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Intention, false beliefs, and delusional jealousy: Insights into the right hemisphere from neurological patients and neuroimaging studies

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Summary

Jealousy sits high atop of a list comprised of the most human emotional experiences, although its nature, rationale, and origin are poorly understood. In the past decade, a series of neurological case reports and neuroimaging findings have been particularly helpful in piecing together jealousy's puzzle. In order to understand and quantify the neurological factors that might be important in jealousy, we reviewed the current literature in this specific field. We made an electronic search, and examined all literature with at least an English abstract, through Mars 2010. The search identified a total of 20 neurological patients, who experienced jealousy in relation with a neurological disorder; and 22 healthy individuals, who experienced jealousy under experimental neuroimaging settings. Most of the clinical cases of reported jealousy after a stroke had delusional-type jealousy. Right hemispheric stroke was the most frequently reported neurological disorder in these patients, although there was a wide range of more diffuse neurological disorders that may be reported to be associated with different other types of jealousy. This is in line with recent neuroimaging data on false beliefs, moral judgments, and intention [mis]understanding. Together the present findings provide physicians and psychologists with a potential for high impact in understanding the neural mechanisms and treatment of jealousy. By combining findings from case reports and neuroimaging data, the present article allows for a novel and unique perspective, and explores new directions into the neurological jealous mind.

key words: **intention • neuroimaging • jealousy • delusional jealousy • intimate relationship • right hemisphere • false beliefs • embodied cognition • forensic neuroscience • mirror neuron system • mental health**

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Background

Jealousy is a frequent human emotional experience, although its nature, rationale and origin are poorly understood. In the past decade, neurological and neuroscientific approaches have been helpful in better understanding the neural bases of jealousy. The present article review findings showing accounts of jealousy in patients with structural brain damage or cerebrovascular infarction, and explores new directions in this field. Taking into account the neurology of jealousy is imperative to allow a better understanding of the potential detrimental effects of jealousy [1–3]. For instance, global homicide statistics depict jealousy as the most frequent catalyst of spousal homicide worldwide. Thus there is a crucial need to better apprehend the neural bases of this negative mental state [4–7].

We begin with the paper's focal point and often a common source of confusion i.e., the definition of jealousy.

Definition of jealousy

Jealousy is a complex emotion that is hard to define despite its unequivocal prevalence in interpersonal relationships [1,2]. Although the Latin and Greek roots of the word "jealousy" refer to a fervor, a ardor, or a love to emulate; jealousy is generally characterized as a negative emotional reaction that is evoked when an individual loses (or fears the loss of) a valued relationship due to the threat of a real (or imagined) rival. Despite this clarification, the definition of jealousy remains a topic of debate, which has been the focus of several disciplines. The Diagnostic and Statistical Manual for Disorders, Fourth Edition, Text Revision (DSM-IV-TR) defines clinical jealousy as a delusional disorder-jealousy type [8]. A diagnosis of delusional disorder-jealous type requires that "an individual experiences persistent, unrelenting content-specific delusions of a partner's infidelity that cannot be explained by a conjoint history of schizophrenia, drugs, or physical illness [6,8]. Delusional disorder-jealous type diagnoses occur at an estimated prevalence of less than 1% of the world population [8].

It is important to note that clinical cases of jealousy do not always include delusions [4,9–11]. Various subtypes of jealous reactions may occur. Two common forms of normal jealous reactions are emotional jealousy and sexual jealousy. Emotional jealousy is experienced when an individual's partner forms a real (or imaginary) emotional connection with a potential rival, whereas sexual jealousy is triggered when an individual's partner engages in a real (or imaginary) sexual liaison with a potential rival [1,2].

Many other terms and definitions have been attributed to jealousy including the erroneous belief that jealousy is synonymous with envy. For instance, confusion between jealousy and envy is frequent in everyday usage, and also in the course of clinical work [12]. Often the two words are used either interchangeably or in conjunction with one another, as 'the patient's envy and jealousy' [13]. However, there are several differences between jealousy and envy. For instance, jealousy is linked specifically to a person in the context of an interpersonal relationship, whereas envy extends to inanimate objects. In contrast to jealousy, the experience of envy is defined as "when a person lacks what another has and either desires it or wishes that the other did not have it" [12]. Because jealousy differs from envy (in that jealousy often refers to the fear to lose someone, while envy refers to the will to obtain something), here we will report only neurological cases and neuroimaging of normal and delusional jealousy (not envy).

Based on the above definition of jealousy, we perceive jealousy as being due to flaws in false belief psychological systems. Thus, from a neurological viewpoint, one may expect brain areas involved in false beliefs and social cognition to be specifically involved in jealousy (notably in delusional jealousy). Because of the well-known role of the right hemisphere in emotion, and a growing body of research in neuroscience demonstrating its association with mental state reasoning, moral judgement, false beliefs, delusions [14,15], and also its facilitation effect in understanding actions and intentions of others based on a simple observation of their body language [16,17–20], one may hypothesize a critical role of the right hemisphere in jealousy. In agreement, Richardson et al. suggested that "damage sustained by the right hemisphere may predispose the individual to misinterpret complex information and integrate irrelevant stimuli into false beliefs" [21]. To date, however, there are no reviews documenting the brain mechanisms that sustain jealousy.

To address this question, we undertook an exhaustive review of the literature. Our goals were: (a) to identify all individuals with a stroke, who had been reported to have associated jealousy; (b) to determine what part of the brain is mostly involved in jealousy; and (c) to try to determine what characteristics of these individuals may be categorized as a pattern. Such information, we hope, would provide new directions for future interventions, and stimulate research on jealousy.

Material and Methods

Search procedures

All papers in the literature published through March, 2010 (inclusive) were considered for this review, subject to two general limitations: the publication had to be a manuscript, and the title and abstract had to be available in English. Materials were identified through computer-based searches, as described below.

Computer searches

A systematic computer-based search of the literature was performed using the local university database. The following electronic databases were searched through 2010: Pubmed Medline**;** Psychinfo; and Google Scholar. The following search terms were used: jealousy, delusional jealousy, pathological jealousy, Othello syndrome, neurology, clinical, couple, psychology, sexual medicine, social neuroscience, neuroimaging, brain, fMRI, PET, SPECT, EEG, TMS, neuropsychology, and human.

Inclusion criteria

The set of publications identified from the computer searches was then subjected to the following narrower and more

restrictive criteria: (a) at least 1 of the subject(s) of the paper had to be identified as having "jealousy" for someone, but without necessarily an "envy" for something; (b) the studies had to be reported with a specific neurological or neuroimaging exam; (c) the papers should not include any patients with history of schizophrenia or alcohol abuse; and (d) all studies concerning jealousy have been conducted in accordance with ethical standards and under the supervision of the responsible human subject's committees. Articles concerning broader issues, such as dimensions of developmental and psychoanalytic aspects of jealousy, envy, and delusional jealousy are generally essential for humans' physical and mental health. Since these issues have been addressed in depth previously they will not be reviewed in the present article.

Results

A total of 20 neurological individuals with jealousy post-brain damage were found in 17 published materials that met the criteria for this review (Table 1). The earliest publication was from 1964, and the latest 2008. In addition, we found only two studies that investigated the neural bases of jealousy using neuroimaging. The first study was published in 2006 and the second study was published in 2008. In the 2006's study, the neural bases of normal jealousy were investigated in 22 healthy individuals (n=11 women, n=11 men) using functional magnetic resonance imaging (fMRI) neuroimaging. In the 2008's study, the neural bases of delusional jealousy were investigated in one neurological patient using single photon emission computed tomography (SPECT).

Neurological Case Reports

Measures of jealousy

In the present review, all the clinical cases of jealousy include spontaneous reports from patients who had false beliefs regarding their partner's infidelity (Table 1). Although no clear confirmation of these allegations about infidelity has been done, most of the cases were described as being delusional jealousy according to (or not) the DSM-IV criteria. As we described above, delusional jealousy is a psychiatric phenomenon in which an individual has a delusional belief that their spouse (or sexual partner) is being unfaithful [6]. It is also known as morbid jealousy, pathological jealousy, conjugal paranoia, or Othello syndrome [6]. As described by Easton et al., it remains unclear what differentiates each of these disorders [6]. Nevertheless, it is clear that delusions are only present in individuals suffering from delusional disorder-jealous type [6]: "To be diagnosed, individuals must experience delusions concerning the fidelity of their long-term romantic partner (i.e., the individual is convinced that their partner is or has been unfaithful, but without reasonable or objective evidence). Individuals who suffer from a jealousy disorder, but who do not experience delusions, will not fit the diagnostic criteria for delusional disorder-jealous type and, thus, may not receive appropriate psychiatric attention or treatment" [6]. In the DSM-III (APA, 1980), this same diagnosis was termed paranoid jealousy.

One of the main reasons why some of the present clinical cases do not meet the DSM-IV criteria is the following: When evaluating delusional disorder as a possible diagnosis for the patients' condition, special attention has been paid to the fact that delusional disorder can only be diagnosed if the symptoms cannot be better accounted for by the direct physiological effects of a substance or a general medical condition (as stated by the DSM-IV-R diagnostic criteria; [6]). Since the patients from the present review had a known neurological condition, some of the authors were cautious when trying to account for their symptoms with the diagnosis of delusional disorder. Further studies thus need to integrate this information in their systematic clinical investigations.

One other characteristic of the present clinical cases is that some of the patients' allegations were so intense and threatening that their partners changed their behaviors in response to the patient's accusations. For instance a patient's wife began severely restricting her activities. "She became fearful of getting up at night to go to the bathroom because the patient often awoke to reassert his belief that she was getting up to meet with her lover" [21]. These reports include evidence/assumption from various sources, such as the following ones: "My husband is cheating on me with numerous women, giving away my jewelry, and lying about everything! He sleeps with every woman he sees! [22]"; "trivial events of no account were seen as proof of his wife having been unfaithful [11]"; "she started to accuse her husband of infidelity. She insisted that he was having an affair with a 70-year-old woman who was a member of their ground golf circle [23]". "The patient became suspicious of the alleged affair when he began putting together evidence from various sources. For example, he noticed that his wife began leaving the first floor bedroom window open at night, presumably to allow her "lover" to enter the room while the patient was asleep. On one occasion, he thought he had heard voices in the kitchen, but when he entered the room, only his wife was there preparing breakfast. The patient assumed that his wife had been making breakfast for the neighbor, who fled through the front door on hearing the patient's approach. When asked why he thought his wife would be interested in the neighbor, the patient stated that he recalled his wife remarking that "that boy is a nice-looking fellow"" [21].

Description of the patients

In the present review, we found 20 patients (n=6 women, n=14 men) who experienced spontaneous jealousy secondary to a neurological disorder (Table 1) [6,7,9–11,21–32]. All were older than 18 years of age (male mean age 57.46 years, SD=13.44; female mean age 57.17 years, SD=18.99). Each patient was married, or was in an intimate relationship with a significant other at the time of the delusional jealousy. Men were diagnosed with jealousy more often (60% vs. 40%) than women. Most of the reported cases presented delusional jealousy (95%). Critically, these clinical cases of delusional jealousy exacerbate a hypersexual state (20%) that can include erotic delusions (15%) and coercive paraphilic behavior, such as frotteurism, which is defined as "a practice of touching or rubbing against the clothed body of another person in a crowd as a means of obtaining sexual gratification." (10%) [7,9–11]. Frotteurism, hypersexual states, and jealousy were critically found in patients with Parkinson's disease, which is in line with the current literature on dopaminergic agonists and their influence on sexual drives and behaviors [33].

Table 1. Jealousy case reports associated with neurological disorders.

Case#	Authors	Year of publication	Number of patients	Sex of patient(s)	Age of patient	Characteristic	Origin	Measures of jealousy
1-2	Parigi & Fabiani	1964	2	Female (Case 1), Male (Case 2)	Case 1: 58 Case 2: 57	Cerebral tumor with delusional jealousy, and disturbance of erotism	Rhinoencephalic lesion	« Jealous delirium », as patients falsely accused their spouses of infidelity
3	Richardson, Malloy, & Grace	1991	1	Male	68	Delusional jealousy	Right cerebrovascular infarction	Patient admitted to a psychiatric facility for evaluation of aggressive behavior toward his wife, whom he believed was having an affair with their 25-year-old neighbor.
4	McNamara & Durso	1991	1	Male	74	Delusional jealousy and morbid jealousy	Parkinson's Disease	6-week history of delusional jealousy: patient falsely accused his 68-yr-old wife of infidelity
5	Mistusuhata & Tsukagoshi	1992	1	Female	62	Penduncular hallucinosis with delusion of jealousy and erotic delusion	Cerebellar infarction	Delusional jealousy
6–8	Leong et al.	1994	3	Male	Case 6: 67	Othello Syndrome (morbid jealousy) with hostility	Case 6: right parietal-occipital junction infarct;	Case 6: patient had a 6 months history of falsely accusing his 76-yr-old wife of infidelity (oral and written reports). Also, he was given the DSM III-R diagnoses of organic delusional disorder
					Case 7: 48		Case 7: left cerebellar hemorrhage with mass effect;	Case 7: patient falsely accused his wife of infidelity for the past 3 months; he also met the DSM III-R criteria for organic delusional disorder
					Case 8: 44		Case 8: psycho-stimulants (amphetamines, and marijuana)	Case 8: Hospitalized for depression, and marital difficulties. He spontaneously, and falsely accused his wife of infidelity. Also, he met the DSM III-R criteria for organic delusional disorder.
9	Wong & Meier	1997	1	Male	72	Delusional jealousy	Right cerebral infarction involving the head of the caudate nucleus, globus pallidus, putamen, and internal capsule	Admitted to the emergency department for sudden left-sided weakness, and collapse. After the stroke, the patient spontaneously, and falsely accused his wife of infidelity.
10	Soyka	1998	1	Male	74	Delusional jealousy	Right hemisphere cerebrovascular infarction	Patient falsely accused his wife of infidelity, and attacked her with a knife.

Table 1 continued. Jealousy case reports associated with neurological disorders.

Case#	Authors	Year of publication	Number of patients	Sex of patient(s)	Age of patient	Characteristic	Origin	Measures of jealousy
11	Westlake & Weeks	1999	1	Female	20	Pathological jealousy with depression	Right hemisphere cerebrovascular infarction	Spontaneous reports of the patient's increased jealous and possessive behaviors with her partner
12	Pillai & Kraya	2000	1	Male	42	Morbid jealousy	History of treatment for ADHD	Patient was admitted through the court under Section 5 of the Criminal Law Mentally Impaired Defendants Act (1996), charged with stalking a policeman, whom he believed had an affair with his wife
13	Brune, Gerlach, & Schroder	2001	1	Male	49	Delusional jealousy	Parkinson's Disease	Spontaneous reports about partner's infidelity
14	Chae & Kang	2003	1	Male	63	Delusional jealousy, and hypersexuality	Right hemisphere infarction in the middle cerebral artery distribution	Patient falsely accused his wife of infidelity. Also, he met the DSM-IV critiria of psychotic disorder after a stroke with delusions
15	Predescu et al.	2004	1	Male	38	Delusion of jealousy and persecution, & behavioral disorders	Bilateral mesencephalo-thalamic cerebral ischaemia	Psychotic troubles with delirium subsequent to a cérébral ischemia (DSM-IV criteria)
16	Blasco-Fontecilla	2005	1	Female	71	Delusion of jealousy and Parasitosis	Right hemispheric stroke	Patient falsely, and spontaneously accused her husband of infidelity, despite the lack of objective data
17	Narumoto et al.	2006	1	Female	61	Delusional jealousy	Right orbito-frontal lobe excision	Patient falsely, and spontaneously accused her husband of infidelity. Also, she presented a 1-year history of increasingly jealous behavior
18	Cannas et al.	2006	1	Male	51	Delusional jealousy, hypersexual behavior, & frotteurism	Parkinson's disease	Patient falsely accused his wife of infidelity during psychopathological interview
19	Yusim et al.	2008	1	Female	71	Erotic jealousy	Normal pressure hydrocephalus secondary to aqueductal stenosis, with microvascular changes adjacent to the right frontal horn	Patient falsely accused her husband of infidelity
20	Saldini and Luauté	2008	1	Male	77	Delusional jealousy	Right middle cerebral artery infarct and hypoperfusion in right frontal lobe	Patient falsely accused his wife of infidelity

Description of the patients' neurological results

Our review shows that the cerebral origins of clinical jealousy cases have been traced to a range of neurological complications including right cerebrovascular disorders (45%), cerebellar infarctions (10%), mesencephalo-thalamic cerebral ischaemia (10%), Parkinson's disease (15%), rhinoencephalic lesions (10%) and drug treatment (10%) [6,7,9–11,21,23–32]. Interestingly, these clinical cases were not only observed in elderly patients (older than 75 year-old) who have a brain atrophy. The youngest patient was 20 year-old, and the oldest was 77 year-old. Westlake and Weeks presented this 20 year-old clinical case of pathological jealousy following a right brain infarction without any associated brain atrophy [28]. In brief, this young woman was admitted to a hospital with a right hemispheric stroke associated with a history of severe migraine and the use of oral contraceptives [28]. A CT scan revealed an evolving haemorrhagic cerebrovascular infarction in the right parietal and frontal regions extending into the basal ganglia, including the right caudate nucleus. The patient recovered rapidly with minimal neurological deficits, but one month later she was again admitted for a fever and a flu-like syndrome with headache, nausea and increasing left-sided weakness. Repeated CT scans of the head showed no change in the previously noted right middle cerebral artery territory lesion. Headache and nausea persisted and the patient was given a single dose of sumitriptan, which led to dramatic improvement in symptoms. However, during the subsequent 5-year period, she became increasingly jealous and possessive of her beloved partner. A neuropsychological exam performed at that time revealed mild evidence of right frontal and parietal damage. The patient was diagnosed with a syndrome of jealousy, syndrome that completely disappeared over a 6-week period. Although the authors mentioned a potential role of their treatment with a selective serotonin re-uptake inhibitor (SSRI; 28) on the disappearance of the syndrome of jealousy, one cannot exclude spontaneous brain recovery, and brain plasticity that would be independent of the SSRI treatment. Further pharmacological studies with a bigger cohort of patients need to be done to test the relationships between SSRI and jealousy. Based on the present data, the present review cannot make any causal relationship between SSRI and jealousy treatment. Nonetheless, taken together all the present case reports lend support to a potential relationship between brain infarction and clinical jealousy, notably after a right brain infarction both in a young and elderly population.

Although the role of the right hemisphere in emotion is not new, these findings highlight its specific role in a negative emotion that is often associated with false beliefs, delusions, and misreading of other's actions and intentions [34]. Following the theories of hemispheric specialization and inhibition [35,36], one may hypothesize that the undamaged left hemisphere, then free from the right hemisphere's influence, may verbalize all these misperceptions, and thus facilitate the exacerbation of a jealous brain state [21]. Further studies need to be done to test this assumption. The understanding of mechanisms leading to false beliefs, and misunderstanding of human intentions and actions during an episode of delusional jealousy will provide critical insights on the brain states occurring during jealousy. From such data, a development of preventive therapeutic and pharmaceutical approaches centered on improving intention understanding might then be considered.

Neuroimaging of Normal and Delusional Jealousy

Here below we first describe the neural bases of jealousy by describing the only fMRI study that investigated this question in healthy participants. Then, to better understand the specific neural mechanisms mediating delusional jealousy *per se*, we present the only neuroimaging study we found that investigated this question in a patient with delusional jealousy.

Neural bases of normal jealousy

Although jealousy is hard to investigate in laboratory settings, a nascent field in neuroscience aims to unravel the neural basis sustaining *in vivo* onset of jealousy by investigating emotional versus sexual false beliefs in couples with no brain damage. In a functional magnetic resonance imaging (fMRI) study, Takabashi et al., investigated this question combining 1.5 Tesla scanner recordings and a behavioral task involving jealousy-arousing scenarios [37]. The main goal of this study was to elucidate the neural responses to jealousy as it can be expressed through sentences depicting sexual and emotional infidelity [2,38]. Another goal of this study was to investigate the gender differences as a function of normal jealousy types (emotional versus sexual) since numerous studies in psychology find men to be more sensitive to sexual jealousy than women [2,38]. In their fMRI study, Takahashi et al. investigated these two types of normal jealousy by labeling jealousy-arousing scenarios/beliefs as follows: Three types of short sentences were provided: neutral (e.g., "My girlfriend stayed in a twin-bed room in a hotel with her female friend"), sexual infidelity (e.g., "My girlfriend stayed in a double-bed room in a hotel with her ex-boyfriend."), and emotional infidelity (e.g., "My girlfriend wrote a love letter to another man"). The authors defined sexual infidelity as "a condition explicitly or implicitly indicating a sexual relationship or deep physical contact, and emotional infidelity as a condition indicating diversion of partner's emotional commitment to another boyfriend/girlfriend". Each sentence was written and started with "My girlfriend" for male students and "My boyfriend" for female students. Based on an initial survey that evaluated the jealousy rating of every sentence, the authors selected 18 sentences for each of 3 conditions (neutral, sexual infidelity, and emotional infidelity). The average of men and women for the mean ratings of jealousy for 18 neutral sentences was, respectively, 1.2 (SD=0.3) and 1.2 (SD=0.3), for 18 sentences of sexual infidelity 4.6 (SD=1.4) and 4.6 (SD=1.4), and for 18 sentences of emotional infidelity 4.3 (SD=1.3) and 4.5 (SD=1.2). The sentences were projected during fMRI scanning. During the scanning, participants were instructed to read the sentences silently and were told to imagine the situations described in the sentences. After reading each sentence, the participants were instructed to press a key button with the right index finger, indicating that they had read and understood it. However, no jealousy ratings were collected during the scanning, which can be considered as an experimental downside of this experiment. The experimental design consisted of 6 blocks in which the order of presentation of the 3 conditions (neutral, sexual infidelity and emotional infidelity) was randomized. After the scan, the participants were kindly asked to read the sentences in

the same order as presented during the scanning session, and they were asked to rate them according to "how they would feel if the scenario protagonist was their boyfriend/girlfriend". The participants were also asked to rate the intensity of jealousy and other basic emotions, such as anger, sadness, surprise, fear, disgust, and happiness for each sentence using a 6-point analog scale.

Description of the participants

A total of twenty-two healthy participants (n=11 women, n=11 men) performed this fMRI study [37]. The authors explained that all their participants were university right-handed students (male mean age 20.1 years, SD=0.8; female mean age 21.4 years, SD=1.5 [37]). Each student had not been married, and had been in an intimate relationship with a specific boyfriend/girlfriend. As described in Takahashi et al.'s study, the average length of the intimate relationship was 14.8 months (SD=10.6) for the men and 18.5 months (SD=10.9) for the women [37]. The participants did not have any history of psychiatric disorders or neurological disorders. None of the participants were taking alcohol at the time, nor did they have a history of drug dependence [37].

Description of the participants' results

Although men and women's behavioral self-ratings of jealousy revealed no significant gender differences for sexual and emotional infidelity, behavioral results show that men experienced significantly higher levels of other basic emotions in response to scanned scenarios of jealousy. More specifically, male participants rate significantly higher anxiety (p=.04) and marginally significantly higher fear (p=.06) for jealousy scenarios, in comparison to female participants. Men also rate marginally significantly higher disgust (p=.08) for infidelity scenarios, than women [37]. These results are in agreement with several studies findings that jealousy is significantly correlated with anxiety and basic emotions such as disgust, anger, sadness, and fear [39,40].

Neuroimaging results expanded these behavioral results by revealing that men and women recruit divergent brain networks in the experience of jealousy [37]. These neuroimaging results reinforce theories from neurological case reports, and provide some convincing elements in accounts of a central role of the brain in jealousy in relationship with a brain network mediating false beliefs. More precisely, in men, jealousy mostly involves activation in the visual cortex, limbic system and related areas (amygdala, hippocampal regions, and hypothalamus), and in somatic and visceral states (e.g., insula). Regression analysis revealed a positive linear correlation between males' self-rating of jealousy and the degree of activation in the insula, a brain area involved in the automatic integration of somatic experiences (r=.88, p<.001).

For women, jealousy is related to the recruitment of brain areas that sustain higher-order cognitive functions, such as the so-called mentalizing brain network that is involved in the interpretation of others' intentions based on self inferences and theory of mind [41]. Women demonstrated greater brain activation in the posterior superior temporal sulcus (STS) and angular gyrus (*i.e.* brain areas involved, for instance, in theory of mind, and self representation) [42–44]. In addition, activations were observed in the visual cortex, frontal regions (middle frontal gyrus), thalamus, and cerebellum. Regression analysis showed a positive correlation between self-rating of jealousy for female jealousy and the degree of activation found in the pSTS (r=.88, p<.001), a critical node of the social network and theory of mind [41,45]. The implication of this brain area in many other somatic and addictive experiences might be useful to further investigate in clinical settings.

Together these results highlight the recruitment of brain areas mediating mentalization, basic emotions and somatic and visceral sensations that have been integrated from past experiences [46–48]. Nevertheless, this study has some limitations that need to be addressed in future research studies. First of all, as the authors acknowledge it, their stimuli including sexual infidelity might also involve emotional infidelity, and thus induce both emotional and sexual jealousy. This possible conjoint activation of emotional and sexual jealousy might account for the identical results of self-rating of jealousy in males and females. However, the overall higher ratings of different emotions, including jealousy for sexual infidelity than emotional infidelity is against this argument. Results are in line with previous studies using a similar rating scale for sexual and emotional infidelity.

Second, subjects were aware that the scenarios were hypothetical, which limits the interpretation of the results in comparison with delusional-type jealousy. Thus, neuroimaging studies need to be done in order to test patients with delusional jealousy. Finally, the authors did not collect any behavioral data during their fMRI sessions. Although their data set is solid, their choice of methodology might have influenced the hyper-activation of some subcortical areas (e.g., amygdala), which are often activated especially during implicit emotional processing (rather than explicit emotional processing). Also, it is important to note that the authors did not specifically address the question of individual differences, which can constitute an important limitation in the interpretation of their results. Further studies need to carefully investigate this question.

Neural bases of delusional jealousy

To date, only one study has investigated the neural bases of delusional jealousy using neuroimaging technology [49]. In this study, Luauté and Saladini reinforced the above described clinical cases and specified a right hemispheric dominance by investigating the neuroimaging correlates of one patient who suffered from delusional jealousy after a right middle cerebral artery (MCA) infarct [49]. During hospitalization for a transient left-sided hemiplegia after a right middle cerebral artery infarct, a 77-year-old man became convinced that his wife had an extramarital affair with a teacher many years ago. During the three years following his infarct, the patient had to be hospitalized on several occasions because of verbal and physical abuse toward his wife. The patient also suffered from depression, in which one episode resulted in a serious suicide attempt. A month after his infarct, a detailed neuropsychological investigation revealed that the patient had a mild intellectual impairment and some visuo-spatial memory deficits. Although the patient was generally calm with his friends, he showed a

pronounced lack of emotional control when discussing with his wife. A CT scan of his brain showed a low-density defect of the right temporal and parietal lobes as well as mild cortical atrophy. Luauté and Saladini performed a single photon emission computed tomography (SPECT) using hexamethyl-propyleneamine oxime (HMPAO). This advanced neuroimaging technique revealed a large hypoperfusion of the right hemisphere, involving the right frontal lobe, the possible result of a deafferentation (or diaschisis) effect [49]. This is in line with Levine and Grek study on the anatomical basis of delusions after right cerebral infarction, which suggests that delusions depend primarily on pre-morbid brain atrophy rather than location and size of the lesion. However, this conclusion has been challenged by Westlake and Weeks, as we described above, who presented a young patient with a right infarction.

Of particular interest in the framework of false beliefs and jealousy are the temporo-parietal junction, posterior temporal sulcus, angular gyrus, and insula. Interestingly, other candidate brain areas reflecting brain processes that may potentially subserve other subtypes of social cognition were also observed, such as emotion processing, and executive functioning (action monitoring, attention, dual task monitoring, episodic memory retrieval; [50]), but none of them overlapped uniquely with the regions activated during jealousy *per se*.

Discussion

The present clinical and neuroimaging results provide critical insights for neurological theory on jealousy by unraveling its neural basis.

Right hemisphere and [delusional] jealousy

First, most of the present clinical cases of reported jealousy after a stroke had delusional-type jealousy. Right hemispheric stroke was the most frequently (45%) reported neurological disorder in these patients, although there was a wide range of more diffuse neurological disorders that may be reported to be associated with different other types of jealousy. This is in line with Luaute and Saladini's neuroimaging data that showed a large hypoperfusion of the right hemisphere in a patient with delusional jealousy. The absence of a specific right hemispheric lateralization in the Takahashi et al.'s fMRI study with healthy subjects might be due to the fact that subjects did not experience any delusional jealousy during the fMRI session. Subjects were aware of the hypothetical connotation of every jealousy-arousing sentence. Thus we assume that the authors tested more the participants' feelings for the "what" of the scenarios (e.g., what is my boyfriend doing?) rather than the "why" of the scenarios (e.g., why is my boyfriend writing a letter?). This hypothesis would fit with the current model of action and intention understanding, which suggests that one understands actions and intentions of other people using a bilateral inferior fronto-parietal brain network (extending to pSTS), with the left side being mostly dedicated to the understanding of the "what" of an action, and the right side of the brain being mostly dominant for the understanding of the "why" of an action [16,51]. Further neuroimaging studies need to be done to clarify this point in persons with and without delusional jealousy. This is a critical question since delusional jealousy receives increasing attention from the forensic psychiatry, psychology, and the media due to its linkage with aggression, and domestic violence [52].

Basic emotions and jealousy

Although we cannot exclude that other mechanisms play a role in jealousy, together the present findings suggest, that beyond a right-hemispheric recruitment for delusional jealousy, jealousy recruits a more distributed brain network that mediates various cognitive functions, such as basic emotions, somato-sensory sensations, false beliefs, and prediction of actions and intentions of other people. The role of basic emotions in jealousy has been described throughout the ages [38]. Many studies have found significant interactions between expression of jealousy and other emotions, such as disgust and fear [37,39,53]. The recruitment of brain areas that are part of the emotional brain (e.g., medial temporal lobe) reinforces this assumption. Notably, the involvement (at least in men) of the amygdala, a brain area that is involved in many emotional processes such as fear and anger, reinforces the often-assumed relationship between jealousy and anger. Unfortunately, to date, no specific neuroimaging studies have been performed to allow us to tease apart the relationship between anger and jealousy in further details. Further studies need to further assess these functional differences in order to better understand the neural plasticity as a function of the various types of emotions that may occur in jealousy. This is important as repressed anger, fear, and jealousy are correlated with relationship disturbances and psychological problems that can also cause sexual dysfunctions and difficulties.

Gender differences and jealousy

The present neuroimaging and clinical data show that both men and women exhibit jealousy. Clinical data show, nevertheless, that men were diagnosed with jealousy more often (60% vs. 40%) than women. In healthy subjects, neuroimaging studies show that the brain networks involved in jealousy are slightly different between men and women. Men mainly activate brain areas known to be involved in automatic integration of somatic experiences and basic emotions, although women tend to activate also higher-order cognitive brain areas. Although one may assume that these Takahashi's gender differences found in the medial temporal lobe area might be attributable to some neuro-anatomical dimorphism between men and women, one must emphasize that the present data are very strong because two of the authors, blinded to the gender of the images, have carefully inspected the quality of signal data in the medial temporal regions, and confirmed that all (men and women) individuals' data had good signal quality in the foci where the sex difference was observed. Interestingly, Takahashi et al's study also showed that there was no sex difference in the ratings of jealousy, anger, sadness, surprise, and happiness for the two types of jealousy (i.e., emotional jealousy, and sexual jealousy; $p>.1$). This means that both men and women may experience similar emotions during jealousy episodes. That said, gender differences were found in some cases: men rated higher anxiety and fear for sexual infidelity than women, and rated higher disgust for emotional infidelity than women. Although the modulation of jealousy as a function of gender is sometimes under debate

in psychology [2,38,54–57], the present gender differences are in line with a growing body of research in psychology that repeatedly demonstrates the sexes differ in the experience of jealousy [55]. A key psychological sex difference is the differential "weighting given to cues that trigger jealousy" in response to sexual and emotional infidelity [55,56]. Essentially, men are more sensitive to sexual jealousy, while women are more sensitive to emotional jealousy [56]. For instance, multiple studies carried out by Buss et al., in accordance with psychology's ethical standards, provide support for this hypothesis. In one study, Buss et al. investigated jealousy in 373 men and 748 women, all undergraduate students in the United States. The participants were presented with hypothetical infidelity scenarios in a forced response format. Results show that 25% more men than women were distressed by sexual infidelity as opposed to emotional infidelity [55]. Buss et al. then reinforced these findings with another study by demonstrating that 76% of men and 32% of women were distressed to a greater extent by their partner's hypothetical sexual intercourse with a rival than if their partner formed an emotional relationship with a rival [2,38,55,56]. Evolutionary psychologists suggest that these gender differences for jealousy are a result of the divergent reproductive consequences of partner infidelity for males and females [2]. The evolutionary perspective on the psychology of jealousy proposes that sexual jealousy is an evolved adaptation that functions as a mate retention strategy to protect an individual's mate from potential mate poachers and sustains access to a mate's reproductive resources [2,58]. Buss and Haselton explain that men are more angered by signs of sexual infidelity, since this indicates a significant risk of genetic adulteress [2]. The potential loss of reproductive resources and the lingering paternity uncertainty causes men to focus more on indicators of sexual infidelity rather than emotional infidelity [2]. In contrast, according to Buss et al, women find signals of emotional betrayal more upsetting as these cues threaten a loss of resources and decreasing partner commitment [55]. Along these lines, emotional jealousy can be seen as an evolved psychological mechanism, which triggers the activation of mate retention tactics in potential relationship threatening situations [59]. These mate retention tactics have become commonplace within intimate relationships in contemporary society. Humans are an inherently social species that exhibit complex social emotions in interpersonal relationships [60,61]. Interpersonal relationships are so vital to humans that psychological and physical health is crucially affected by the presence and absence of interpersonal relationships [60,61]. Humans strive to protect and sustain their relationships using available tactics [2,62]. Thus, emotional jealousy seems inherently essential to guard these valued social relationships from potential threats [2,62]. Taken together, these studies provide insightful information to the understanding of gender differences in the experience of jealousy.

False beliefs and [delusional] jealousy

One of the characteristics of delusional jealousy is its linkage with false-beliefs. Despite the small number of neuroimaging studies on jealousy, their results provide very interesting insights because they may be related to a broader field in neuroscience i.e., neuroimaging of false beliefs, and moral judgment [63–67]. The present activation of higher-order brain areas (e.g., pSTS) mediating mentalization, other's behavior interpretation, prediction, and false beliefs suggests a role of complex inferential thinking in jealousy. The assumption here is that delusional jealousy may result of disorder between critical nodes of the network decoding intentions of others [12,51,67]. This model of jealousy posits that jealousy is critically affected by the way individuals interpret actions of other people. Based on both neuroimaging studies of jealousy and those of false beliefs we suggest that predicting emotional responses and behaviors of other people involves generating and using internal affective representations. As emphasized by D'Esposito's team, this ability to predict someone else's behavior based on their belief state calls for advanced mentalizing skills involving integrating knowledge about beliefs [20,68]. Critically, the brain areas involved in inferring temporary states such as intentions, desires and goals of other people (even when they are false and unfair) recruits a broad network involved in mentalizing, theory-of-mind and self-mirroring (e.g., the temporo-parietal junction (TPJ); inferior parietal lobe, superior temporal sulcus, medial prefrontal cortex (mPFC), somatosensory related cortices, insula, inferior frontal gyrus) [20,44,50,68–70], brain areas that are also activated in jealousy. As suggested by Van Overwalle and others, the role of a TPJ-related and inferior parietal lobe-related mirror neuron system is particularly interesting for understanding mechanisms involved in inferring temporary intentions of other people, although the mPFC may play a crucial role in integrating "*social information across time and allows reflection and representation of traits and norms, and presumably also of intentionality, at a more abstract cognitive level*" [50,51,71]. As discovered and described by Rizzolatti et al. [51,72,73], the mirror neuron system is located in the inferior frontal gyrus and inferior parietal lobe (notably the anterior inferior parietal sulcus) of the brain; i.e., in brain areas that are activated when one moves, and also when one sees someone else moving. Furthermore, Rizzolatti and his collaborators demonstrated that the mirror neuron system is important not only when one acts, or looks at someone else acting, but also when one understands the actions and the intentions of someone else just by looking at their body movement [51,72,73]. Since this finding, a growing body of evidence has reinforced the role of the mirror neuron system in intention understanding. The mirror neuron system is important for understanding 'what' someone else is doing (e.g., grasping a cell phone), and also 'why' this person is moving (e.g., grasping a cell phone in order to call a girlfriend; [51,72,73]. This is important in social cognitive neuroscience, as the mirror neuron system may be important for mediating the understanding of emotions, actions and intentions of other people based on our past-integrated bodily experiences [51,72,73]. This might be critical in jealousy in the sense that one may accuse their spouse on infidelity based on their own integrated past experiences [20,74]. This would be in line with the concept of embodied cognition (i.e., "the existence of an implicit memory system that encodes knowledge of a person's physical competencies and a person is capable of interacting with the physical world"; [71,75]). In other words, embodied cognition is a cognitive mechanism that enables people to understand other people's body motor actions based on the implicit re-activation/re-enactment of their own past bodily experiences [71,75]. Although this mechanism may occur consciously, it often occurs unconsciously (i.e., automatically; without the subject's awareness). This notion has been used in a broad range of

psychological theories, including explanations on the origins of language, motor development, artificial intelligence, and as a means for explaining the coupling between physical cues and emotional inference in people [71,75]. Based on the present neuroimaging results and evidence demonstrating that jealousy calls for the recruitment of brain areas mediating integrated somato-sensorial experiences and self-representation (which assumes a relationship between self representation, integration of self-related experiences, and jealousy), here we assume that mechanisms of embodied cognition might take place in jealousy.

Future perspectives

Although the present data are very interesting, further study could be done in order to better understand the neural basis of jealousy, and notably delusional jealousy. First of all, further studies need to test further how and when the understanding of actions and intentions of other people (notably significant others) may be distorted and transformed into false beliefs. To do so, researchers need to use neuroimaging techniques (such as high-density 4D electroencephalogram (EEG) neuroimaging [76]) that provide high spatial and temporal resolution in order to study the brain chronoarchitecture (i.e., brain spatio-temporal dynamics) of people experiencing delusional jealousy.

Then, in order to better understand the role of the right hemisphere in false beliefs and delusional jealousy, a systematic study of jealousy in stroke patients is needed. To date it is unclear whether the small number of case reports on jealousy after a stroke is due to a small prevalence of this disorder in stroke patients, or whether it is due to the fact that it is under-investigated. Systematic neuroimaging studies of neurological patients could be then helpful [77]. Also, studies need to further evaluate whether the different types of jealousy may vary as a function of other basics emotions such as anger, and fear. Then, further studies need to be done to better understand gender differences as a function of right hemispheric modulation. To do so, researchers may study jealousy in women over their menstrual cycle and also life span (i.e., before and after menopause).

Finally, in line with current models of false beliefs and intention understanding, future studies need to be conducted in order to highlight the social implications that arise from jealousy and the overall impact on people's self-representation and their understanding of their partner's intentions. Findings from such studies could have critical and helpful impact on subjects' health and well-being.

CONCLUSIONS

Jealousy is an important concept to understand and study because of its potential dangerous, and negative implications for relationship health. By combining standard psychological approach with neuroimaging techniques, researchers and clinicians could better understand and prevent the mechanisms beyond a delusional jealous mind.

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