Supplementary Material

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

Hernando Santamaría-García, Sandra Baez, Reyes Pablo, José A. Santamaría-García, José M. Santacruz-Escudero, Diana Matallana, Analía Arévalo, Mariano Sigman, Adolfo M. García, Agustín Ibáñez.

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1. Supplementary Methods

1.1. Stimuli:

Here we presented the full battery of situations in English of the scenarios for each situation (legality, morality, deservingness, for both envy and *Schadenfreude*).

Envy situations:

Deservingness

She/he got a good grade on the exam although she/he did not study.

She/he achieved sports recognition although she/he did not train.

She/he got a raise because she/he is friends with the boss.

She/he won the lottery but is the son of a multi-million dollar family.

She/he managed to get accepted at the University because she/he is the son/daughter of the Dean.

Morality

She/he avoided cueing for two hours at the bank by simulating a disability.

She/he claimed the work of an employee as his own and received a promotion.

She/he won the race after pushing her/his rival.

She/he got the best student award although she/he cheated in the exams.

She/he received government grants even though she/he has a high salary.

Legality

She/he went on vacation with the money she/he saved by evading taxes.

She/he got a meritory grade despite plagiarizing the thesis.

She/he avoided a fine by bribing the police officer.

She/he bought a luxury cell phone with the money he stole from her/his brother.

She/he got big life insurance after poisoning her husband.

Neutral situations

She/he bought a bag to store the clothes.

She/he read the latest news in her/his favorite newspaper.

She/he cleaned the bathroom and the kitchen of the house.

She/he turned off the light and closed the door before leaving home.

She/he took a shower in her/his house before going to work took.

Schadenfreude

Deservingness

She/he smeared the suit with wine while mocking a woman/man for being fat.

She/he came drunk to the exam and failed.

She/he presumed to be the best speaker and failed at the conference.

She/he was punished at work for being late every day.

She/he was excluded from her/his group of friends after discovering that she/he told lies.

Morality

She/he hit the dog with a stick and the dog bit her/him

He pretended to have success with the opposite sex until her/his partner discovered her/him being unfaithful.

She/he cheated on a test and she/he was expelled.

She/he tried to get on a bus without paying and the other passengers accused her/him with authorities.

She/he fell down trying to skip the metro register.

Legality

She/he was discovered as being corrupt and he/she was denounced.

She/he was fined for driving under the influence.

She/he tried to cheat an older person and the police discovered her/him.

She/he crashed her/his car after crossing a red light.

She/he was penalized and had her/his Facebook account closed after posting inappropriate photos.

Neutral situations

She/he mowed the lawn of his yard last month.

She/he turned on the light to search for her/his glasses.

She/he searched for an Internet address and wrote it down in his notebook.

She/he locked the door before going to bed.

She/he brushed her/his teeth after eating.

1.2 Experimental task

Validation of legal, moral and deservedness dimensions in *Schadenfreude* and envy blocks

For each emotion type (*Schadenfreude* and envy), we created situations which emphasized specific dimensions, namely, (1) deservingness, (2) morality, and (3) legality. Five situations were created for each domain in each emotion type. A group of 82 participants (22 females), between 22 and 59 years old (mean age 44 years), rated each situation on a 10-point Likert scale according to their (1) degree of deservingness (to what extent this sentence raises a situation of deservingness?); (2) degree of morality (to what extent does this sentence describe a situation with moral implications?), and (3) degree of legality (to what extent does this sentence describe a situation with legal implications?). Results are shown in methods sections and Figure 1 in the main text.

Schadenfreude dimensions

An ANOVA using content (scores of deservedness, morality and legality) and type of situations (deservingness, moral and legal) as within-subject factors showed a main effect of content ($F(2, 161)$

= 17.59, $p < .001$, $\eta2 = .37$) and an interaction between content and situation ($F(4, 161) = 26.93$, $p < .0001$, $\eta2 = .42$). Post-hoc analyses revealed differences in content for each type of situation.

Deservingness situations: Post-hoc analyses (Tukey HSD, MS = 277.6, *df* = 4) showed higher scores for deservingness than for morality ($P < .05$) and legality ($P < .01$) in this group of situations. No differences were observed between morality and legality scores in this group of situations ($P > .2$).

Moral situations: Post hoc analyses (Tukey HSD, MS = 277.6, *df* = 4) showed higher scores for morality than for deservingness ($P < .01$) and legality ($P < .01$) in this group of situations. No differences were observed between deservingness and legality scores in this group of situations ($P > .2$).

Legal situations: Post hoc analyses (Tukey HSD, MS = 277.6, *df* = 4) showed higher scores for legality than for morality ($P < .05$) and deservingness ($P < .01$) in this group of situations. No differences were observed between deservingness and morality scores in this group of situations ($P > .3$).

Envy dimensions

Following the same type of analyses used for *Schadenfreude*, we ran an ANOVA using content (scores of deservedness, morality and legality) and type of situation (deservingness, moral and legal) as within-subject factors. Analyses revealed a main effect of content ($F(2, 161) = 11.12$, $P < .001$, $\eta2 = .31$), a main effect of situation ($F(2, 161) = 17.59$, $P < .001$, $\eta2 = .66$) and an interaction between content and situation ($F(4, 161) = 26.93$, $P < .001$, $\eta2 = .46$). Post-hoc analyses revealed the expected differences in content by each type of situation.

Deservingness situations: Post hoc analyses (Tukey HSD, MS = 133.4, *df* = 4) showed significantly higher content scores for deservedness than for morality ($P < .03$) and legality ($P < .01$). No differences were observed for scores between morality and legality content ($P > .2$).

Moral situations: Post-hoc analyses (Tukey HSD, MS = 133.4, *df* = 4) showed higher scores for morality than for deservingness ($P < .01$) and legality ($P < .01$) content. In addition, post-hoc analyses also showed higher scores for legality than for deservingness in this group of situations ($P < .05$).

Legal situations: Post-hoc analyses (Tukey HSD, MS = 133.4, *df* = 4) showed higher scores for legality content than for deservingness ($P < .01$) and morality ($P < .01$) in this group of situations. Post hoc analyses also showed higher scores for morality than for deservingness ($P < .05$).

Together, group results for envy and *Schadenfreude* dimensions confirm that the situations constructed

to elicit differential levels deservingness, morality, and legality were effective at doing so.

Validation of emotional profile of *Schadenfreude* and envy situations

A group of 39 subjects (18 females), with a mean age of 42 ($SD = 8$) and 15.7 years of education in average ($SD = 3.1$), rated the emotion evoked by each situation presented. Participants rated each situation, including neutral ones, on a 10-point Likert scale according to how much the situations evoked (i) a general emotional state (pleasure/displeasure); (ii) the target moral emotions, namely, *Schadenfreude*/envy; and (iii) other socio-moral emotions, such as pride/guilt (see (Jankowski and Takahashi, 2014)). In particular, for *Schadenfreude*, participants were required to score the situations according to how much the situations evoked (a) pleasure, (b) *Schadenfreude*, and (c) pride. As regards envy, participants rated the situations in terms of how much they induced (a) displeasure, (b) envy, and (c) guilt.

Emotional profile evoked by each group of situations for each type of emotion:

Schadenfreude emotional profile

We evaluated the degree of different types of emotions (including pleasure, *Schadenfreude*, and pride) evoked by deservingness, moral, legal, and neutral situations. An ANOVA using type of emotions and situation type as within-subject factors showed a main effect of situation type ($F(4, 152) = 47.17$, $p < .0001$, η2 = .54) and type of emotion ($F(2, 76) = 30.22$, $p < .0001$, η2 = .44), alongside an interaction between both factors ($F(8, 304) = 9.75$, $p < .0001$, η2 = .2). The post hoc analyses (Tukey HSD, MS = 304.1, $df = 8$) revealed a similar pattern as the ratings for pleasure and *Schadenfreude* were higher for deservingness, moral and legal situations compared to the scores for those emotions in neutral situations (all ps < .01). For deservingness, moral, and legal situations, the post-hoc analyses (Tukey HSD, MS = 304.1, $df = 8$) revealed a similar pattern. Post hoc analyses showed higher scores for pleasure than for *Schadenfreude* ($p < .01$) and pride ($p < .01$). *Schadenfreude* showed higher scores than pride ($p <. 01$) (see Supplementary Figure 1).

Envy emotional profile

We followed the same type of analyses used for *Schadenfreude* but in this case we evaluated different types of emotions (displeasure, envy, and guilt) evoked by different situation types including deservingness, moral, legal, and neutral scenarios. Analyses revealed a main effect of situation type ($F(4, 152) = 67.56$, $p < .0001$, η2 = .82) and type of emotion ($F(2, 76) = 62.21$, $p < .0001$, η2 = .81), alongside an interaction between situation type and type of emotion ($F(8, 304) = 18.75$, $p < .0001$, η2 = .5). The post hoc analyses (Tukey HSD, MS = 304.1, $df = 8$) revealed that the ratings for displeasure and envy were higher for deservingness, moral, and legal situations in comparison with emotional scores assigned in neutral situations ($p < .01$) For deservingness, moral, and legal situations, the post-hoc analyses (Tukey HSD, MS = 304.1, $df = 8$) revealed a similar pattern, with higher scores for

displeasure than for envy ($p < .01$) and guilt ($p < .01$). In addition, envy scores were higher than guilt scores ($p <. 01$) (see Supplementary Figure 1).

Together, results of the type of emotions evoked by different domains in envy and *Schadenfreude* blocks confirm that the situations elicited more displeasure/pleasure than envy/*Schadenfreude*. However, pleasure/displeasure and envy/*Schadenfreude* showed higher scores than another group of socio-moral emotions (pride/guilt). In addition, the results showed that deservingness, moral, and legal situations elicited significantly higher scores for displeasure/pleasure and envy/*Schadenfreude* than neutral situations.

1.3. Task' comprehension:

Pilot study to assess task comprehension in groups of patients.

Before the task, all patients completed a pilot study assessing the degree of fortune in situations affecting a third party. Patients were asked to determine the type of valence (fortunate vs. unfortunate) of three situations with positive outcomes (e.g., "She/he has won the lottery"), three situations with negative outcomes (e.g., "She/he crashed her/his car"), and three neutral-outcome situations (e.g., "She/he turned off the light before leaving"). Patients assessed how fortunate each situation was on a 9-point Likert scale, assigning 1 point to situations deemed "unfortunate", 9 points to situations deemed "fortunate", and 5 to situations deemed "neutral".

Task' comprehension assessment in groups of patients

Mean values of the ratings of positive situations for BvFTD and AD patients were 7.9 ($SD = 1.18$) and 7.8 ($SD = 1.12$), respectively. The mean ratings for negative situations were 1.84 ($SD = 1.26$) for bvFTD patients and 1.45 ($SD = 1.19$) for AD patients. The mean values for neutral outcome situations for bvFTD and AD patients were 5.44 ($SD = 1.61$) and 5.34 ($SD = 1.43$), respectively. An ANOVA using situation type (positive, negative, neutral) as a within-subject factor, and group (bvFTD and AD patients) as a between-subject factor revealed a significant effect of situation type ($F(1, 43) = 22.73$ $p < .0001$). No other effects were found. A post hoc analysis (Tukey HSD, MS = 84.78, $df = 2$) showed differences between positive and neutral situations for both bvFTD ($p < .001$) and AD patients ($p < .001$), as well as significant differences between negative and neutral situations for both groups (all ps $< .001$).

1.4 Supplementary data analysis

Behavioral variability scores: First, we assessed the intra-individual score range by exploring the standard deviation of trial-by-trial scores in each subject for each situation type. Second, we calculated the range of inter-individual scores (the mean of the standard deviation of each subject in comparison to the mean standard deviation of the group) to measure the level of fluctuation among the subjects in each group.

2 Supplementary Results

Intra-individual score range: The standard deviation of trial-by-trial scores according to the type of situation (deservingness, morality, and legality) in each moral emotion (*Schadenfreude* and envy) was computed to estimate the consistency of scores of each subject in the task. We used an independent ANOVA for *Schadenfreude* and envy. In each ANOVA we used situation type (deservingness, morality, legality, and neutral) as a within-subject factor, and group (bvFTD, AD and healthy controls) as a between-subject factor. Analyses in variability of *Schadenfreude* scores only showed a significant effect of group ($F(2, 82) = 2.73$, $p < .05$, $\eta2 = .04$). A post-hoc analysis revealed that control subjects were different from bvFTD ($p < .01$) and AD ($p < .01$) patients. No differences were found between bvFTD and AD patients. Analyses in variability of envy scores only showed a significant effect of group ($F(2, 82) = 2.98$, $p < .05$, $\eta2 = .06$). A post-hoc analysis revealed that control subjects were different from bvFTD ($p < .01$) and AD ($p < .01$) patients. No differences were found between bvFTD and AD patients.

Inter-individual score range: We also computed the standard deviation of each subject in relation with mean standard deviation of the group for each situation type (deservingness, morality, and legality) in each moral emotion (*Schadenfreude* and envy). This index was obtained to assess the consistency of scores of each subject in relation to his/her group. We followed the same analysis pipeline employed to assess the intra-individual score range. Analyses in variability of *Schadenfreude* scores showed a significant effect of group ($F(2, 82) = 2.38$, $p < .05$, $\eta2 = .05$). A post-hoc analysis revealed that control subjects were different from bvFTD ($p < .01$) and AD ($p < .01$) patients. No differences were found between the latter two groups. Analyses in variability of envy scores only showed a significant effect of group ($F(2, 82) = 2.13$, $p < .05$, $\eta2 = .04$). A post-hoc analysis revealed that control subjects were different from bvFTD ($p < .01$) and AD ($p < .01$) patients. No differences were found between bvFTD and AD patients.

As an additional behavioral analysis, we controlled for group differences in *Schadenfreude* and envy with the intra-individual score range. The analyses showed that scores of *Schadenfreude* [$F(2, 82) = 11.24$, $p < .001$, $\eta2 = 0.19$] and envy [$F(2, 82) = 9.28$, $p < .001$, $\eta2 = 0.07$] remained significant after adjusting for this measure.

3. Supplementary figures
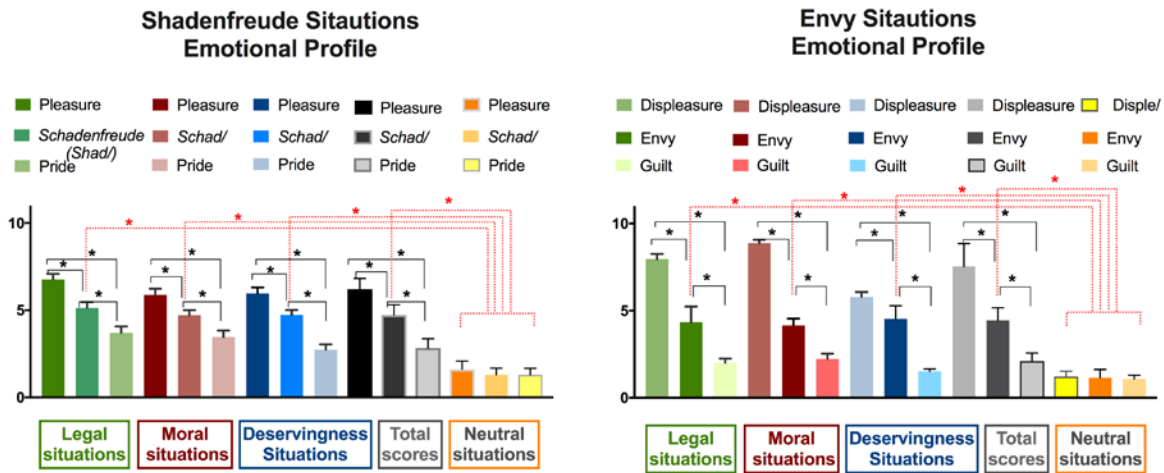
Supplementary Figure 1: Scores for different emotions for each group of situations (deservingness, moral, legal, neutral) of each moral emotion (envy and *Schadenfreude*). The left panel (A) shows scores for the *Schadenfreude* block. In general, all *Schadenfreude* situations had higher scores for both pleasure and *Schadenfreude* emotions in comparison to emotional scores given to neutral situations and other socio-moral emotions. Dashed red lines depict the differences in *Schadenfreude* scores for deservingness, moral, and legal, and neutral situations. The right panel (B) shows scores for the envy block. All envy situations had higher scores for both displeasure and envy emotions compared to scores given to neutral situations and compared to other socio-moral emotions. The differences in envy scores for deservingness, moral, and legal situations, and neutral situations are depicted by dashed red lines.

GM volume differences between BvFTD and Controls
BvFTD<Controls
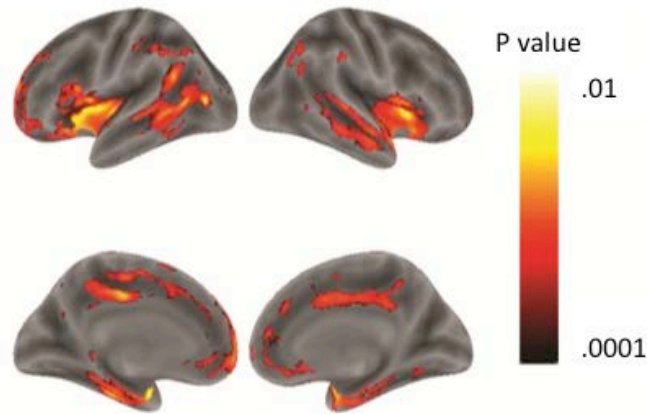
Supplementary Figure 2. **Profile of atrophy in the group of behavioral variant frontotemporal dementia (bvFTD) patients.** Whole-brain analyses revealed reduced gray matter volume in bilateral dorsolateral Prefrontal cortices, bilateral orbitofrontal cortices, bilateral anterior cingulate cortices, insular and superior temporal areas, among others.
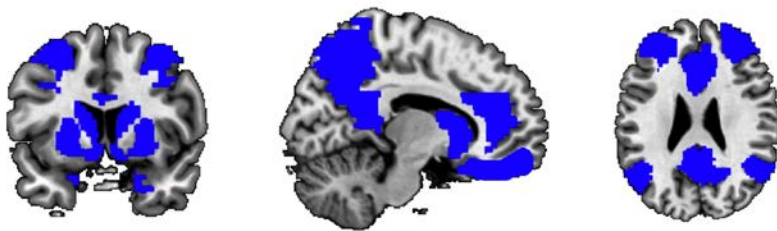
Supplementary Figure 3: Mask used for VBM analysis. The mask was selected based on previous studies on moral cognition and moral emotions and following the main areas proposed by the meta-analytic Neurosynth database, which aggregates activation from thousands of previous fMRI studies in the field of socio-moral cognition (http://www.neurosynth.org) (Yarkoni *et al.*, 2011).
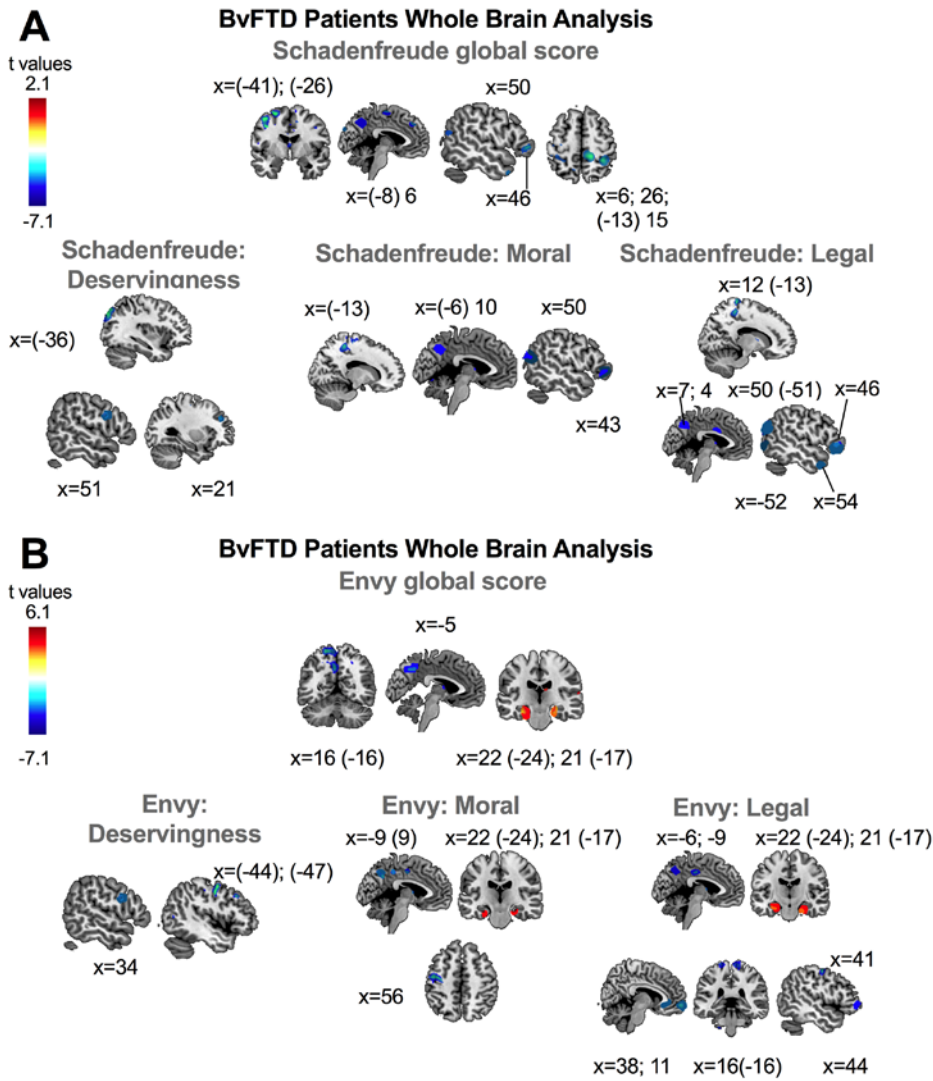
Supplementary Figure 4: Significant correlations between *Schadenfreude* and envy scores and brain areas in bvFTD. All results are reported using a whole-brain analysis at *p* < .001 uncorrected. In supplementary table 2 (whole-brain analysis), the fully list of brain areas associated to dimensions of moral emotions are reported with the MNI coordinates.
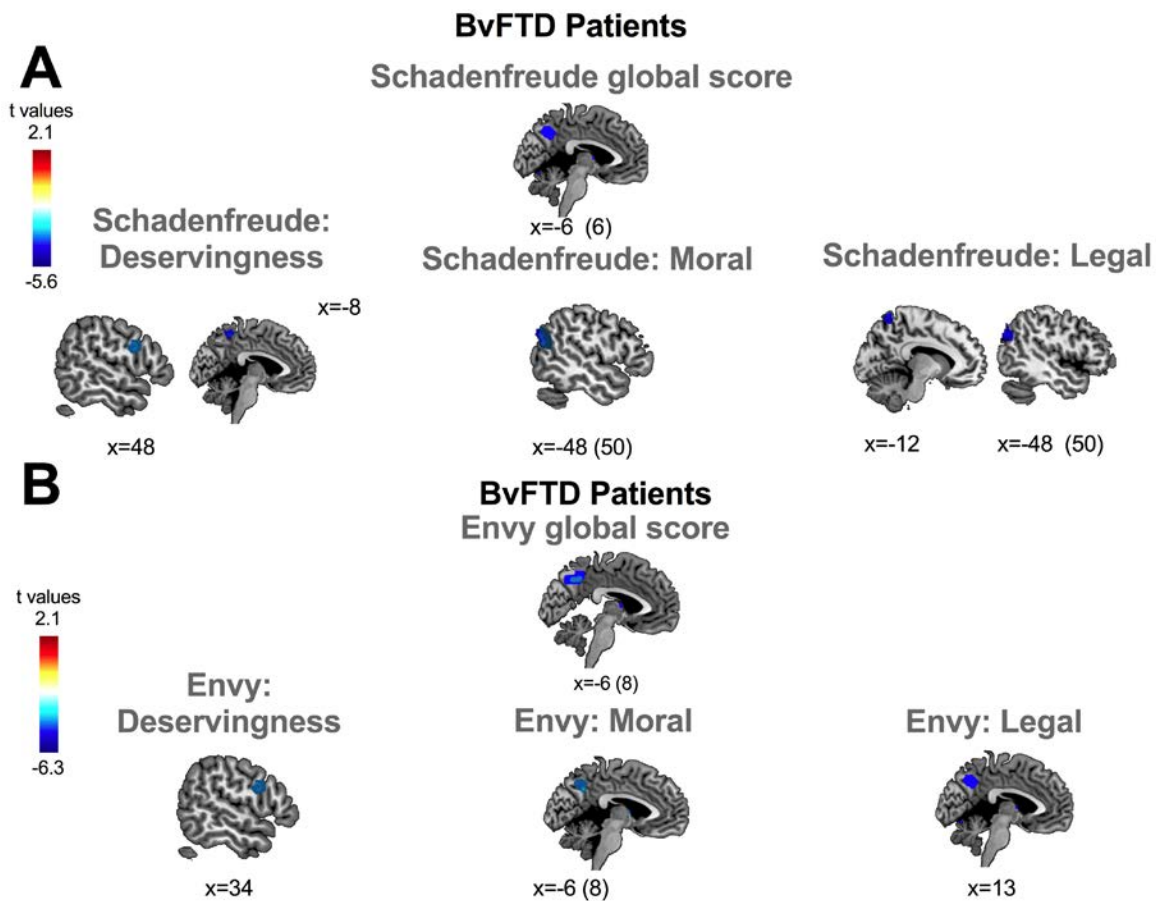
Supplementary Figure 5: Significant correlations between *Schadenfreude* and envy scores and brain areas in bvFTD patients after controlling for Hayling and RMET scores. All results are reported using a whole-brain analysis at *p* < .001 uncorrected. In supplementary table 3, the fully list of brain areas associated to dimensions of moral emotions after covarying for Hayiling and RMET tests are reported with the MNI coordinates.

4. Supplementary Tables

Supplementary Table 1. Whole brain analyses (uncorrected at p< .001) of associations between gray matter volume and scores for each dimension of Schadenfreude and envy in BvFTD patients.

Moral emotion by group analyses	Brain Regions (+) (-)	Coordinates x, y, z {mm}	Cluster size	Peak T
SCHADENFREUDE DIMENSSIONS				
BvFTD *Schadenfreude* Mean	Right Frontal pole (-)	46 47 25	388	6.22
	Bilateral Precuneus (-)	(-8 *) 6 -48 9	523	6.13
	Bilateral angular gyrus (-)	50 (-52)* -64 24	412	6.61
	ateral Superior Parietal Lobe (-)	6-26 (-41&-26)* -46 55	142	4.51
	Bilateral Sensory Association Area (-)	15 (-13) -40 67	69	4.82
BvFTD *Schadenfreude* (deservingness dimension)	Right DLPFC (-)	51 39 1	442	5.66
	Right Sup Frontal Gy (-)	21 47 25	112	3.98
	Left Superior parietal lobe (-)	-36* -61 54	72	4.16
	Right Sensory Association Area (-)	15 -40 67	69	4.82
BvFTD *Schadenfreude* (moral dimension)	Right Frontal pole (-)	43 46 6	638	6.42
	Bilateral Precuneus (-)	-6 (10) -48 9	523	6.94
	Bilateral angular gyrus (-)	50 (-51)* -64 24	682	7.11
	Left Sensory Association Area	-13 -33 48	126	4.59
BvFTD *Schadenfreude* (legal dimension)	Right Frontal pole (-)	21 47 25	638	6.42
	Bilateral Precuneus (-)	8(-6) * -48 9	523	6.94
	Right Temp Sup Lobe(-)	62 -13 9	122	4.5
	Bilateral angular gyrus (-)	47 (-48)* -64 24	682	7.11
	Bilateral Sensory Association Area (-)	-13 (12) * -33 48	101	4.79
	Right Posterior Cingulate Cortex(-)	4 -22 34	118	4.06
ENVY DIMENSSIONS				

BvFTD envy Mean	Bilateral Precuneus (-)	5 (-6) * -48 9	127	3.44
	Bilateral Amygdala (+)	21 (-17)*-1 -22	101	4.41
	Bilateral Parahippocampus (+)	22 (-24)* -19 24	243	4.49
	Right Superior parietal lobe	16 (-16) * -78 48	290	5.56
BvFTD envy (deservingness dimension)	Right DLPFC (-)	34 38 35	236	4.69
	Left Frontal Intermedia Area (Brodmann 8) (-)	-44 -47 15 41	132	4.08
BvFTD envy (moral dimension)	Bilateral Precuneus (-)	5 (-6) -48 9	323	3.94
	Bilateral Amygdala (+)	19 (-17)*-6 -15	138	5.43
	Bilateral Hippocampus (+)	16 (-19)* -33 1	243	8.49
	Bilateral Sensory Association Area (-)	56 -21 41	173	4.86
BvFTD envy (legal dimension)	Right ACC (Rostral)(-)	2 3 45	336	3.79
	Bilateral Precuneus (-)	8 (-6)* -48 9	447	8.66
	Bilateral Amygdala (+)	19 (-17)*-6 -15	210	4.43
	Bilateral Parahippocampus (+)	16 (-19)* -33 1	544	6.46
	Bilateral Superior parietal lobe (-)	16 (-16) * -78 48	290	5.56
	Right Frontal pole lobe (-)	44 46 3	165	5.46
	Right Supplementary motor area (-)	44 -11 53	112	4.13

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

Supplementary Table 3: Whole brain analyses (uncorrected at p< .001) of associations between gray matter volume and scores for each dimension of Schadenfreude and envy in BvFTD patients, using as covariates scores of Hayling test (inhibitory control measure) and Reading mind in the eyes test (RMET) (Theory of mind measure).

Moral emotion by group analyses	Brain Regions (+) (-)	Coordinates x, y, z {mm}	Cluster size	Peak T
***SCHADENFREUDE* DIMENSSIONS**				
BvFTD *Schadenfreude* Mean	Bilateral Precuneus (-)	(-6 *) 6 -48 9	316	4.57
BvFTD *Schadenfreude* (deservingness dimension)	Right DLPFC (-)	48 39 1	263	4.11
	Left Precuneus (-)	(-8) * -47 9	101	3.97
BvFTD *Schadenfreude* (moral dimension)	Bilateral angular gyrus (-)	50 (-48)* -64 24	331	5.01
BvFTD *Schadenfreude* (legal dimension)	Bilateral angular gyrus (-)	47 (-48)* -64 24	682	7.11
	Left Precuneus	-12 * -46 12	145	4.17
ENVY DIMENSSIONS				
BvFTD envy Mean	Bilateral Precuneus (-)	8 (-6) * -48 9	79	4.13
BvFTD envy (deservingness dimension)	Right DLPFC (-)	34 38 35	236	4.69
BvFTD envy (moral dimension)	Bilateral Precuneus (-)	5 (-6) -48 9	323	3.94
BvFTD envy (legal dimension)	Right Precuneus (-)	13 -48 9	323	5.14

*Left x axis coordinates

(+) Positive associations between moral emotion scores and gray matter volume.

(-) Negative associations between moral emotion scores and gray matter volume.

5. Supplementary Discussion

5.1 Supplementary Discussion 1

Previous research has revealed that there are dissociable emotional sources of envy and *Schadenfreude* (Feather and Sherman, 2002; Portmann, 2002; Smith and Kim, 2007; Tomlin, 2008; Chester *et al.*, 2013; Portmann, 2017). Envy is mainly triggered when someone else obtains something that the experiencing subject would like to have (Smith and Kim, 2007). Nonetheless, some studies have shown that, in daily social interactions, perceiving the receptor's success on its own is enough to elicit envy regardless of one's deservingness, morality, and legality (Feather and Sherman, 2002; Tomlin, 2008; Chester *et al.*, 2013). Indeed, envy can be modulated by implicit notions of fairness and justice in social comparison scenarios (Smith *et al.*, 1999; Portmann, 2002; Smith and Kim, 2007; Chester *et al.*, 2013; Ben-Ze'ev, 2014). In particular, the receptor's success might generate envy because not having the same success as the receptor can be construed as a disadvantage or an injustice onto oneself. Unpleasant emotional experiences related to envy might be experienced by events desirable for oneself (Dvash *et al.*, 2010; Chester *et al.*, 2013) or even by events presumed to be only desirable for someone else (Ortony *et al.*, 1990; Clore and Ortony, 2013).

In our study, we introduced scenarios eliciting different degrees of displeasure for others' success. In addition, envy situations differed in the degree of desirability of the receptor's outcome. Certainly, in deservingness situations the outcomes are more desirable than in moral and legal situations. However, although moral and legal situations are non-desirable a priori, those situations might also trigger unpleasant emotions, including envy (Ortony *et al.*, 1990; Smith and Kim, 2007). Our results align with this claim, as shown by the validation of the emotional profile of all situations. Those results showed that although moral and legal situations generated less envy than deservingness situations, they evoked significantly more envy than neutral situations –see Supplementary data (Results and Supplementary Figure 1). The reason is simple: even if a situation implies a legal or moral transgression, the agent involved in the scenario obtains a positive outcome, better than what would be expected for situations in which a social norm has been transgressed. Consistently with this finding, other studies tapping social cognition domains, including social decision-making (Sanfey *et al.*, 2003; Yamagishi *et al.*, 2012) and moral emotions (Portmann, 2002; Ben-Ze'ev, 2014), have shown that when others obtain a benefit by transgressing moral and legal norms, participants report unpleasant affective states.

Moral emotions are considered complex or tertiary emotions (Plutchik, 1980; Fiske, 1992; TenHouten, 2006, 2016). Authors in the fields of philosophy (de Spinoza, 1883) and sociology (Fiske, 1992; TenHouten, 2006) referred to complex emotions as mixed affective

states integrating primary and secondary emotional states and high-order cognitive mechanisms (Plutchik, 1980; Ekman, 1992). From these perspectives, even morally mediated emotions, such as envy and *Schadenfreude*, could emerge from a combination of more general and primary emotional states (Haidt, 2003; Tangney *et al.*, 2007; Fontenelle *et al.*, 2015). Thus, feelings of envy could be composed of (at least) disgust or displeasure and anger (TenHouten, 2016). Compatibly, we found that stimuli with different social and moral relevance, including situations dominated by deservingness, moral, and legal contents, also elicited basic emotional responses of displeasure/pleasure besides envy/*Schadenfreude* (see Supplementary data). These results support the notion that complex emotions partially stem from integrated affective and cognitive processes. The mixed nature of those emotions contributes to the ecological study of the interplay between cognitive, and socio-moral cognitive processes.

5.2 Supplementary Discussion 2

Most of the brain-behavior correlations for envy and *Schadenfreude* in bvFTD patients remain significant after covarying for Hayling and RMET scores (see Supplementary Figure 5). In particular, the negative association between socio-moral cognitive areas (such as the precuneus and the angular gyrus) and scores for *Schadenfreude* and envy domains remained significant after covariation for all domains. This pattern suggests that exacerbation of moral emotions in bvFTD is not fully explained by disinhibition and mentalizing deficits observed in the patients. Apparently, the precuneus and the angular gyrus are not only associated with social and moral cognitive computations; rather, those areas seem to be crucial for the experience of moral emotions. The association between moral emotions' scores and frontal brain regions was not significant after covarying for Hayling test and RMET scores. This result suggests that executive dysfunctions reported for bvFTD patients, including disinhibition, could partially explain their exacerbated moral emotions. Frontal areas (in particular, the frontal pole) have shown to be crucial in processing inhibitory control and favoring more regulated social and emotional behaviors (Collette *et al.*, 2001; Nathaniel-James and Frith, 2002; Roca *et al.*, 2009; Eslinger *et al.*, 2011b; Volle *et al.*, 2011). These results align with previous studies that support a direct relationship between disinhibition and affective deregulation in bvFTD patients, who might present overfamiliarity, jocularity, euphoric mood in roughly 40% of cases and inappropriate affectivity (Levenson *et al.*, 2014). Nonetheless, these brain-behavior correlations are in line with the patients' behavioral effects, as they shown that exacerbation in moral emotions in bvFTD is not a simple manifestation of social and behavioral disturbances, but rather a new expression of the social and affective

deregulation in bvFTD.

5.3 Supplementary discussion 3

The whole brain analyses in bvFTD revealed a similar pattern of associations between *Schadenfreude* and envy scores and key brain areas, as they were negatively associated with the precuneus, the angular gyrus, the dorsolateral prefrontal areas, and the frontal pole. In addition, positive associations were found between envy (global, moral, and legal dimensions) and volume of the amygdala and the parahippocampus. Furthermore, the whole-brain analyses revealed additional negative associations between *Schadenfreude* and envy scores and the superior parietal lobe (Brodmann 7), a brain area also involved in moral cognitive processes in healthy subjects and, more importantly, in subjects with antisocial behaviors (Moll *et al.*, 2008). Other associations were observed between envy (global score, moral, and legal dimensions) and *Schadenfreude* (global score, moral, and legal dimensions) scores and sensory associations areas. Previous studies have postulated that sensory association areas have a crucial role in attending, evaluating, and preparing to respond to unpleasant or emotionally arousing sensory stimuli (Reiman *et al.*, 1997; Chang *et al.*, 2014). This pattern of association in bvFTD patients may suggest that higher scores of moral emotions scores could also be related to alterations in structures involved in regulating and responding to salient emotional stimuli.

5.4 Supplementary discussion 4

The PCC, MTL, and parietal regions, has been associated with bvFTD. These temporo-posterior regions, beyond the classical atrophy pattern of bvFTD, are also disturbed and associated with neurocognitive disturbances in this disorder (Whitwell *et al.*, 2009; Rohrer *et al.*, 2010; Whitwell *et al.*, 2011; Lagarde *et al.*, 2015; Santamaria-Garcia *et al.*, 2016). Similarly, the PCC, precuneus, and MTL are involved in moral cognition and moral emotions (assessment of other's success and misfortunes) (Schaich Borg *et al.*, 2011; Chester *et al.*, 2013; Bastin *et al.*, 2016). The PCC and parietal regions have been involved in social cognition (e.g., theory of mind) (Mitchell, 2009; Han and Ma, 2014; Schlaffke *et al.*, 2015; Bzdok *et al.*, 2016), and the MTL is associated with mentalizing future and past situations (Okuda *et al.*, 2003; Tamir *et al.*, 2016). Thus, our findings are convergently accounted for by the disruption of these regions in bvFTD and their involvement in relevant cognitive and socio-affective processes underlying moral emotions. At a more speculative level, our findings suggest that these medial-posterior regions are critically involved in moral emotions only when fronto-temporo-striatal deficits are present. This follows from the observation of

AD patients, who usually exhibit temporo-posterior atrophy, were unimpaired in processing moral emotions. This hypothesis could be directly tested in future studies comparing the atrophy of bvFTD and AD in relation with moral emotions.

5.5 Supplementary discussion 5

Second, abnormal heightened moral emotions in bvFTD can be related to affective deregulation in bvFTD patients, as an emotional expression of disinhibition (Lanata and Miller, 2016). Emotional alterations in those patients range from altered emotional processing (Werner *et al.*, 2007; Sturm *et al.*, 2015; Baez *et al.*, 2016c; Cohen *et al.*, 2016) to a major prevalence of inappropriate and accentuated affective behaviors including euphoric mood states, overfamiliarity, jocularity, and silliness (Levenson *et al.*, 2014).

Our results also invite new research on the relationship between basic emotion impairments in bvFTD (Eslinger *et al.*, 2011a; Kumfor *et al.*, 2013; Baez *et al.*, 2014c; Kamminga *et al.*, 2014; Melloni *et al.*, 2014; Sturm *et al.*, 2015; Van den Stock *et al.*, 2015; Baez *et al.*, 2016c; Hutchings *et al.*, 2017) and the exacerbation of moral emotions in this condition. Given our study's goals, we did not include basic emotions tasks, but it is worth noting that bvFTD patients are typically impaired in emotional recognition (Bora *et al.*, 2016; De Winter *et al.*, 2016; Paholpak *et al.*, 2016; Hutchings *et al.*, 2017), which argues against the possibility that our finding reflects a general exacerbation of emotional processing. Further research into middle-level processes across basic and social emotions could shed light on this matter. For instance, in our study, the stronger the experience of *Schadenfreude* and envy for bvFTD patients, the lower their ToM skills as assessed with the RMET. Note that this task indexes basic emotional ToM levels, namely, the emotional inference of others' states. This result suggests that at least mid-level emotional inference could be related to processing of moral emotions. Although beyond the scope of this study, further research parameterizing different levels of emotional complexity could illuminate the role of basic, middle, and social emotions in the exacerbation of *Schadenfreude* and envy.

Third, the exacerbation of moral emotions is also consistent with classical behavioral disturbances in bvFTD patients (Lanata and Miller, 2016). In this context, an increase in the moral emotions of bvFTD patients might be deemed an additional manifestation of disinhibited behaviors, such as impulsivity (Kloeters *et al.*, 2013; O'Callaghan *et al.*, 2016), risk-taking, careless gambling, and others (Manes *et al.*, 2011; Kloeters *et al.*, 2013). Disinhibition has been reported as one of the most striking features of bvFTD (Lanata and Miller, 2016). This symptom may be manifest as impulsivity, such as overeating, risk taking, gambling, excessive use of drugs or alcohol, and disruptive immoral and illegal behaviors

(Mendez, 2010; Baez *et al.*, 2014b). In addition, disinhibition has been associated to affective deregulation in bvFTD patients who often exhibit accentuated positive affect (e.g., smiling and laughing, overfamiliarity, jocularity, and silliness), added to euphoric mood or inappropriate affectivity (Levenson *et al.*, 2014). Impairments in neurocognitive processes that subsume behavioral control and emotional regulation seem to be a reliable bridge to connect disinhibition and changes in affective states in bvFTD patients (Ibanez and Manes, 2012; Levenson *et al.*, 2014). The abnormally heightened moral emotions we observed could be considered an additional expression of affective deregulation in bvFTD. This manifestation seems associated to disinhibition and other social cognitive mechanisms as revealed by correlational analyses showing a positive relationship between moral emotion effects and impairments in inhibitory control and theory of mind skills in bvFTD patients.

Fourth, 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).

The study of *Schadenfreude* and envy, represents an integrated and ecological way to assess affective processes and their interactions with cognitive and social performance (Takahashi *et al.*, 2009; Jankowski and Takahashi, 2014; Fontenelle *et al.*, 2015). In particular, the complex nature of moral emotions seems to provide a more transparent model of everyday affective processes. In this sense, moral emotions are linked to the interest or welfare of extended social groups, as they are evoked by circumstances that extend beyond self-experiences and interests (Frijda, 1988; Haidt, 2003) and prove decisive to encourage or inhibit behaviors depending on their social acceptability (Moll and de Oliveira-Souza, 2009; Yoder and Decety, 2014). Thus, these emotions provide a new agenda to expand routine clinical assessment and better characterize the symptomatology of bvFTD, including disinhibition, social norm violation, and abnormal social interaction. In fact, bvFTD patients typically present deficits in the mosaic processes required for moral emotions, including empathy (Baez *et al.*, 2014d; Baez *et al.*, 2016c; Dermody *et al.*, 2016; Ibanez *et al.*, 2016; O'Callaghan *et al.*, 2016; Ibanez *et al.*, 2017; O'Callaghan and Hornberger, 2017), prosocial behaviors (Moll *et al.*, 2011), and moral judgment (Baez *et al.*, 2014a; Baez *et al.*, 2016b),

alongside an increase in antisocial and illegal behaviors (Mendez, 2010).

Therefore their integration of empathy, emotional processing, and higher resources including moral cognition, theory of mind, and socio-behavioral regulation, moral emotions emerge as a new potential target to assess complex behaviors in bvFTD's clinical practice, as they allow exploring the links between moral cognition and typical disruptive behaviors (i.e., disinhibition) relevant for diagnosis and progression (Hornberger *et al.*, 2011; Carvalho *et al.*, 2013; Santamaria-Garcia *et al.*, 2016). In sum, the triad of socio-moral cognition, cognitive processes, and behavior underlying moral emotions might provide a new way to explore early disruptions in bvFTD and other frontal disorders (Baez *et al.*, 2012; Ibanez and Manes, 2012; Baez and Ibanez, 2014; Baez *et al.*, 2016a). Future studies should assess the relations between the symptomatology of bvFTD and the neurocognitive correlates of moral emotions.

5.6. Supplementary discussion 6

First, previous studies followed a similar procedure considering only bvFTD patients (Rosen *et al.*, 2002; Irish *et al.*, 2012; Caminiti *et al.*, 2015; Van den Stock *et al.*, 2015; Baez *et al.*, 2016c). In those studies, lack of a contrastive neurodegenerative condition did not hinder robust interpretations of task-specific neural correlates. In our study, we went beyond such an approach by including behavioral measures of moral emotions in AD patients as a pathological control group. This allowed us to show that (a) task comprehension and performance were not compromised by neurodegeneration per se, and that only bvFTD patients presented alterations in moral emotions relative to healthy controls. Considering that AD patients usually exhibit a more extended pattern of brain atrophy (Rathore *et al.*, 2017), it is more difficult to track which specific neural areas are associated with the experience of moral emotions. In fact, the specificity of the pattern observed in bvFTD is strengthened given that AD showed no such distinctive pattern, even despite the greater overall atrophy typically observed in this group. In addition, the brain areas related to moral emotions in our study (including prefrontal areas, the precuneus, and the amygdala) are classically reported in the brain atrophy pattern of bvFTD (Whitwell *et al.*, 2007; Whitwell *et al.*, 2009; Pievani *et al.*, 2011; Chiong *et al.*, 2013; Baez *et al.*, 2016b; Santamaria-Garcia *et al.*, 2016; Sedeno *et al.*, 2016).

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