with atrophy of the right DLPFC and the left precuneus. Enhanced moral *Schadenfreude* was negatively associated with the bilateral angular gyrus, and right frontal pole. Legal *Schadenfreude* scores were negatively associated with the bilateral angular gyrus, bilateral precuneus, and right frontal pole (Fig. 5B and Table 2).

Increased envy was correlated with reduced grey matter volume in the bilateral precuneus. Scores for the deservingness dimension of envy were negatively associated with grey matter volume of the right DLPFC. Moral envy scores were negatively associated with the volume of the right precuneus. Legal envy was negatively associated with

the volume of the right DLPFC and the right precuneus (Fig. 6B and Table 2).

The brain–behaviour association in patients with bvFTD remained similar even using a more general volumetric analysis (whole-brain analysis, Supplementary Fig. 4). This analysis revealed negative correlations between *Schadenfreude* and envy dimensions and a set of areas including the precuneus, the angular gyrus, the dorsolateral prefrontal cortex, and the frontal pole. In addition, using this analysis we observed an additional association between legal scores of *Schadenfreude* and the left superior parietal lobe (Brodmann area 7). Furthermore, regarding envy scores, (global score, moral, and legal dimensions), a positive association was observed with the bilateral amygdala and the parahippocampus. Also, other associations were observed beyond the regions included in the mask. Schadenfreude was associated with bilateral sensory association areas (deservingness, moral, and legal dimensions), the superior temporal lobe (global score), and the posterior cingulate cortex (legal dimension). In the same line, envy

was associated with the superior parietal lobe (global score), the left frontal area (deservingness dimension), sensory association areas (moral and legal dimensions), and the right supplementary motor area (legal dimension) (Supplementary Fig. 4 and Supplementary Table 1.

Analysis of envy and *Schadenfreude* dimensions controlling by inhibitory control and theory of mind

For mean scores of *Schadenfreude*, only the association between the mean scores and atrophy of the precuneus remain significant after covarying for Hayling test and RMET scores. The negative association between *Schadenfreude* for the deservingness dimension and atrophy of the precuneus and DLPFC was preserved after controlling for such two measures. For moral *Schadenfreude*, only the negative association with atrophy of the angular gyrus survived the correction analyses, as the negative association with dorsolateral prefrontal cortex disappeared. Legal *Schadenfreude* scores remained associated with atrophy of the precuneus and the angular gyrus. As in the case of moral *Schadenfreude*, the negative association with frontal areas disappeared after covarying for RMET and Hayling scores (Supplementary Fig. 5 and Supplementary Table 2).

Increased envy remained negatively associated with reduced grey matter volume in the precuneus after correction for Hayling and RMET measures. The negative association between DLPFC and deservingness envy was preserved after covarying with Hayling and RMET scores. Moral envy scores remained negatively associated with the volume of the right precuneus after controlling for Hayling and RMET scores, too. The same was true for legal envy, although the negative association between this dimension and the ventromedial prefrontal cortex disappeared after covariation (Supplementary Fig. 5 and Supplementary Table 2).

Discussion

This study relied on a neurodegenerative lesion model (bvFTD) to offer the first examination of the neuroanatomical signatures of three key dimensions of *Schadenfreude* and envy (deservingness, legality, and morality).

Results supported our behavioural hypothesis. Healthy controls showed more emotional responses in situations with prominent moral and legal components compared to deservingness situations. Similarly, bvFTD patients experienced exacerbated degrees of envy and *Schadenfreude* relative to the other two groups. Results also provide support for the partially differentiated but overlapped dimensions of moral emotions (Hamann, 2012; Lindquist *et al.*, 2012, 2013). These contextual differences in emotional responses between domains (deservingness, moral and legal) were supported by several findings. First, although the type of situations seem to elicit different degrees of emotional responses, all of them elicit pleasure in the context of *Schadenfreude* and displeasure in the context of envy

situations. Second, those situations showed only partially dissociable brain patterns. Third, they seem to be related to different cognitive processes, as shown by correlations between moral emotion scores and scores in the theory of mind task and the Hayling test.

Regarding the neuroanatomical hypothesis, present results confirmed the critical role of the striatum in *Schadenfreude* and of the ACC in envy, while showing additional involvement of temporo-parietal regions related to social and moral cognition processes. Our results also provide evidence of a convergent pathway for the legal and moral dimensions, but not for deservingness, which involves parietal regions in the case of *Schadenfreude* and anterior temporal regions for envy.

Moral dimensions across groups

Relative to patients with Alzheimer's disease and healthy controls, patients with bvFTD had increased scores for all dimensions of envy and *Schadenfreude*. Moreover, an increased experience of *Schadenfreude* and envy in bvFTD was associated with alterations in social cognition, executive functions, and behavioural disturbances reported in those patients. Specific analyses revealed that the legal and moral dimensions elicited higher scores than the deservingness dimension in all groups. These results suggest that envy and *Schadenfreude* are multi-dimensional emotions, in agreement with the notion that they can be elicited by a broad spectrum of social situations, dominated by feelings of deservingness but also (and especially) by notions of justice linked to moral and legal conventions (Shamay-Tsoory *et al.*, 2007; Kipps *et al.*, 2009; Jankowski and Takahashi, 2014). Judgements of moral and legal rightness recruit high emotional resources and require more pacing between cognitive and emotional processes (Moll *et al.*, 2003; Moll and de Oliveira-Souza, 2007). Such processes are highly rooted in our cognitive systems and require special moral assessment, punishment evaluation, and semantic knowledge of a particular action (Moll *et al.*, 2003; Moll and de Oliveira-Souza, 2007).

Our results are consistent with these previous findings, as they show enhanced emotional experience for fortunate or unfortunate situations that occur to other individual in both the moral and legal dimensions. Interestingly, our results also show that even in bvFTD patients, who exhibit various executive, emotional, and socio-cognitive alterations, judgements over morality and legality invoke higher emotional responses compared to deservingness (Supplementary material). Given the social and moral transgression in bvFTD (de Oliveira-Souza *et al.*, 2008; Mendez, 2010; Baez *et al.*, 2014a, 2016a; Liljegren *et al.*, 2015), exacerbated emotional responses can be expected in these patients irrespective of the type of situations presented to elicit displeasure/envy.

The source of displeasure and envy facing moral and legal situations seems to be different from the source of displeasure for the purer deservingness situations. For

moral and legal situations, displeasure and envy are probably associated to implicit inequity produced by an apparent success that the receptor achieves by avoiding sanctions in punishable situations. By contrast, for deservingness situations, the source of displeasure and envy are directly related to the receptor's success in obtaining a desirable outcome. Thus, by exploring those differential dimensions of moral emotions, we have shown that scenarios featuring moral, legal, and deservingness situations can trigger different processes related to envy. Our design does not allow clarifying whether the displeasure reported in all envy scenarios (including deservingness, moral, and legal situations), is generated by the degree of desirability of each situation a priori, or by the third-party outcome described in each situation. Future studies should explore these questions and assess to what extent an undesirable situation modulates moral emotions and evokes other emotional responses.

Structural brain signatures of experiencing moral emotions in all subjects

First, through a combined analysis between bvFTD patients and healthy controls, we aimed to tackle individual differences in VBM analyses. The VBM analyses in all subjects showed that global *Schadenfreude* scores were positively associated with the volume of the striatum, confirming functional MRI evidence (Takahashi *et al.*, 2009; Jankowski and Takahashi, 2014). In addition, our analyses showed that brain signatures of *Schadenfreude* go beyond the striatum, as reduced grey matter volume of the bilateral angular gyrus was negatively associated with the moral and legal *Schadenfreude* dimensions. By contrast deservingness was related with the right caudate and putamen but also with bilateral precuneus. The angular gyrus has been reported as a crucial area involved in moral judgements (Moll *et al.*, 2005) and in the processing of third-party moral and legal judgements (Raine and Yang, 2006). In addition, regarding to precuneus, previous studies have associated this area to mentalizing abilities and socially valued decision-making processes (Bzdok *et al.*, 2012; Schlaffke *et al.*, 2015; Niemi *et al.*, 2017). The precuneus has been reported as impaired in bvFTD patients (Ibañez and Manes, 2012; Devenney *et al.*, 2014; Baez *et al.*, 2017c). Thus, *Schadenfreude* would not only involve reward-related regions, but also more extended networks indexing moral and legal dimensions of this emotion.

Regarding envy, we provide the first lesion-based evidence of a positive association with the volume of the right ACC in all subjects, as previously reported with functional MRI (Takahashi *et al.*, 2009; Cikara and Fiske, 2013; Jankowski and Takahashi, 2014). This region is modulated by threat of self-concept, similar to cognitive dissonance (Moll *et al.*, 2005), or social pain (similar to social exclusion) (van Veen *et al.*, 2009). In addition, the grouped analysis showed an association between bilateral the parahippocampus and amygdala with the moral and legal dimensions (deservingness was negatively associated with the right DLPFC). Both regions (parahippocampus and amygdala) are engaged in emotional appraisal (Levenson *et al.*, 2014) and during unfair social comparisons (Jankowski and Takahashi, 2014; O'Callaghan *et al.*, 2016). The amygdala seems to be a critical region for the early detection of the basic mosaic of moral evaluation [i.e. intention to harm (Hesse *et al.*, 2016)]. Furthermore, previous studies have reported abnormal amygdala volume in subjects who engage in antisocial behaviours (Raine and Yang, 2006; Yang *et al.*, 2009). In this report, envy scores were obtained by asking subjects about the level of displeasure they feel in deservingness, moral, and legal situations. The positive correlation between the volume of the amygdala/parahippocampus and scores of envy facing moral and legal situations fits well with previous studies reporting associations between the volume of the amygdala/paralimbic cortex and self-reported displeasure in emotion tasks (Vicario *et al.*, 2017).

Neurocognitive correlates of moral dimensions in bvFTD

We also analysed results from the bvFTD group alone, which afforded a lesion model to explore which areas are critical for the cognitive process targeted in our task. Most of the brain-behaviour correlations for envy and *Schadenfreude* in bvFTD patients remain significant after covarying for Hayling and RMET scores (Supplementary Fig. 5 and Supplementary material). These results suggest that exacerbation in moral emotions in bvFTD is not a simple manifestation of social and behavioural disturbances, but rather a new expression of the social and affective deregulation in bvFTD. Moreover, the whole brain analyses in bvFTD confirmed a similar pattern of associations plus additional relevant regions (Supplementary material).

Schadenfreude

In bvFTD patients, the increased experience of *Schadenfreude* was associated with reduced volume in the bilateral angular gyrus and precuneus, and in the right frontal pole. Furthermore, as in the grouped analyses, we found a dissociable pattern between *Schadenfreude* dimensions. Deservingness showed a negative association with volume of the right DLPFC and the precuneus. These regions subserve social decision-making, moral cognition and mentalizing skills (Lieberman, 2007) and are disrupted in bvFTD (Kipps *et al.*, 2009). Thus, higher experience of *Schadenfreude* in situations of deservingness would be related to disrupted social decision-making and moral-mediated behaviours.

Higher scores for the moral dimension were associated with a volume reduction of the bilateral angular gyrus, and the right frontal pole, while increased legal scores were

associated with reduced volume of the bilateral angular gyrus, the right precuneus and the right frontal pole. These structures are activated during processing of emotionally salient stimuli and moral judgements (Moll *et al.*, 2005), and are related to social cognition impairments in bvFTD (Bertoux *et al.*, 2012; Ibañez and Manes, 2012; Couto *et al.*, 2013; Bertoux *et al.*, 2014; Baez *et al.*, 2016*a*). In fact *Schadenfreude* implies implicit self-other comparison of mental states (Shamay-Tsoory *et al.*, 2007). In bvFTD, an impaired long-term self-other's perspective integration is observed (Melloni *et al.*, 2016). Accordingly, higher *Schadenfreude* scores in patients with atrophy in those social cognition regions support the gap between *Schadenfreude* and mentalizing skills (this interpretation is also supported by the negative correlation found between *Schadenfreude* and theory of mind).

Envy

BvFTD patients presented a negative association between envy and bilateral precuneus. In addition, a dissociable brain pattern was found between envy dimensions in this group. Scores for envy situations dominated by deservingness score (as in the case of *Schadenfreude*) were negatively associated with the DLPFC, further supporting the converging role of this area in high level social cognition in bvFTD. The envy elicited in the moral dimension in bvFTD patients was associated with volume reduction the precuneus, a region related to the interplay between mentalizing abilities and social decision-making (Bzdok *et al.*, 2012), and affected in bvFTD (Ibañez and Manes, 2012). Feelings of envy associated with mentalizing involve precuneus engagement for immoral and illegal scenarios (Yamada *et al.*, 2012; Baez *et al.*, 2016*a*). Finally, scores for the legal dimension of envy were negatively associated with volume in the right VMPFC and the right precuneus. The VMPFC is engaged in scenarios with possible negative social consequences (Moll *et al.*, 2005; Shamay-Tsoory *et al.*, 2007). Arguably, reduced volume of this area in bvFTD may be associated to high scores for legal contexts, as these kinds of situations arguably recruit more emotional and cognitive resources.

The relevance of studying moral dimensions in bvFTD

Most of the reported anatomical pathways of *Schadenfreude* (ventral striatum, DLPFC, and frontal pole), and envy (ACC, prefrontal cortex, the parahippocampus, and the amygdala) correspond to targets of atrophy in bvFTD, namely, fronto-temporal (Piguet *et al.*, 2011; Tosun *et al.*, 2012; Sedeno *et al.*, 2016) and striatal regions (Pan *et al.*, 2012; Bertoux *et al.*, 2015). Also, other relevant structures, such as the posterior cingulate cortex, medial temporal lobe, and parietal regions, has been associated with this condition (Supplementary material).

Our results pave the way for comprehending the interplay between more complex and ecological emotions and other cognitive processes affected in bvFTD. First, the increase in moral emotions, also considered as counter-empathy emotions, aligns with previous studies showing disruptions in social and morally determined behaviours, such as impairments in affective sharing (Eslinger *et al.*, 2011*a*; Kumfor *et al.*, 2013; Baez *et al.*, 2014*c*, 2016*b*; Melloni *et al.*, 2014; Kamminga *et al.*, 2015; Sturm *et al.*, 2015; Van den Stock *et al.*, 2015; Hutchings *et al.*, 2017), alterations in perspective taking and the more cognitive sides of empathy (Baez *et al.*, 2014*c*, 2016*b*; Dermody *et al.*, 2016; Ibanez *et al.*, 2016; O'Callaghan *et al.*, 2016; Ibanez *et al.*, 2017; O'Callaghan and Hornberger, 2017), and diminished motivation for prosocial behaviours (Moll *et al.*, 2011; O'Callaghan *et al.*, 2016), alongside of a disruption in processing moral judgements (Baez *et al.*, 2014*a*, 2016*a*) and an increase in immoral and illegal behaviours (de Oliveira-Souza *et al.*, 2008; Mendez, 2010; Liljegren *et al.*, 2015). The impaired moral emotions in bvFTD observed in the present results can be related to affective deregulation; to the relationship between basic emotion impairments and moral cognition; or to behavioural disturbances in these patients (Supplementary material).

Moreover, recent studies on bvFTD have shown that patients exhibit deficits in integrating self-perspectives with those of others and rewarding benefits (Melloni *et al.*, 2016; O'Callaghan *et al.*, 2016; Ibanez *et al.*, 2017). These impairments are associated with impairments in frontotemporal structures. The integration of self-preferences with the outcomes of another person seems to be a crucial aspect of the *Schadenfreude* and envy (Jankowski and Takahashi, 2014; Fontenelle *et al.*, 2015). Deficits in assessing self and other perspectives in bvFTD might abnormally enhance moral emotions irrespective of their positive/pleasant valence (as in the case of *Schadenfreude*) or negative displeasing valence (as in the case of envy).

Previous authors have suggested that although compliance with basic social norms can be maintained in bvFTD, more complex normative behaviours (prosociality or behaviour modulation in function of social information) that require integration of social contextual information are usually disrupted in this condition (O'Callaghan *et al.*, 2016; Baez *et al.*, 2017*a*). Thus, higher emotional scores for both *Schadenfreude* and envy seen in bvFTD patients could be related to impulsive behaviours, such that patients fail to integrate the implicit social information present in emotional situations with different social normative challenges.

Nonetheless, our results suggest that the exacerbation in moral emotions in all categories in bvFTD is not fully explained by social cognitive and executive deficits. In fact, responses in moral emotions in bvFTD patients remain preserved after controlling for inhibitory (Hayling test) and social cognitive measures (RMET). The exacerbation of moral emotions in bvFTD seems to be a partially

independent and new hallmark of the disruption of social, behavioural, and affective processes in bvFTD.

Taken together, the above alterations seem related to deficits in the integration of social contextual information seen in bvFTD, arguably due to deficits in the frontal-temporo-insular network (Ibañez and Manes, 2012; Baez *et al.*, 2017*a*). The bvFTD emerges as a relevant lesion model tapping into the 'mystery of frontal lobes' (Burgess *et al.*, 2009): patients provide accurate responses to abstract, isolated and decontextualized cognitive tasks, but they typically fail in more ecological paradigms demanding a combination of cognitive, affective, and social processes (Ibañez and Manes, 2012; Melloni *et al.*, 2014; Baez *et al.*, 2017*a*). Such social contextual deficits would lie at the core of the behavioural, socio-moral, and emotional impairments observed in bvFTD. Future studies should further explore the links between specific compromise of the social context network and moral emotions.

Limitations and further assessments

Our study has some limitations. First, diagnosis in our patient sample was based on established clinical assessments, but it lacked pathological confirmation. However, such confirmation is not required for diagnosis at the probable level, as shown in several studies (Rascovsky *et al.*, 2011; Chiong *et al.*, 2016; García-Cordero *et al.*, 2016; Melloni *et al.*, 2016; Sedeno *et al.*, 2016; Ahmed *et al.*, 2017). Moreover, we have followed international standards (Knopman and Roberts, 2011; Piguet *et al.*, 2011; Rascovsky *et al.*, 2011), as diagnosis was performed in a memory clinic after deliberative consensus by a highly experienced group composed of geriatricians, neurologists, neuropsychologists, and psychiatrists (Baez *et al.*, 2014*a*, 2016*b*; García-Cordero *et al.*, 2016; Melloni *et al.*, 2016; Sedeno *et al.*, 2017). In particular, all diagnoses were performed following criteria by (Rascovsky *et al.*, 2011), for probable bvFTD patients, and international criteria (McKhann *et al.*, 2011), for patients with Alzheimer's disease.

Second, our approach did not allow us to assess the relationship between envy and *Schadenfreude* dimensions with other cognitive processes, including reward processing, and other social cognitive processes such as emotional sharing (e.g. empathy). Further studies should explore the particular relationship between dimensions of moral emotions and their relationship with cognitive processes including social reward and socio-cognitive skills (including perspective taking and affective sharing), moral judgement, and cognitive control among other processes.

Third, we compared the behavioural responses of bvFTD patients to moral emotions relative to those of a contrastive lesion model (Alzheimer's disease), to control for task comprehension problems associated with neurodegeneration. Future studies should explore the brain correlates of processing those emotions in Alzheimer's disease (as well as other neurodegenerative conditions) to fully comprehend the role of other brain areas usually impaired across neurodegenerative conditions. Although our study did not include VBM analysis of patients with Alzheimer's disease, several reasons attest to the validity of the neurocognitive pattern observed in bvFTD (Supplementary material). Despite these considerations, future studies should evaluate the degree of atrophy specificity by comparing bvFTD with other conditions, such as Alzheimer's disease, other forms of FTD, and Huntington's disease (another neurodegenerative condition associated with moral emotion impairments (Baez *et al.*, 2017*d*).

Finally, we only found correlations between global scores of moral emotions and measures tracking social, cognitive, and behavioural impairments in bvFTD. Since this relationship was only reported with global scores, we do not know to what extent performance on each sub-dimension of envy and *Schadenfreude* is related to other cognitive and behavioural dimensions in bvFTD. Further studies should explore the extent to which the deservingness and moral-legal dimensions are related to specific cognitive and behavioural processes. The relationship between recognition and third-party evaluation of moral and legal situations and social cognitive processes (including empathy, emotion perception, and social decision-making) represents a promising avenue for future research.

Conclusions

Classical theoretical approaches have hinted at the multidimensional nature to the moral emotions of envy and *Schadenfreude*. Those earlier theories suggested that moral emotions are complex cognitive and affective states that, depending on the circumstances, may be considered the worst evil emotions (Schopenhauer 1788–1860) or, alternatively, good-natured emotions based on principles of fairness (Nietzsche 1844–1900). Together, our results provide unprecedented evidence of an exacerbated experience of moral emotions in bvFTD, while reinforcing the multidimensional nature of envy and *Schadenfreude*. Our results highlight the importance of analysing new and more ecological moral emotions in this population, with a view to examining relevant interactions between cognitive, moral, and emotional processes. In addition, our study reveals a new behavioural profile in bvFTD, which may help clinicians identify patients with neurocognitive disorders with mixed cognitive and behavioural alterations.

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Supplementary material

Supplementary material is available at *Brain* online.

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