The Neural Basis of Love as a Subliminal Prime: An Event-related Functional Magnetic Resonance Imaging Study

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Abstract

■ Throughout the ages, love has been defined as a motivated and goal-directed mechanism with explicit and implicit mechanisms. Recent evidence demonstrated that the explicit representation of love recruits subcorticocortical pathways mediating reward, emotion, and motivation systems. However, the neural basis of the implicit (unconscious) representation of love remains unknown. To assess this question, we combined event-related functional magnetic resonance imaging (fMRI) with a behavioral subliminal priming paradigm embedded in a lexical decision task. In this task, the name of either a beloved partner, a neutral friend, or a passionate hobby was subliminally presented before a target stimulus (word, nonword, or blank), and participants were required to decide if the target was a word or not. Behavioral results showed that subliminal presentation of either a beloved's name (love prime) or a passion descriptor (passion prime) enhanced reaction times in a similar fashion. Subliminal presentation of a friend's name (friend prime) did not show any beneficial effects. Functional results showed that subliminal priming with a beloved's name (as opposed to either a friend's name or a passion descriptor) specifically recruited brain areas involved in abstract representations of others and the self, in addition to motivation circuits shared with other sources of passion. More precisely, love primes recruited the fusiform and angular gyri. Our findings suggest that love, as a subliminal prime, involves a specific neural network that surpasses a dopaminergic–motivation system. ■

INTRODUCTION

Love, one of the deepest forms of human endeavor, is defined as a complex state involving chemical, cognitive and goal-directed behavioral components (Bianchi-Demicheli, Grafton, & Ortigue, 2006; Aron et al., 2005; Fisher, Aron, & Brown, 2005; Bartels & Zeki, 2000, 2004; Buss, 2003; Mashek, Aron, & Fisher, 2000; Sternberg & Barnes, 1988; Aron & Aron, 1986, 1996; Hatfield & Walster, 1978). When involved in a passionate and intimate relationship, the person actively strives for the happiness of the loved person (Clark & Mills, 1979). Passionate love is often coupled with the inability to feel passion for more than one person at a time (Berscheid & Meyers, 1996). In this sense, love has often been intertwined with passion and defined as a motivated, goal-directed desire (Aron & Aron, 1996; Aron et al., 2005; Ovid, 1986). For instance, the old adage "Do what you love and never have to work another day in your life" illustrates the motivation component of love.

As a goal-directed motivator, love has various behavioral effects. For instance, different explicit effects of love have been reported, such as euphoria, loss of appetite, hyperactivity, delay of the onset of fatigue, and a decreased need for sleep (Aron et al., 2005; Buss, 2003; Sternberg & Barnes, 1988; Hatfield & Walster, 1978). It has also been shown that love has stress-reducing and health-promoting potentials (Esch & Stefano, 2005).

Recently, two functional magnetic resonance imaging (fMRI) studies reinforced the assumption that love is a goal-directed state that leads to a range of emotions, rather than a specific emotion (Aron et al., 2005; Bartels & Zeki, 2000). These studies showed that intense ongoing love, as compared to friendship, recruits subcorticocortical pathways mediating reward, emotion, and motivation systems (Aron et al., 2005; Fisher et al., 2005; Bartels & Zeki, 2000, 2004). More precisely, the blood oxygen level dependent signal (BOLD) specific to explicit viewing of photographs of a loved partner revealed activity focally restricted to the mid insula, anterior cingulate cortex, head of the caudate nucleus, ventral tegmental area, putamen, bilateral posterior hippocampus, left inferior frontal gyrus, left middle temporal gyrus, and cerebellum (Aron et al., 2005; Bartels & Zeki, 2000) as well as the right parietal lobe (only in Aron et al., 2005). Critically, the central role of the dopaminergic–motivation system in ongoing love

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has been emphasized by high positive correlations between the subjective feeling of love (passionate love scale [PLS] scores; Hatfield & Sprecher, 1986) and BOLD responses recorded from the anteromedial caudate nucleus (Aron et al., 2005). Thus, there is now some explicit functional evidence supporting the hypothesis that love, as a motivator, is a powerful source of behavior via dopaminergic circuits (e.g., Berscheid & Meyers, 1996; Sternberg & Barnes, 1988; Aron & Aron, 1986, 1991).

However, it is unknown if the implicit representation of love involves similar motivation/dopaminergic circuits. The previous two functional studies of the neural systems underlying love used only explicit tasks with faces (Aron et al., 2005; Bartels & Zeki, 2000) where explicit perception of familiar stimuli and conscious processing are potential confounds (due to top-down interference) for assessing selective unconscious mechanisms (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene & Changeux, 2000; Dehaene, Kerszberg, & Changeux, 1998). Thus, the true benefit of love and its neural network on information processing without any top-down conscious interference remains unknown.

Here, we specifically assessed this question by combining event-related fMRI and a behavioral lexical decision task embedded in a subliminal priming paradigm, which is one of the more reliable ways of observing unconscious mechanisms if they exist. Subliminal priming is indeed a powerful experimental manipulation that provides a unique opportunity to examine the mechanisms of implicit cognition. Typically, in subliminal priming, a brief presentation (approximately less than 50 msec) of a masked visual stimulus induces a change (e.g., facilitation) in the speed or accuracy of the processing of a following target stimulus (priming effect; e.g., Bianchi-Demicheli et al., 2006; Henson, 2003; Musch & Klauer, 2003; Dehaene, Naccache, et al., 1998; Eimer & Schlaghecken, 1998; Murphy & Zajonc, 1993; Fazio, Sanbonmatsu, Powell, & Kardes, 1986). Facilitation effects due to subliminal priming may occur not only when the relation between primes and targets is a perceptual one, but also when it is a conceptual one (e.g., Spruyt, Hermans, De Houwer, & Eelen, 2004; Musch & Klauer, 2003; Dehaene, Naccache, et al., 1998). Love (as opposed to friendship) can be considered as a goal-directed drive that may induce implicit facilitation effects on cognitive behavior due to motivational and emotional mechanisms rather than a pure selective emotion without any motivational component (Bianchi-Demicheli et al., 2006; Aron et al., 2005). In light of this, one might expect our subliminal priming paradigm used in combination with event-related fMRI to show that the unconscious processing of a beloved's name (as opposed to a control friend's name) facilitates the behavioral processing of a subsequent stimulus through the recruitment of dopamine-rich brain regions (Bianchi-Demicheli et al., 2006; Aron et al., 2005;

Fisher et al., 2005; Aron & Aron, 1986, 1996). However, a beloved's name and a friend's name do not vary exclusively on the motivation dimension. Many variables can induce differential brain activities between these two types of stimuli. One of these variables is the simple frequency with which someone thinks about their significant other, as opposed to their friend. The amount of time someone spends thinking about a beloved or a friend or both may indeed play a crucial role on the salience of each of these stimuli and thus lead to distinct brain activities between these stimuli. In order to exclude this confounding variable, we also included a novel type of prime as a control for frequency of thoughts, that is, a descriptor for a passionate interest, tailored to each individual, that induced frequency of thoughts that were equivalent to the frequency of thoughts about a beloved. Thus, in the present study, each experimental trial was randomly preceded by the subliminal presentation of one out of three different types of visual stimuli (primes): the name of the participant's beloved (love prime), and two control primes, that is, a name of the participant's friend (friend prime), or the participant's passion (passion prime).

This design allowed us to test whether the neural basis of the unconscious mental representation of love depends on (a) motivational/emotional components (by contrasting love primes vs. friend primes and passion primes vs. friend primes), (b) salience of the stimuli (by contrasting love primes vs. passion primes), or both. For instance, although we cannot exclude that passion for a person is different from passion for sports, art, or objects, we assume that love primes and passion primes, as implicit motivators, might share some common neural mechanisms (as opposed to friend primes) that could affect cognition, as previously predicted (Bianchi-Demicheli et al., 2006). This neurofunctional assumption is coherent with the recent Dehaene–Changeux computational model that suggests the reinforcement (via Hebbian-type learning) of conceptual associations by reward-motivated learning mechanisms (Dehaene & Changeux, 2000; Gisiger, Dehaene, & Changeux, 2000). According to this model, the internal representation of a reward signal is coded in n cortical areas of contribution weighted by "synaptic efficacities" $w_0, w_1, \ldots, w_n$. Both reward and expectation signals converge at the level of the ventral tegmental area, and learning modifies synaptic weights to minimize the discrepancies between the two. The output of this ventral tegmental area adequately reproduces dopamine release during performance of various tasks (Gisiger et al., 2000). This Hebbian-based model illustrates the principle of cognitive learning by production and selection of pre-representation. Critically, because this model also posits that mental representations of stimuli may be distributed over different brain areas according to their conceptual structure (Pulvermuller, 1996, 1999), one might expect that our three types of prime stimuli (love, friend, and passion) have overlapping

and partly distinct neural representations on the basis of any differences in contextual encoding.

METHODS

Participants

Thirty-six healthy heterosexual women, aged 20.1 ± 3.2 (mean ± *SD*) years who were dating, engaged, or married to someone and who had a favorite passion in life (e.g., science, sports, art) provided written informed consent to participate in this experiment, which was approved by the Committee for Protection of Human Subjects. Participants were recruited from the Dartmouth College experiment scheduling system on the basis of advertisements indicating that experimenters were seeking individuals who were currently intensively in love. All participants had normal or corrected-to-normal vision, were not taking antidepressant medication, and had no chemical dependency and psychiatric or neurological illnesses. All participants were right-handed (Edinburgh Handedness Inventory, Oldfield, 1971).

Just prior to the scanning session, one of us (S.O.) interviewed each participant in a semistructured format to obtain general personal information (such as date of birth; handedness) and to establish the range of each participant's feelings of passionate love. This semistructured interview, based on standard studies, provided insights into the women's feelings about their beloved, the duration and the intensity of their love relationship, and the percentage of time they think about their beloved during their waking hours (Fisher, 2004; Hatfield & Sprecher, 1986). Then, each participant completed one standard self-report questionnaire: the PLS (Hatfield & Sprecher, 1986; example items: ''For me, (name of the beloved) is the perfect romantic partner''; ''I would rather be with (name of the beloved) than anyone else''; ''I have an endless appetite for affection from (name of the beloved)''. The reported duration of ''being in love'' with their partner was 1–60 months (15.3 ± 14.5 [mean ± *SD*]).

On average, participants had a PLS score of 7.7 ± 1.22 (*SD*) out of 9 points. The participant's subjective intensity of love for their partner was 7.36 ± 1.85 (*SD*) on a 9-point scale.

As part of the same interview, participants were also asked about their passions in life, and every participant provided the name of a passionate hobby. As a selection criterion, only participants who reported thinking about their passion 60% of the day were included in the experiment. A *t* test conducted between percent of thoughts dedicated to the partner and percent of thoughts dedicated to the passion did not reveal any significant difference, $t(35) = 0.299$, $p = .766$. Because this selection criterion was used for all participants, there was a ceiling effect of this variable. No correlation could have been done with reaction times (RTs), accuracy, or functional imaging data. Finally, participants were asked to provide the name of a male friend of similar age, sex and duration of friendship as their partners, with the imposed condition that they did not feel any emotional, physical, or intellectual attraction for him, such that this friend was neutral in the love dimension. The names of the participant's beloved, passion, and friend were used as primes during the fMRI scanning as detailed below.

Procedure

During the scanner session, participants were instructed to perform a lexical decision task each time that they saw a visual stimulus flash onto the screen. They were asked to indicate as rapidly and as accurately as possible whether or not an English word was presented on that trial. Responses were made by pressing one of two response buttons on a keyboard with fingers of the right hand (''yes'' response with the index finger to words and ''no'' response with the middle finger to nonwords or blanks).

The visual stimulus on each trial was composed of a sequence of three frames (Figure 1) following a standard subliminal priming paradigm. First, a prime word was presented for 26 msec, followed by a mask of ########## symbols for 150 msec and then the target word for 26 msec. Stimulus onset asynchrony (SOA; i.e., the interval between the onset of the prime and the onset of the target) was 176 msec. Trials were separated by an interstimulus interval randomly chosen between 1500 and 6000 msec to allow accurate modeling of the hemodynamic response. All stimuli were presented using Cogent 2000 running in Matlab 7.0.1 under Windows XP, which provides control of display durations and accurate recordings of reaction times. Stimuli appeared in lowercase 43-point Courier New font, in white on a black background.

Each trial was composed of one of three primes together with one of 40 words, or one of 40 nonwords, or one of 40 ''blank'' trials, giving a total of 360 possible trials. Each of the possible trials was then randomly assigned to one of six blocks by means of a Latin square, which ensures that each block contained an equal number of beloved primes, passion primes, and friend primes, and an equal number of words, nonwords, and blanks; and words were never presented twice in a block. Trial order within a block was pseudorandomized with the constraint of no more than three consecutive trials with the same target type. Each participant performed six blocks with 60 trials in each block, for a total of 360 trials, which took up to 40 min including breaks between each block.

Prime Stimuli

For each participant, three unique words (3 to 11 characters long) were used as prime stimuli. The first

Figure 1. Experimental design. Stimulus sequence. The visual stimulus on each trial was composed of a sequence of three frames. First, a prime word was presented for 26 msec, followed by a mask of ########## symbols for 150 msec and then the target word for 26 msec. Subjects were not informed of the presence of the prime. The type of target letter strings (emotional words, nonwords, or blanks) and the type of the primes (beloved, e.g., Romeo; neutral friend, e.g., Albert; and passion, e.g., piano) were randomly presented according to a Latin square calculated over the six experimental blocks. This means a target stimulus was not presented twice in the same block in order to avoid any effects of familiarization. In addition, the order of experimental trials was random, with the constraint of no more than three consecutive trials with the same target type.
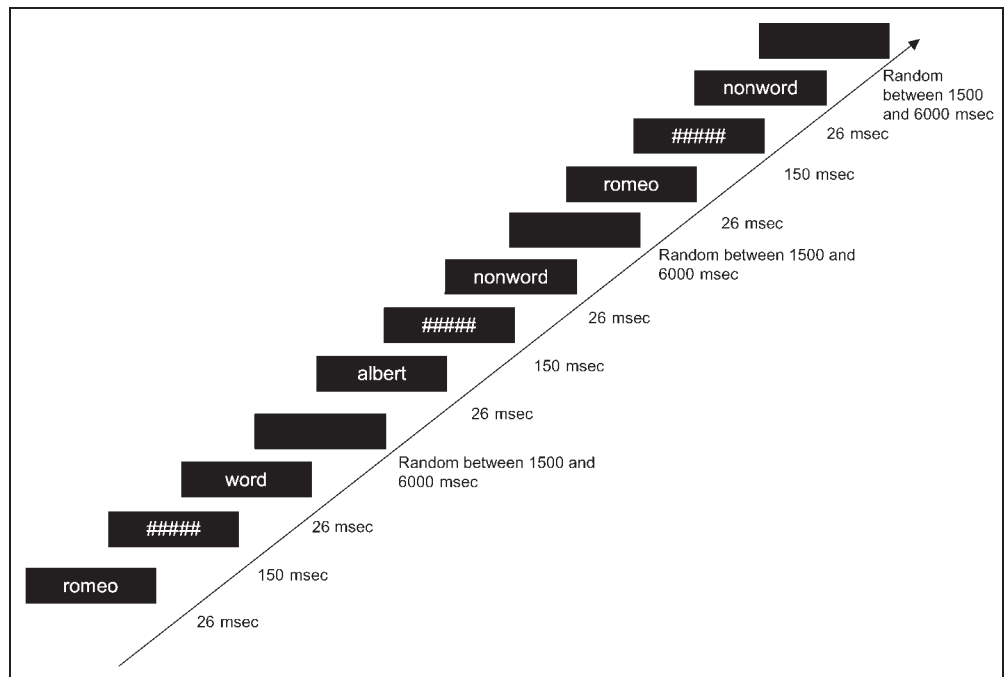
name (either full first name, such as Robert, or shortened first name, such as Bob) of the participant's beloved was designated as the "love prime." No nickname was used in the present study. A noun describing the participant's passion in life (e.g., dance, piano, softball), as supplied by the participant, was designated as the "passion prime," and finally, the name of a friend was designed as the "friend prime" or "control prime." No difference in name length between love, friend, and passion primes was observed, $F(2,70) = 2.69$; $p = .08$. The presence of the prime was not mentioned to the subjects. To check that participants were not aware of the type of prime stimuli, we used an extensive debriefing procedure in which participants were asked increasingly specific questions about the study. This procedure revealed that all participants reported that they had seen the flash of the mask. However, no participant could report on the specific emotional or semantic contents of the flashes.

Target Stimuli

The 80 target letter-string stimuli (3 to 11 characters long) included 40 positive emotional English nouns and a set of 40 pronounceable nonwords (following the same consonant/vowel structure as words). Emotional words were selected from the Affective Norms for English Words (Bradley & Lang, 1999). In order to control any effect of word frequency, one half of the words

were selected to be high in written word frequency, and the other half were low in written word frequency according to the Kucera and Francis linguistic database (Kucera & Francis, 1967). In addition, a 2×3 analysis of variance (ANOVA) performed between low- versus high-frequency targets and the prime types did not show any main interaction: $F(2,70) = .44$, $p = .65$ for reaction times; $F(2,70) = .41$, $p = .96$ for accuracy. All words were selected to be high in valence and high in arousal (Bradley & Lang, 1999). High- ($M = 220.95$, $SD = 144.67$) and low-frequency ($M = 27.6$, $SD = 27.13$) emotional words were matched in word length (high-frequency words: $M = 5.9$, $SD = 1.48$; low-frequency words: $M = 6.3$, $SD = 1.95$; $p = .48$), valence (high-frequency words: $M = 7.40$, $SD = 0.64$; low-frequency words: $M = 7.55$, $SD = 0.66$; $p = .57$), arousal (high-frequency words: $M = 5.89$, $SD = 0.44$; low-frequency words: $M = 6.42$, $SD = 1.17$; $p = .054$), abstractness (high-frequency words: $M = 407,38$, $SD = 123,64$; low-frequency words: $M = 404.6$, $SD = 118.84$; $p = .95$; Coltheart, 1981).

Magnetic Resonance Imaging

Imaging was performed with a 3T Phillips MRI scanner using an eight-channel phased-array head coil. For each functional run, an echo planar gradient-echo imaging sequence sensitive to BOLD contrast was used to acquire 30 slices per repetition time (TR) (4 mm thickness,

0.5 mm gap), with a TR of 1976 msec, echo time (TE) of 35 msec, flip angle of 90°, field of view (FOV) of 240 mm, and 80 × 80 matrix. One hundred fifty-seven whole-brain images were collected in each run. After all the functional runs, a high-resolution T1-weighted image of the whole brain was acquired using a spoiled gradient recalled 3-D sequence (TR = 9.9 msec; TE = 4.6 msec; flip angle = 8°, FOV = 240 mm; slice thickness = 1 mm, matrix = 256 × 256).

Functional Image Processing

All analysis was carried out in SPM2 (www.fil.ion.ucl.ac.uk/spm). First, functional images were realigned to correct for head movement. Then, data were coregistered to the SPM2 EPI template, and normalized to a standardized Montreal Neurological Institute (MNI) stereotaxic space to give images with 2 × 2 × 2-mm voxels. A design matrix was fitted for each subject with the trials in each cell of the three-by-three factorial design (3 primes × 3 target types) modeled by a standard hemodynamic response function and its temporal derivative. Each trial was modeled as a single event with zero duration, starting at the onset of the prime stimulus. Rest was not modeled. The design matrix weighted each raw image according to its overall variability to reduce the impact of movement artifacts (Diedrichsen & Shadmehr, 2005). The design matrix was fit to the data for each participant individually. After estimation, betas were smoothed (10-mm full width half maximum) and taken to the second level for random effect analysis.

Second−level Data Analysis

Our analysis aimed to identify which brain areas within the standard ''prime network'' were preferentially activated by love and passion regardless of the target type. To this purpose, we first identified the brain regions involved in the primed lexical decision task. This contrast of all primes > rest was thresholded at $p < .001$ uncorrected and used to generate an inclusive mask of the priming network in the brain. Within this mask, we calculated contrasts for love > friend, passion > friend, love > passion, and passion > love, and report results that passed a threshold of $p < .01$ and a cluster size of 10 voxels. We used a masking approach to restrict the likelihood of false positives rather than a region-of-interest approach, because the lack of previous studies of subliminal priming for love and passion means that we cannot make strong a priori predictions of the locations of our results.

RESULTS

Behavioral Results

In order to compare our results with two previous fMRI studies (Aron et al., 2005; Bartels & Zeki, 2000)

that used a recruitment method similar to ours, we first calculated correlations between the various scores we obtained. We tested whether the questionnaire data correlated significantly with relationship length or percent of thoughts (or whether any of these variables correlated with each other); they did not (Table 1). That is, as was found by Aron et al. (2005), there were no significant correlations among PLS scores and length of being in love (Pearson correlation, $r = .15$, $p = .39$). Because in the present study, scores obtained at the PLS, 9-point scale, and the percent of daily thoughts dedicated to the beloved were highly correlated with each other (Table 1), we calculated a composite measure by combining the individual measures of these three scales (averaged as Z scores). There was no correlation between this composite measure and length of being in love (Pearson correlation, $r = .15$, $p = .38$; Table 1).

Our behavioral results showed that both the subliminal presentation of passion (580 ± 19.58 msec [mean ± SE]) and love (581 ± 19.92 msec [mean ± SE]) induced beneficial effects (faster reaction times) on the explicit detection of words, love: $F(1,35) = 5.22$; $p = .03$; passion: $F(1,35) = 6.74$; $p = .01$, compared to the subliminal presentation of a control friend's name (607 ± 23.4 msec [mean ± SE]). No behavioral difference was found between love and passion ($p = .95$). No specific beneficial effect of prime was found for nonword detection, $F(2,70) = 0.15$; $p = .87$. However, a general main effect of prime was found independently of the target, $F(2,70) = 4.09$; $p = .02$, indicating that subjects were faster to respond after a beloved prime (608 ± 19.49 [mean ± SE]) or a passion prime (607 ± 19 [mean ±

Table 1. Pearson's r Correlation Coefficient between Each Measure of Love (PLS, 9-Point Scale, and Percent of Thoughts) and Length of Duration

Pearson's r Correlation Coefficient	PLS	9-Point Intensity Scale	Percent of Thoughts	Length of Duration	Composite
PLS	1	S***	S***	ns	–
9-Point intensity scale	.86	1	S***	ns (trend)	–
Percent of thoughts	.73***	.61***	1	ns	–
Length of duration	.15	.33	−.02	1	.15
Composite	–	–	–		1

Composite averages the individual measures of the three love scales (as Z scores), that is, PLS, 9-point intensity scale, and percent of thoughts. PLS = passionate love scale; S = significant; ns = nonsignificant, $p > .05$; trend = trend of significance, $.05 < p < .06$.

***$p < .001$.

SE]) than after a friend prime (621 ± 21.41 [mean ± *SE*]). A 2 × 3 ANOVA involving simple effects of primes (love, friend, passion) and letter-string types (words, nonwords) revealed a trend of significant interaction, $F(2,70) = 2.83, p = .06$, suggesting that participants tend to be faster in detecting target words (and not nonwords). This effect occurred especially if the target words were primed by love/passion (as opposed to friendship). An overall 3 × 3 ANOVA did not show any interaction between the different types of targets (words, nonwords, blanks) and the different types of primes (love, friend, passion), $F(4,140) = 1.79; p = .13$, mainly due to absence of main effect of primes for a blank target, $F(2,70) = 0.28, p = .75$.

A trend of negative correlation was observed between PLS scores and reaction times (the more participants were in love, the faster they were) for target stimuli primed by a beloved's name (Pearson correlation, $r = -.29, p = .04$). A similar trend of correlation was found between PLS scores and reaction times to passion primes (Pearson correlation, $r = -.29, p = .04$). No similar correlation was found between PLS scores and reaction times to friend primes (Pearson correlation, $r = -.25, p = .07$). A test evaluating the significance of differences between these two correlation coefficients ($r = -.25$ and $r = .29$) was nonsignificant ($p = .86$).

In addition, a negative correlation was found between the percentage of daily thoughts for the partner and reaction times (the more participants thought about their beloved every day, the faster they were) for target stimuli primed by a beloved's name (Pearson correlation, $r = -.40, p = .008$). A similar negative correlation was also found between percentage of thoughts for the beloved and reaction times to passion primes (Pearson correlation, $r = -.38, p = .01$) as well as with reaction times to friend primes (Pearson correlation, $r = -.29, p = .04$). A test evaluating the significance of differences between the two correlation coefficients related to love and passion primes ($r = -.40$ and $r = -.38$) or between love/passion and friend primes was nonsignificant (love vs. passion: $p = .92$; love vs. friend: $p = .61$; passion vs. friend: $p = .68$).

No significant correlation was observed between length of love relationship and reaction times (Pearson correlation, for beloved primes: $r = .21, p = .11$; for friend primes: $r = .20, p = .12$; for passion primes: $r = .24, p = .08$).

No significant effects were observed for accuracy. An overall 3 × 3 ANOVA did not show any interaction between the different types of targets and primes, $F(4,140) = .78, p = .54$. A 2 × 3 ANOVA involving simple effects of primes (love, friend, passion) and letter-string types (words, nonwords) did not reveal any significant interaction, $F(2,70) = 0.037, p = .96$. There was no main effect of love, $F(1,35) = 0.93, p = .34$, or passion, $F(1,35) = 0.68, p = .41$, on the detection of target words, compared to the subliminal presentation of neutral

friend's name. There was also no specific beneficial effect of prime on target nonword detection, $F(2,70) = 0.06; p = .94$, or target blank detection, $F(2,70) = 0.49, p = .61$. No general main effect of prime was found independently of the target, $F(2,70) = 0.31; p = .73$.

Functional Imaging Results

First, our functional results showed that the subliminal presentation of a beloved's name (as opposed to a friend's name) recruited a cerebral network that is partly concordant with the cerebral network previously found for the explicit presentation of love-related stimuli (Aron et al., 2005; Bartels & Zeki, 2000). More precisely, in comparison with a control stimulus (love > friend contrast), the subliminal presentation of a beloved's name recruited the caudate nucleus, ventral tegmental area, insula, bilateral fusiform regions, parahippocampal gyri, angular gyrus, left dorsolateral middle frontal gyrus, left inferior temporal gyrus, occipital cortex, and cerebellum (Table 2). The two previous studies (Aron et al., 2005; Bartels & Zeki, 2000) that investigated the explicit mechanisms of love using a similar contrast showed brain area activation restricted to the mid insula, anterior cingulate cortex, head of the caudate nucleus, ventral tegmental area, putamen, bilateral posterior hippocampus, left inferior frontal gyrus, left middle temporal gyrus, and cerebellum as well as the right parietal lobe (only in Aron et al., 2005).

On the other hand, our study demonstrated that the subliminal presentation of another motivator, such as a passion's descriptor (as compared to a friend's name, i.e., passion > friend contrast), showed greater activation in the caudate nucleus, insula, bilateral fusiform regions, parahippocampal gyri, right angular gyrus, occipital cortex, lingual gyrus, and cerebellum (Table 2). Taken together, our functional results thus showed potentially overlapping brain activation between love (love > friend contrast) and passion primes (passion > friend contrast). Both love primes (love > friend contrast) and passion primes (passion > friend contrast) led to increases in BOLD signal in regions within motivation and emotion systems, compared with a control friend prime ($p < .01$; Table 2). Specifically, both love and passion primes activated the caudate nucleus, insula, bilateral fusiform regions, parahippocampal gyrus, right angular gyrus, occipital cortex, and cerebellum.

Finally, when we directly compared BOLD responses obtained from love and passion primes ($p < .01$; Figure 2; Table 2), we found some differences of brain activation. Love primes (as opposed to passion primes, love > passion contrast) revealed significant activation in bilateral angular gyri (Table 1; in orange in Figure 2A and B); and bilateral fusiform regions (Table 2; in orange in Figure 2C and D).

On the other hand, passion primes (as opposed to love primes, passion > love contrast) showed significant

**Table 2.** MNI Coordinates of Cerebral Activation Peaks

Regions	Coordinates				Love > Friend		Passion > Friend		Love > Passion		Passion > Love	
	x	y	z	t	t	Cluster Size	t	Cluster Size	t	Cluster Size	t	Cluster Size
Thalamus	6	−8	10	6.14								
Caudate nucleus	6	12	0	5.34	4.39	80	3.49	193				
Brainstem/midbrain	6	−22	−22	4.90	3.21	13						
Insula	−26	20	−4	4.97	3.75	2275	3.47	7				
	36	−4	2	3.73	3.72	291	3.01	193				
Occipitotemporal/ fusiform region	36	−88	−18	5.33	2.38	49					2.58	17
	−48	−50	−24	4.65	3.33	57	2.62	17	3.11	148		
	64	−52	16	4.25			2.47	21	2.66	113		
	−56	−70	−2	3.47							3.18	52
Parahippocampal gyrus	34	−18	−28	5.03	4.06	405	2.71	21				
	−40	−8	−34	4.91	2.79	46	3.15	100			3.30	191
Angular gyrus	−64	−50	22	4.35					2.65	51		
	66	−44	32	4.33	2.45	27	2.62	46	2.43	68		
Dorsolateral middle frontal gyrus	−46	26	26	4.51	3.09	112						
	52	38	22	3.78								
Superior temporal gyrus	66	−14	−8	4.18								
Inferior temporal gyrus	−44	−26	−20	4.39	2.70	43					2.40	21
	−64	−22	−10	4.52								
Occipital cortex	−18	−96	−8	6.00	2.51	138	2.61	42				
	18	−94	−8	5.22			3.72	744				
Precuneus	16	−76	20	4.32								
Lingual gyrus	−12	−68	−2	4.05			2.41	52				
Cingulate gyrus	10	−40	20	3.97								
	−6	−42	8	3.25							3.21	19
Precentral gyrus	64	2	24	3.66							2.96	160
Cerebellum	12	−48	−38	5.17	2.76	142	3.48	518				
	−36	−78	−52	4.04	4.3	651	4.45	510			2.63	184

activation in the bilateral temporo-occipital junction, left parahippocampal and inferior temporal gyrus, left cingulate gyrus, right precentral gyrus, and cerebellum (Table 2; in blue in Figure 2).

In order to specifically compare our results with those obtained previously by Aron et al. (2005), we performed a between-subjects random effect analysis correlating BOLD responses and participant's scores on the PLS scores, first focusing on the love > friend contrast, as the Aron et al. analysis did. This method used previously by Aron et al. is known to provide strong evidence for the link of a function with an activated area. In the Aron et al. study, PLS scores had high positive correlations with activation in two of the regions that were significant for the contrast by itself, the right anteromedial caudate body ($r = .60, p = .012$) and the septum–fornix region ($r = .54, p = .008$). That is, the Aron et al. study participants who self-reported higher levels of love than others also showed greater activation than others in this region of the caudate and septum when viewing their beloved (Aron et al., 2005). (For planned comparisons, Aron et al. applied small volume corrections with a sphere as a region of interest. The coordinates for the centers of the following regions of interest were reported: VTA, caudate nucleus, putamen, accumbens/ subcallosal cortex/ventral striatum, amygdala, posterior

Figure 2. BOLD responses obtained for love compared to passion (love > passion in orange; passion > love in blue), shown on lateral views of the fiducial left and right side of the brain. BOLD time courses, averaged over prime type (red, love; blue, passion; yellow, friend) were extracted for the significant regions between love and passion (love > passion) contrasts and are shown for the angular gyrus (A, left; B, right) and fusiform gyrus (C, left; D, right). Brain activities were mapped using the PALS human cortical atlas from Caret5 software (Van Essen, 2005).
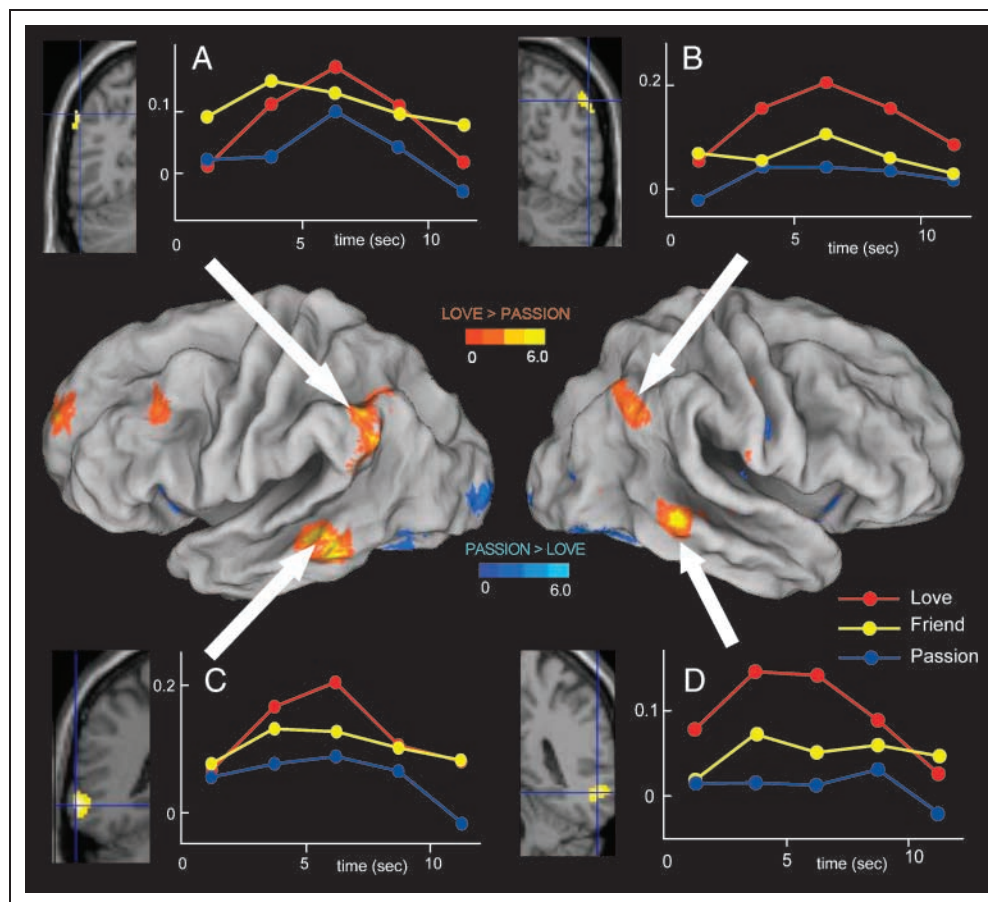
hippocampus, cingulate, insula, retrosplenial cortex, and medial and lateral orbitofrontal cortex). As we did for our previous analyses described above, we performed this focused "love > friend contrast" between-subjects random effect analysis within the prime network (as described in Table 2). We corrected our correlations for multiple comparisons and only allowed a significant threshold at $p < .01$. Our results showed similar and also distinct findings as compared to the findings of Aron et al. Focusing on the love > friend contrast, our findings showed that PLS scores had high positive correlations with activation in some of the cerebral regions that were significant for the contrast by itself, that is, the caudate nucleus ($r = .48$, $p = .003$), right parahippocampal gyrus (Pearson correlation, $r = .46$, $p = .005$), angular gyrus ($r = .39$, $p = .01$), insula (left: $r = .41$, $p = .01$; right: $r = .38$, $p = .02$), ventral tegmental area ($r = .38$, $p = .02$), and the left dorsolateral middle frontal gyrus ($r = .40$, $p = .01$). That is, participants who self-reported higher levels of love than others exhibited greater activation than others in these brain regions.

A similar method of analysis applied for the passion > friend contrast (as reported in Table 2) did not reveal similar significant correlation between BOLD responses and participant's scores on the PLS scores.

Focusing on the love > passion contrast (as described in Table 2), we found the same method of analysis showed high positive correlations between PLS scores and three of the cerebral regions that were significant for the contrast by itself, the left angular gyrus (Pearson correlation, $r = .50$; $p = .002$; Figure 3, Table 3) and the fusiform region bilaterally (left: $r = .46$; $p = .005$; right: $r = .47$; $p = .003$; Table 3). That is, participants who self-reported higher levels of love than others also exhibited greater activation than others in these brain regions. Because no studies have investigated the love > passion contrast previously, we also performed additional analyses correlating BOLD responses and the different love measures (9-point subjective intensity scale, percent of thoughts, length of being in love). This approach offers a broad overview of the present findings, although they were highly correlated with each other (as shown in Table 1). The 9-point subjective intensity scale had similarly correlated with the same brain regions: the left angular gyrus ($r = .43$, $p = .009$) and the fusiform region bilaterally (left: $r = .46$, $p = .005$; right: $r = .44$, $p = .007$; Table 3). On the other hand, percent of thoughts only showed a positive correlation with the right fusiform region ($r = .43$, $p = .008$) and a trend to a positive correlation with the left angular gyrus ($r = .396$, $p = .017$; Table 3). No correlation was observed between the
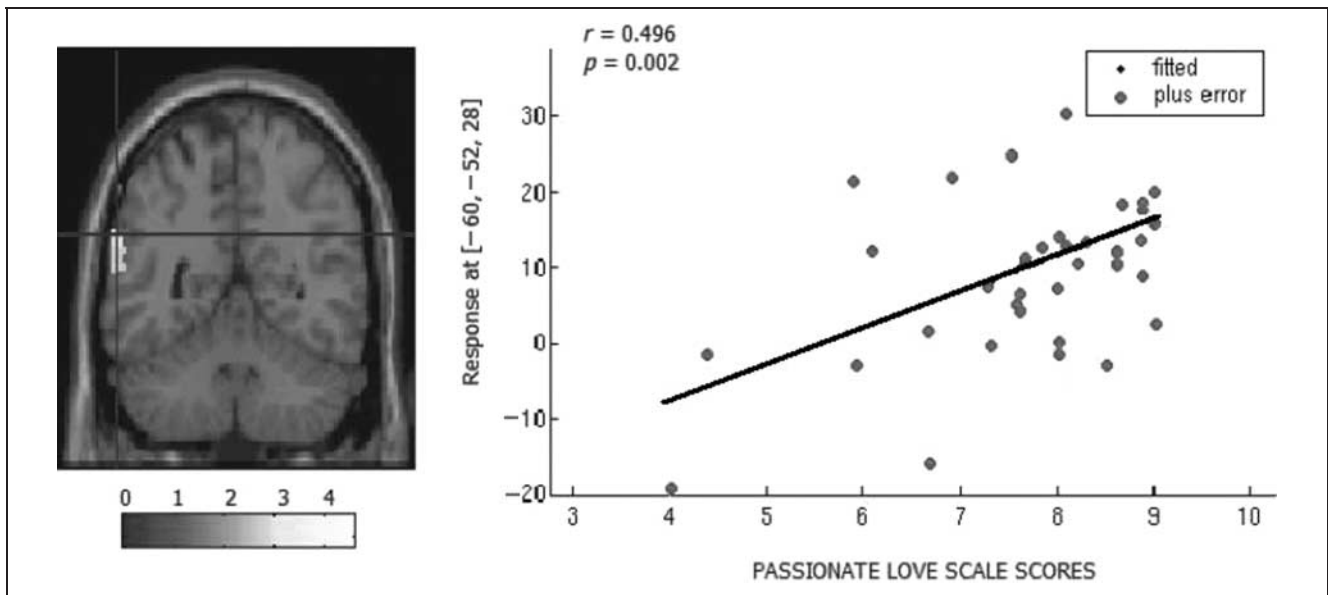
Figure 3. Brain activation correlated with the passionate love scale (PLS) scores of participants ($p < .01$ corrected). (Left) Angular gyrus location for the correlation. (Right) Correlation of activity in the left angular gyrus with PLS scores. Participants who scored higher on the PLS scale showed stronger activations in a specific site ($-60, -52, 28$; x, y, z [mm] MNI coordinates) of a larger part of the angular gyrus.

length of time in love and the regions that were significantly activated for this specific contrast.

DISCUSSION

Taken together, our results provide the first functional evidence that the subliminal presentation of a beloved's name (as compared to a friend's name) activates a specific pattern of brain activity, and these regions are more active for people who are more in love. This network for implicit effects of a beloved's name is partly concordant with the love-related network demonstrated by previous studies that investigated the explicit mechanisms of love. Nevertheless, our findings also reveal the involvement of some distinct brain areas. Thus, our results may have important future implications for understanding the unconscious mental representation of love in the brain.

Love as an Implicit Motivator

First, we aimed to test whether facilitation priming effects could occur for unconscious representation of a beloved's name using a subliminal priming paradigm. The results are clear-cut. Two main results are important in this respect. First, we found that participants were faster to detect target stimuli when subliminally primed by a beloved's name, and not when subliminally primed by a friend's name. This phenomenon occurred especially for word detection. This demonstrates that the subliminal facilitation effect of love occurs at an associative level rather than a perceptual level. Women in love are not inherently faster based on a general emotional arousal but they are faster because of the mental associations they unconsciously created in their mind in relation to their internal state of being passionately in love. This indicates that subliminal passionate/emotional associations are sufficient to lead to automatic priming

Table 3. MNI Coordinates of Correlations between BOLD Responses for Love Minus Passion and Three Different Measures of Love (PLS, 9-Point Scale, and Percent of Thoughts)

Regions	Coordinates				Love > Passion	PLS Scores		9-Point Scale		Percent of Thoughts	
	x	y	z	t		p	Cluster Size	p	Cluster Size	p	Cluster Size
Occipitotemporal/ fusiform region	−48	−50	−24	4.65	3.11	.005	37	.005	23	–	–
	64	−52	16	4.25	2.66	.003	115	.007	24	.008	49
Angular gyrus	−64	−50	22	4.35	2.65	.002	210	.009	40	.017	8
	66	−44	32	4.33	2.43	–	–	–	–	–	–

on the basis of associative relatedness, which is defined as the extent to which the activation of one concept will call to mind another concept (e.g., Spruyt et al. 2004). Moreover, as expected, we found similar facilitation effects with a passion prime, in comparison with a friend prime. This highlights that the observed associative relatedness does not only call on emotional associations, but also on motivation mechanisms. This is coherent with Hebbian models of cortical language representation, which suggest that the representations of words are considered to include not only words' visual forms, but also their related memories (e.g., sounds, smells), and contextual encoding (Pulvermuller, 1996, 1999). Within such a Hebbian model, the behavioral priming effect arises when subliminal love or passion primes activate mental representations that are part of that particular state and, thus, implicitly modulates behavior, as previously suggested for other facilitation priming effects (Fergusson & Bargh, 2004; Innes-Ker & Niedenthal, 2002; Dehaene, Naccache, et al., 1998). In other words, our data suggest that the representation of a beloved's name may call for a goal-directed state sustained by higher order mechanisms rather than a specific emotion without any motivational or reward components (Bianchi-Demicheli et al., 2006; Aron et al., 2005; Aron & Aron, 1986). These selective facilitation effects also suggest underneath associative mechanisms that may be due to implicit automatic spreading of activation from both emotional and motivational associations (e.g., Spruyt et al., 2004; Musch & Klauer, 2003; Innes-Ker & Niedenthal, 2002).

Unconscious Mental Representation of a Loved One

Our fMRI results show that the subliminal presentation of a beloved's name (as compared to a friend's name) activates some cortical regions that are known to be also recruited during the conscious presentation of beloved's faces (Aron et al., 2005; Bartels & Zeki, 2000). Thus, our results suggest that the subliminal presentation of love-related stimuli correspond to variations in neural response that extend beyond a visual memory for subliminal words. The subliminal presentation of a beloved's name may implicitly activate the structural visual form of the word and also a more complex representation of the beloved. In agreement, our fMRI results highlight that love calls for higher order motivational and reward mechanisms rather than a specific emotion per se. First, the overlap between the neural network observed for love primes (love > friend contrast) and that observed for passion primes (passion > friend contrast) demonstrates that both love and passion primes recruited emotion/motivation/dopamine systems (Aron et al., 2005; Bartels & Zeki, 2000; Gisiger et al., 2000). In accordance with the Dehaene–Changeux model as well as the Aron et al. (2005) motivation assumption, these results reinforce our behavioral results by demonstrating dopaminergic-driven facilitation effects of both love and passion on reaction times. Then, the subliminal presentation of a beloved's name (as opposed to another motivator such as a passion's descriptor, love > passion contrast) also show activation in higher order brain areas, such as those known to be involved in conceptual thinking and metaphors (von Bubnoff, 2005). These differences of brain activation contrast with the equivalent behavioral results we obtained for passion and love primes. Although this result might seem surprising, it is coherent with Hebbian models of cortical language representation, which suggest that the representations of words may be segregated throughout cerebral hemispheres by their conceptual structures (Gisiger et al., 2000; Pulvermuller, 1996, 1999).

Love and the Self

Critically, love primes recruited bilateral fusiform and angular gyri, two brain regions involved in integration of abstract representations (Arzy, Seeck, Ortigue, Spinelli, & Blanke, 2006; Jackson, Brunet, Meltzoff, & Decety, 2006; Saxe & Kanwisher, 2003; Blanke, Ortigue, Landis, & Seeck, 2002). Although some might attribute our effects to some bottom-up attention mechanisms because of the specific salience of the subliminal stimuli (Anderson, 2005; Corbetta & Shulman, 2002; Anderson & Phelps, 2001), this could not account for all brain activations. For instance, even if we agree that arousal mechanisms may take place when contrasting primes with different salience (such as ''love > friend'' or ''passion > friend''), automatic arousal mechanisms could not explain the difference of brain activation between two stimuli with equivalent salience, or at least with equivalent frequency of thoughts on target (such as love primes and passion primes). Instead, the implication of these brain areas calls for higher order mechanisms. Our assumption is reinforced by the positive correlation between BOLD responses in these brain areas and the different measures of love (PLS scores, intensity, and percent of thoughts). On the other hand, the absence of correlation between brain activation in these brain areas and the length of being in love underlines that the fusiform region and the angular gyrus do not seem directly ''love time dependent.'' This is coherent with the only previous study that assessed this question (Aron et al., 2005) and showed changes in several regions as the relationship changes, but not in the angular gyrus and the fusiform regions. Instead, activity related to the length of the relationship was found in the right insula, the right anterior and posterior cingulate cortex, and the right posterior cingulated/retrospenial cortex (Aron et al., 2005).

Moreover, a growing body of evidence demonstrates that the angular and fusiform gyri not only call for automatic attentional mechanisms but also higher order

processes, such as episodic retrieval and conceptual knowledge (Ashby & O'Brien, 2005; Giesbrecht, Camblin, & Swaab, 2004). For instance, love could be considered as a learned response from episodic memories and positive associative reinforcements that may be primary (such as pleasant feeling) and secondary (such as mental association between the beloved's presence and good feelings; Brehm, Miller, Perham, & Miller, 2002; Smith & Queller, 2000; Carlston & Smith, 1996; Sternberg & Barnes, 1988). More critically, the angular gyrus is known to be involved in the abstract representation of the self (Arzy et al., 2006; Blanke et al., 2002). This lets us speculate that the unconscious representation of a beloved's name is among others directed to the self. This is concordant with previous studies suggesting that intense lifetime achievements (e.g., love) are a central human motivation to "expand the self" (Aron & Aron, 1986, 1996; Epstein, 1973; Rogers, 1969; White, 1959). Our findings are also in agreement with theories in social psychology suggesting that the expansion of the self involves two phases: expansion, then integration of each new expansion by incorporating aspects (e.g., new skills, attitudes, resources, behaviors) of another into the self (Aron & Aron, 1986, 1996; Hatfield & Walster, 1978; Epstein, 1973; Rogers, 1969; Bataille, 1962; White, 1959). The angular gyrus is important in (a) integration of abstract representations of others (Jackson et al., 2006), (b) social cognition related to the ability to reason about the contents of mental states, such as desire (Saxe & Kanwisher, 2003), or both. In addition, the temporoparietal junction is an association brain area considered pivotal in carrying out cross-modal information (Bremmer, Schlack, Duhamel, Graf, & Fink, 2001; Calvert, Campbell, & Brammer, 2000). This is of particular importance for the concept of love, which is based on multidimensional components (Sternberg & Barnes, 1988; Hendrick & Hendrick, 1986). Because "a love experience will not expand the self if it cannot be integrated" (Aron & Aron, 1986; James, 1890/1950), this brain area might be crucial for self-expansion by integrating different love-related sensations and extracting a common, abstract representation from them.

Possible Limitations and Future Directions

There are some factors that restrict our interpretation of the data in this study and that could be examined more closely in the future. Because there are not many previous studies of the neural basis of love and none about the neural basis of passion, our study constitutes a first step and includes some limitations. First, because no study has previously unraveled the implicit neural basis of love and passion, we did not feel justified in using only regions of interest, which might exclude important and novel results. In particular, the reliance on a priori regions of interest increases the likelihood that researchers focus on a narrowly defined

set of brain areas for particular cognitive functions. Although that approach is appropriate for cognitive processes such as face recognition where the neural substrates are well defined, the field of fMRI research into love and abstract concepts is so novel that we do not feel a region-of-interest approach is sensible. By using a masking approach, we are able to obtain adequate protection against false positives without limiting our conclusions.

Second, in our experiment the participants were only women. This selection criterion could make the results a bit different from those obtained in the two previous studies that used a mix of genders (Aron et al., 2005; Bartels & Zeki, 2000).

Finally, due to the absence of a "passionate scale" for hobby, as was available for love, no correlation between intensity of passion and BOLD responses could be done in the present study. This area would benefit from the development of standardized questionnaires evaluating the different types and degrees of passion. This would be helpful to better understand the neural modulation of a passion with respect to its intensity.

Our study of subliminal love primes is the first fMRI investigation of this phenomenon, which is considered to be both a concept and a motivational factor. Further work will be needed to distinguish between different types of passions (for objects or for hobbies) and different types of love (for a partner or a child) and to better understand the conceptual framework underlying love representations in the brain.

Conclusion

The present study reveals that the neuroscience of love might provide not only essential clues for understanding emotion and motivation systems, but also how one's unconscious may be enhanced by desire.

Acknowledgments

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