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Reward, Motivation, and Emotion Systems Associated With Early-Stage Intense Romantic Love

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Aron, Arthur, Helen Fisher, Debra J. Mashek, Greg Strong, Haifang Li, and Lucy L. Brown. Reward, motivation, and emotion systems associated with early-stage intense romantic love. *J Neurophysiol* 94: 327–337, 2005; doi:10.1152/jn.00838.2004. Early-stage romantic love can induce euphoria, is a cross-cultural phenomenon, and is possibly a developed form of a mammalian drive to pursue preferred mates. It has an important influence on social behaviors that have reproductive and genetic consequences. To determine which reward and motivation systems may be involved, we used functional magnetic resonance imaging and studied 10 women and 7 men who were intensely "in love" from 1 to 17 mo. Participants alternately viewed a photograph of their beloved and a photograph of a familiar individual, interspersed with a distraction-attention task. Group activation specific to the beloved under the two control conditions occurred in dopamine-rich areas associated with mammalian reward and motivation, namely the right ventral tegmental area and the right postero-dorsal body and medial caudate nucleus. Activation in the left ventral tegmental area was correlated with facial attractiveness scores. Activation in the right anteromedial caudate was correlated with questionnaire scores that quantified intensity of romantic passion. In the left insula-putamen-globus pallidus, activation correlated with trait affect intensity. The results suggest that romantic love uses subcortical reward and motivation systems to focus on a specific individual, that limbic cortical regions process individual emotion factors, and that there is localization heterogeneity for reward functions in the human brain.

INTRODUCTION

Intense romantic love is a cross-culturally universal phenomenon. In a survey of 166 contemporary societies, Jankowiak and Fischer (1992) found evidence of romantic love in 147 of them; they noted that the 19 remaining cases were examples of ethnographic oversight—the anthropologists failed to ask the appropriate questions; they found no negative evidence. They concluded that romantic love constitutes a "human universal. . .or near universal" (Jankowiak and Fischer 1992). Romantic love is also associated, particularly in early stages, with specific physiological, psychological, and behavioral indices that have been described and quantified by psychologists and others (Fisher 1998; Gonzaga et al. 2001; Harris and Christenfeld 1996; Hatfield and Sprecher 1986; Hatfield et al. 1988; Shaver et al. 1987; Tennov 1979). These include emotional responses such as euphoria, intense focused attention on a preferred individual, obsessive thinking about him or her, emotional dependency on and craving for emotional union with this beloved, and increased energy. Tennov (1979) coined the term "limerance" for this special state, and Hatfield and Sprecher (1986) developed a questionnaire scale to measure it. The universality, euphoria, and focused attention of romantic love suggest that reward and motivation systems in the human brain could be involved (Fisher 1998; Liebowitz 1983).

In addition, cross-cultural descriptions of romantic love regularly include reward-related images and suggest strong motivation to win a specific mating partner. For example, the oldest love poem from Summeria, "Inanna and Dumuzi," dating ~4,000 yr ago and found on cuneiform tablets in the Uruk language is translated, "My beloved, the delight of my eyes. . ." (Wolkstein and Kramer 1983). From the Song of Songs, the Hebrew 10th century poem comes, ". . .your love is more wonderful than wine . . .the sound of your name is perfume . . . . I sought the one my soul loves. . ." (Wolkstein and Kramer 1983). Furthermore, among the ethnographies canvassed in the review of Jankowiak and Fischer (1992) is one by Harris (1995) who cited evidence of the yearning for love and the motivation to win the beloved among the peoples of Mangaia, Cook Islands, Polynesia. These people have a word for "dying for love." They translate it as, "You don't want anything else; you die for love, but you don't mind if you die; you don't feel ashamed about loving that person to death. If you really love someone nothing will stop you." Worldwide, romantic love plays a key role in courtship, suggesting that it evolved as a primary aspect of the human mating system (Fisher 1998). Its ubiquity and strong, measurable properties make it an excellent candidate for understanding the human neural systems associated with reward, positive emotion, and attention, as well as the neurobiology of an important phase in human reproductive relationships, which have genetic consequences.

We used functional MRI (fMRI) methods to test two predictions about the neural systems involved in romantic love. First, romantic love would specifically involve subcortical regions that mediate reward, such as the ventral tegmental area (VTA) and ventral striatum/nucleus accumbens (Esposito et al. 1984; Hollerman et al. 2000; McBride et al. 1999; Porrino et al. 1984; Robbins and Everitt 1996; Schultz 2000; Wise and Hoffman 1992). Several of the behavioral aspects of romantic love suggest that it can be like cocaine-reward producing exhilaration, excessive energy, sleeplessness, and loss of ap-

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petite (Fisher 1998). Consistent with animal studies of cocaine addiction (David et al. 2004; Kalivas and Duffy 1998; McBride et al. 1999; Wise and Hoffman 1992), acute cocaine injection has been shown to activate the VTA in fMRI studies of humans (Breiter et al. 1997). In addition, fMRI studies have shown that secondary rewards like money activated the nucleus accumbens/subcallosal region and VTA (Breiter et al. 2001; Delgado et al. 2000; Elliott et al. 2000, 2003, 2004; Knutson et al. 2001). Furthermore, chocolate, acting as a food reward, activated the VTA and subcallosal region (Small et al. 2001). These regions decreased their metabolic activity with decreasing desire for more chocolate. More data implicating reward regions and dopamine as an important neurotransmitter for the feelings and behaviors of romantic love have been summarized previously (Fisher 1998).

In addition to basic reward functions, further evidence from studies of monogamous prairie voles suggests that the nucleus accumbens, striatum, and dopamine could be involved in human romantic love. When a female prairie vole is mated with a male, she forms a distinct preference for this partner; however, when a dopamine agonist is infused into the nucleus accumbens, she begins to prefer a male present at the time of infusion, even if she has not mated with this male (Gingrich et al. 2000; Liu and Wang 2003). Furthermore, a striatal output region through the ventral pallidum is strongly implicated as critical to male prairie vole mate preference behaviors (Lim et al. 2004). Also, electrochemical studies in male rats have shown increased dopamine release in the dorsal and ventral striatum in response to the presence of a receptive female rat, more so even than during copulation (Montague et al. 2004; Robinson et al. 2002). These data suggest that the nucleus accumbens and dopamine release are major factors underlying rodent mate preference. Thus several lines of evidence from both human fMRI and animal studies support the prediction that multiple reward regions using dopamine could be activated during feelings of romantic love.

Our second prediction about the neural systems involved in early-stage romantic love was that it would be associated with other goal and reward systems, such as the anterior caudate nucleus. The caudate plays a role in reward detection and expectation, the representation of goals, and the integration of sensory inputs to prepare for action (e.g., Lauwereyns et al. 2002; Martin-Soelch et al. 2001; O'Doherty et al. 2004; e.g., Schultz 2000). While some investigators view romantic love largely as a specific emotion (Gonzaga et al. 2001; Shaver et al. 1987, 1996), others have proposed that romantic love is a goal-directed state that leads to varied emotions (Aron and Aron 1991). It tends to be hard to control, is not associated with any specific facial expression, and is focused on a specific reward. The caudate nucleus is a brain region that could represent rewards and goals in a complex behavioral state like romantic love because it has widespread afferents from all of the cortex except V1 (Eblen and Graybiel 1995; Flaherty and Graybiel 1995; Kemp and Powell 1970; Saint-Cyr et al. 1990; Selemon and Goldman-Rakic 1985) and is organized to integrate diverse sensory, motor, and limbic functions (Brown 1992; Brown et al. 1998; Eblen and Graybiel 1995; Haber 2003; Parent and Hazrati 1995; Parent et al. 1995; Parthasarathy et al. 1992).

One previous fMRI study (Bartels and Zeki 2000) used methods similar to ours, but investigated romantic love in a later stage. Participants in that study had been in love substantially longer than those in our study [28.8 vs. 7.4 mo; $t(32) = 4.28$, $P < 0.001$]. Also, participants in that study were less extremely in love, based on the same standard questionnaire [scores of 7.55 vs. 8.54, $t(31) = 3.91$, $P < 0.001$]. Thus this report is the first fMRI study of *early stage* romantic love. We also show novel effects in the human VTA that may be associated with different aspects of reward, novel time-dependent effects in the cingulate and insular cortex, and novel brain activation correlations with quantified self-reports of passion intensity and trait affect intensity.

METHODS

Participants

Ten women and seven men were recruited from the State University of New York at Stony Brook community, the Rutgers University community, and the New York City area by word of mouth and with flyers seeking individuals who were currently intensely in love. All participants preferred their right hand (Edinburgh Handedness Inventory, Oldfield 1971) and were not taking antidepressant medications. The age range was 18–26 yr (mean = 20.6 yr; median = 21 yr). The reported duration of ”being in love“ was 1–17 mo (mean = 7.4 mo; median = 7 mo). All participants gave informed written consent and each received $50 for his or her participation. The institutional review boards at Stony Brook and Rutgers approved all procedures.

Interviews and questionnaires

A few days in advance of the scanning session, one of us (H.E.F.) orally interviewed each participant in a semistructured format to establish the duration, intensity, and range of his or her feelings of romantic love. Just prior to the scanning session, each participant also completed two self-report questionnaires: *1*) the passionate love scale (PLS) (Hatfield 1986; example items: “I want ___ physically, emotionally, and mentally”; “Sometimes I can't control my thoughts; they are obsessively on ___”) (Cronbach's α for questionnaire reliability in this study = 0.81; Cronbach 1951) and *2*) the affect intensity measure (AIM) (Larsen et al. 1987; Cronbach's α in this study = 0.85; example items: “I get overly enthusiastic”; “Sad movies deeply touch me”), which assesses the general tendency to experience emotions intensely. After the scanning session, two of us (H.E.F. and D.J.M.) conducted exit interviews to determine whether the participants followed the instructions and what they thought about. Also, we tested whether any of the questionnaire data correlated significantly with sex, relationship length, or the other questionnaire (or whether any of these variables correlated with each other); they did not. That is, there were no significant correlations among AIM scores, PLS scores, relationship length, and sex.

Stimuli

The stimuli and length of presentation we used were based on a preliminary investigation that identified a photograph of the beloved as better than other stimuli (e.g., touch, voice) for eliciting feelings of intense romantic love (Mashek et al. 2000). Also, Mashek et al. (2000) found that the intensity of feeling tended to diminish after about 30 s of exposure to the photograph. Before the scanning session, each participant provided a photograph of the beloved (positive stimulus) and a similar photograph of a familiar, emotionally neutral acquaintance of the same age and sex as the beloved (neutral stimulus). Photographs were digitized and sized to show the head only. An angled mirror was mounted on the RF coil, enabling the participant to view each image, which was projected on a screen placed directly outside the MRI tube, subtending a visual angle of 17°. To be sure that the quality of the photos provided by participants was not a factor, we had a group of individuals rate picture quality. The quality of the positive and neutral photos did not differ significantly ($P = 0.88$). Also, picture quality did not correlate significantly with PLS, AIM, relationship length, sex, or separately rated attractiveness of the face (all Ps > 0.14).

Because it is difficult to quell intense feelings of romantic love, we devised a protocol to decrease the carryover effect after the participant viewed the positive stimulus. We interspersed the positive stimulus and neutral stimulus with a distraction, serial countback task. This task involved viewing a number such as 8,421 on the screen and mentally counting backward in increments of seven beginning with this number. A randomly selected different starting number was presented each time the task was given. Pilot testing established that 40 s of the countback task effectively erased feelings associated with the previous positive stimulus in most individuals. To provide a similar distraction after the neutral stimulus (but reduce experiment duration), participants did the countback task for 20 s. The different lengths of the countback task preceding the positive and neutral stimulus presentations was a possible confound. However, the length of the stimulus presentation block was likely great enough to reduce any carryover effects from the countback task. Indeed, inspection of the data showed that the positive and neutral conditions began at the same response magnitude rather than different response magnitudes, which would be indicative of carryover effects from the previous block.

Instructions to participants and exit interviews

In preliminary studies, participants reported that in addition to a photo, thinking about specific events relating to their beloved was the best circumstance to elicit intense romantic love during a 30-s time period (Mashek et al. 2000). Thus the instructions to the participants were to think about events that occurred with the beloved that were especially pleasurable, but not sexual, while they viewed the positive picture. To control for event recall, instructions for the neutral picture were to think about events with the person in that picture also. During the interview before the experiment, the interviewer established pleasurable events that the participant might think about while looking at the beloved, and neutral events, like watching television, while viewing the neutral stimulus. These events were discussed also just before the fMRI session. During exit interviews, the participants reported that they had, indeed, thought about specific events when they looked at the stimuli. For example with regard to the positive stimulus: "I thought about the time we both woke up at 3 AM and walked back from the 7/11 store, it was fun walking back and kissing." With fewer sexual overtones, one said, "I felt I could really rely on her, I could open up to her, I felt protected by her." One felt a rush of euphoria; one felt "happy" and "comfortable." These are descriptions of positive, rewarding feelings. Regarding the neutral stimulus, participants reported that they thought about the specified events with the neutral person that were discussed before the experiment, and that by comparison, one felt "bored." All reported that they did the countback task, although we had no behavioral verification. Several reported that it was hard to do the countback task after the positive stimulus but not after the neutral stimulus, which is additional evidence that they carried out the task.

Experimental design and procedures

The protocol consisted of four tasks presented in an alternating block design. *1*) For 30 s, the participant viewed the positive stimulus; *2*) for the following 40 s, the participant performed the countback distraction task; *3*) for the following 30 s, the participant viewed the neutral stimulus; and *4*) for the following 20 s, the participant performed the countback task. The starting image was either the neutral stimulus or positive stimulus and was counterbalanced across participants. The four-part sequence was repeated six times; the total stimulus protocol was 720 s (12 min).

Image acquisition and analysis

Data were acquired using a 1.5-T Marconi (Phillips) Edge MRI system. We measured the blood oxygen level–dependent (BOLD) response and took in-plane anatomical data for each participant. The images were *1*) anatomical, axial T1-weighted Spin-Echo Scans: 14-ms TE, 600-ms TR, 90° flip angle, 24-cm FOV, 4-mm slice thickness, 0-mm gap, 256 × 256 matrix size, 20 slices; and *2*) functional, T2-weighted Gradient-Echo EPI scans: 70-ms TE (not optimal), 5,000-ms TR, 90° flip angle, 24-cm FOV, 4-mm slice thickness, 0-mm gap, 64 × 94 matrix size (0 filled into 128 × 128 before FFT and the resulting 128 × 128 images were averaged into 64 × 64 before analysis), 20 slices. Voxel size for the functional images was 3.75 × 3.75 × 4.00 mm.

The fMRI data analyses were performed using Statistical Parametric Mapping software (SPM 99 Wellcome Department of Imaging Neuroscience, London, UK; Friston et al. 1995). Functional images were realigned, smoothed with a Gaussian kernel of 8 mm, and normalized to the SPM EPI template brain (19 participants were recruited, but 2 were dropped from the study because they moved >2 mm). We treated each of the stimulus types (positive, neutral, countback1, countback2) as a separate regressor, modeled as a boxcar function convolved with the canonical hemodynamic response; we applied a high-pass filter with a cut-off of 240 s to remove low-frequency signal components. We created contrast images for each comparison for each participant. We then analyzed the contrast images across participants using a mixed-effects general linear model, treating participants as a random effect and conditions as a fixed effect. Interpretation of the group analyses was facilitated by inspection of individual results. Time-course data are reported as "response," a calculation by SPM99 based on raw data that uses the mean of all the conditions as the baseline.

For planned comparisons (hypothesis-driven analyses), we applied small volume corrections with a sphere as a region of interest ($P \leq 0.05$, corrected for multiple comparisons). The coordinates for the centers of the regions of interest were based on a review of 15 fMRI articles that had studied reward or romantic love (Table 1). Rewards in the previous studies included acute cocaine injection, receipt of money, and eating chocolate.

To investigate unpredicted regions of activation, we thresholded the images at $P < 0.001$, corrected for multiple comparisons. There were no significant differences found.

Using SPM99, we performed correlations between participant questionnaire scores and brain responses for the PLS and AIM. Also, because another study showed that there are specific BOLD responses in humans to faces rated as beautiful compared with faces rated as average (Aharon et al. 2001), we had five men and five women (nonparticipants) rate the images for overall "attractiveness." We correlated the attractiveness score *difference* between positive and neutral for each participant with their neural response (for the positive-minus-neutral contrast). In addition, because we thought that differences between our data and the findings of the study of longer-term romantic love (Bartels and Zeki 2000) might be caused by the difference in relationship length, we correlated brain responses and months the participants reported having been in love.

We tested for differences between men and women; however, none met the criterion of $P < 0.001$, corrected for multiple comparisons.

Anatomical localization

To aid our identification of regions affected, we used the atlas of Duvernoy (1999) and the Talairach Daemon Client (Version 1.1, Research Imaging Center, University of Texas Health Science Center, San Antonio, TX). Data were analyzed for individuals on their T1

TABLE 1. *Predicted regions of change*

Region	Talairach Coordinates			Reference Papers*
	x	*y*	*z*	
VTA/SN	0	−10	−10	1,3,5,6,9,10,11,14,15
Caudate head/body	10	10	12	2,5,7,12,13
Putamen	10	0	0	2,5,13,15
Accumbens/subcallosal cortex/ventral striatum	0	10	0	4,5,6,7,9,13,15
Amygdala	20	−2	−14	2,5,6,10
Posterior hippocampus	35	−30	−5	2,5
Anterior cingulate	5	25	24	2,5,13
Posterior cingulate	1	−25	28	2,5,12,13
Mid-insula	34	10	2	2,4,5
Retrosplenial cortex	26	−54	12	8,15
Medial orbitofrontal cortex	0	55	0	10,11
Lateral orbitofrontal cortex	50	30	−9	11

Talairach and Toumeau (1988) coordinates (*x,y,z*) used for the center of the small volume search sphere. Sphere diameter was 4 mm. Both left and right sides were searched. *Selected fMRI reference papers that studied reward, beautiful faces or romantic love and on which the small volume search coordinates were based: [1]Aharon et al. 2001; [2]Bartels and Zeki 2000; [3]Bartels and Zeki 2004(VTA coordinates: personal communication); [4]Bems et al. 2001; [5]Breiter et al. 1997; [6]Breiter et al. 2001; [7]Delgado et al. 2000; [8]Denton et al. 1999; [9]Elliott et al. 2000; [10]Elliott et al. 2003; [11]Elliott et al. 2004; [12]Garavan et al. 2000; [13]Knutson et al. 2001; [14]O'Doherty et al. 2002; [15]Small et al. 2001.

images, on the mean T1 image for the group, and on the average 305 T1 MNI template in SPM99. To display some of the data, we chose the SPM99 Single Subject T1 (scanned multiple times) dataset because major landmarks are more visible than in the other renderings. The calculated error for SPM99 anatomic normalization within a group is ≤8 mm between sulci, and there is 94% overlap among the same gray matter regions (Hellier et al. 2001, 2002). Thus the Talairach descriptions of the locations of cortical changes that include Brodmann's areas (BAs) are an approximation only; we include them in the report because they are useful to compare with other studies. In addition, the data were smoothed with a Gaussian kernel of 8 mm so that any single localization point reported in the tables should be considered within an area of ~8 mm. Technical considerations limited us to 20 slices that did not cover the entire brain. Parts of the dorsal neocortex (~1–3 cm from the superior surface) were not sampled in some participants, whereas the ventral temporal lobe was not included in others. Thus we analyzed separately the amygdala and ventral hippocampus in the nine participants (6 women and 3 men) who had data in those regions.

Localization of activation to the medial caudate appeared to be partially in the ventricle in the normalized group images. To confirm that it was caudate activation, we examined unnormalized individual data. We calculated the distance (in mm) from the anterior commissure to the caudate peak activation in each individual and plotted it on a horizontal section from the Montreal Neurological Institute average brain template based on scans from 305 individuals (Fig. 1).

RESULTS

Positive-minus-neutral stimulus contrast (activations)

Predicted, small volume measurements showed significant differences in the right medial caudate (Fig. 1*A*; Table 2), in the right antero-dorsal caudate body (Fig. 1*B*, Table 2), in another region of the right dorsal caudate body, and in the right BA30/retrosplenial cortex (Table 2). Significant bilateral caudate activations were in the antero-dorsal region (Table 2).

In the ventral midbrain, significant activation was localized in the region of the VTA/A10 dopamine cells (Fig. 2, *A* and *B*). Also, plots of the time-course of the BOLD response show that neural activation increased in response to the positive image relative to the other conditions, whereas there was a decrease in the BOLD signal for each control task relative to the positive stimulus (Fig. 2*C*). No caudate region showed a similar time-course.

Positive-minus-countback

We had included the countback task to provide a distraction between positive and neutral stimuli. However, we reasoned that it might serve as a supplementary control condition. That is, areas showing strong activation for the positive-minus-neutral subtraction that also showed activations for a positive-minus-countback subtraction may be additional evidence that these represent areas associated with intense romantic love. The positive-minus-countback subtraction yielded activations overlapping with the positive-minus-neutral subtraction for the right ventral midbrain and the right postero-dorsal caudate (Table 2), providing more evidence that activation in these regions is specific to the image of the beloved.

Self-report of degree of passionate love

Focusing again on the positive-minus-neutral contrast, we conducted a between-subject random effects analysis correlating degree of the BOLD response and participants' scores on the PLS. (Recall that there were no significant correlations among PLS scores, AIM scores, relationship length, and sex.) As shown in Fig. 3 and Table 2, PLS scores had high positive correlations with activation in two of the regions that were significant for the contrast by itself, the right antero-medial caudate body ($r = 0.60$; $P = 0.012$, Fig. 3*C*) and the septum-fornix region ($r = 0.54$; $P < 0.008$). That is, those who self-reported higher levels of romantic love than others also showed greater activation than others in this region of the caudate and septum when viewing their beloved. As noted by Kosslyn et al. (Kosslyn et al. 2002), the consistency of a between-subject correlation with a subtraction result provides particularly strong triangulating evidence for the link of a function with an activated area.

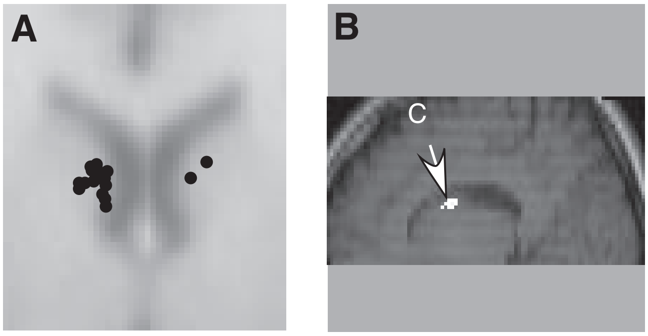

FIG. 1. Caudate nucleus activation, positive-minus-neutral contrast. *A*: an enlargement of an axial section through the caudate nucleus from the MNI T1 template that averaged 305 subjects. Black dots show peak activation points for each participant in the present study. Activation points were near the medial edge of the caudate in the vicinity of Talairach coordinates 12, 11, 14 (dark gray areas are lateral ventricles). *B*: a sagittal section from an individual participant shows the extent of the posterior dorsal caudate activation (arrow). Images in this and all following figures are presented in radiologic convention (participants' left on the right side of the image). C, caudate.

TABLE 2. *Regional activations specific to the picture of the beloved compared to a picture of a familiar, neutral acquaintance*

	Left				Right			
	x	*y*	*z*	*P*	*x*	*y*	*z*	*P*
Positive-minus-neutral contrast								
Caudate body, medial†					12	11	14	0.005
Caudate body, postero-dorsal*†					18	−18	22	0.005
Caudate body, antero-dorsal†	−16	1	22	0.014	14	−4	22	0.014
Posterior cingulate/BA30/Retrosplenial cortex†					30	−52	4	0.014
Ventral tegmental area*†					2	−15	−9	0.025
Passionate love scale correlation								
Caudate body, antero-medial*					8	6	14	0.012
Septum/fomix					0	−1	17	0.008

Talairach and Toumeau (1988) coordinates (*x,y,z*) for the highest intensity voxel in a cluster. *Cluster for positive-minus-neutral contrast overlapped with the cluster in the same region for the positive-minus-countback contrast. †Regions predicted to change, small volume, corrected for multiple comparisons. BA, Brodmann's area.

Attractiveness effects of the positive and neutral faces

The correlation between the BOLD response and independently rated attractiveness for the positive image minus the attractiveness of the neutral image was significant for voxels in the *left* VTA ($r = 0.74$, $P = 0.009$; Fig. 4). This is a different location from activation for the positive-minus-neutral contrast, which was in the *right* VTA (Fig. 2).

Neutral-minus-positive stimulus (deactivations)

The only predicted region of change to show a deactivation was the amygdala (coordinates: 20, −3, −15, $P < 0.002$).

Length of time in love

Because our participants were in love for a shorter amount of time than those in the study done by Bartels and Zeki (2000), we correlated degree of activation and participant's reported length of time in love. The correlation was done for the positive-minus-neutral contrast. As shown in Fig. 5 and Table 3, several regions of special interest showed changes as the relationship lengthened: the right mid-insular cortex; the right anterior and posterior cingulate cortex; and the right posterior cingulate/retrosplenial cortex. Scatter plots of the correlation in the anterior cingulate cortex and retrosplenial cortex suggest that participants in longer relationships (8–17 mo) were different from those engaged in relatively short relationships (1–7 mo; Fig. 5). Thus it appears that length of time in love is a major factor for neural activity in the insula and cingulate/retrosplenial cortex when looking at an image of a romantic partner.

One brain region showed *greater* activation the *shorter* the length of time in love: the left posterior cingulate cortex/retrosplenial cortex region (Table 3).

Self-report of general tendency for emotional intensity

Once again using the positive-minus-neutral contrast, we correlated degree of activation and participants' scores on the AIM (the AIM was not significantly correlated with the PLS). The AIM is a self-assessment of general affect tendencies, and the correlation with the BOLD response tested for a potentially important trait difference among participants in a study that may involve emotion. The left mid-insular cortex (Talairach coordinates −42,−6,0) was correlated with AIM score ($r = 0.58$; $P < 0.01$), a region similar to one where Bartels and Zeki (2000) reported activation in their study. Thus a left insular cortical region was affected by the positive stimulus, but the response varied depending on an individual's self-report of how strongly the person experiences affect in general.

DISCUSSION

Several results support our two predictions that *1*) early stage, intense romantic love is associated with subcortical reward regions that are also dopamine-rich (e.g., Fisher 1998)

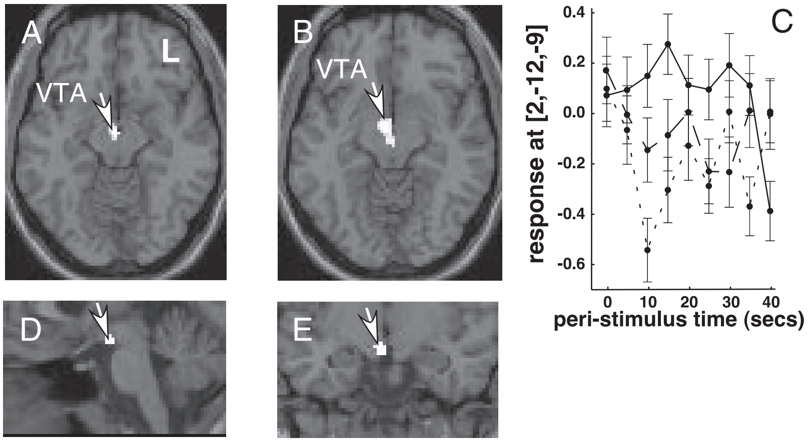

FIG. 2. Group mean data and an individual subject show the localized ventral midbrain effect. *A*: positive-minus-neutral contrast. *B*: positive-minus-countback contrast. Activity in the right VTA region (arrows) specifically increased in response to the positive image compared with both control conditions. The regional activation is highly localized to the medial A10 dopamine cell region with little inclusion of the medial substantia nigra. *C*: time-course of the BOLD response (means ± SE, 0 = mean of all conditions) for a voxel in the right VTA shows that the signal increased to the positive image (solid line) relative to the others; the signal during control stimuli presentations decreased relative to the positive image, especially for the countback task (short-dash line; 40-s countback task shown). Long-dash line, neutral stimulus. *D*: in a single subject, a sagittal view shows the anteroposterior extent of the right VTA activation (arrow). *E*: in the same subject, a coronal view of the right VTA activation (arrow) shows how it is limited to the medial midbrain. Locations of responses shown in the graph are given in Talairach coordinates. L, left side; VTA, ventral tegmental area.

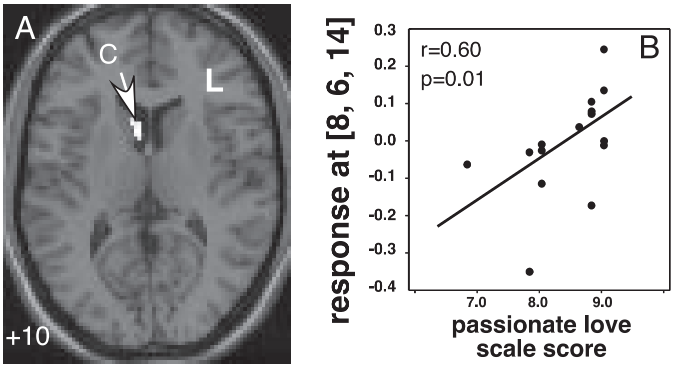

FIG. 3. Activation in the anteromedial caudate body was correlated with the passionate love scale (PLS) scores of participants. *A*: caudate location for the correlation (arrow). *B*: correlation of activity in the caudate with PLS scores. Location of responses shown in graph are given in Talairach coordinates. C, caudate; L, left side.

and *2*) romantic love engages a motivation system involving neural systems associated with motivation to acquire a reward rather than romantic love being a particular emotion in its own right (Aron and Aron 1991). Foremost, when our participants looked at a beloved, specific activation occurred in the right ventral midbrain around the VTA, dorsal caudate body, and caudate tail. These regions were significant compared with two control conditions, providing strong evidence that they are associated with specific aspects of romantic love.

The VTA contains dopaminergic cells (A10) that send projections to several brain regions (Gerfen et al. 1987; Oades and Halliday 1987; Williams and Goldman-Rakic 1998), including the medial caudate where we found specific activations. In addition, both the VTA and caudate regions activated in this study receive visual afferents and respond to visual stimuli (Caan et al. 1984; Horvitz et al. 1997; Saint-Cyr et al. 1990). Although fMRI is limited to measurements of location and relatively long-term neural responses, and cannot determine neurotransmitters used, other electrophysiological, lesion, fMRI, voltammetry, drug infusion, and self-stimulation studies have established that the VTA, dopamine, and the caudate nucleus play major roles in reward and motivation in the mammalian brain (Delgado et al. 2003; Kawagoe et al. 1998; Martin-Soelch et al. 2001; Phillips et al. 2003; Salinas and White 1998; Schultz 2000; White and Hiroi 1998; Wise 1996). Most importantly, Zald et al. (2004) found that predictable monetary reward presentation caused dopamine release in the medial caudate body where we found activation. The combined findings implicate reward and motivation functions as likely aspects of early-stage romantic love and dopamine as one of the candidate transmitters involved.

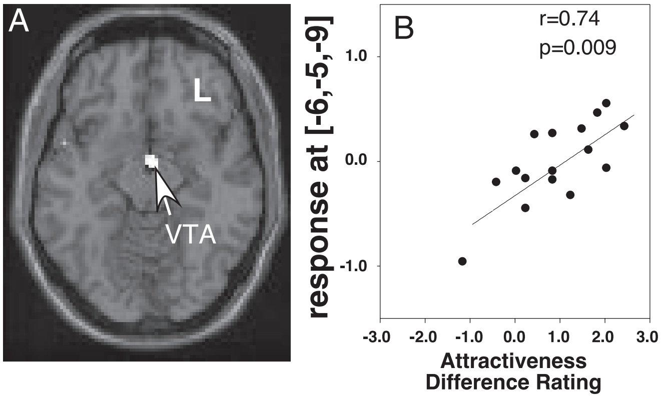

FIG. 4. Activity in the VTA for the positive-minus-neutral contrast was correlated with the independently rated attractiveness of the positive minus the attractiveness of the neutral faces. *A*: activation is on the *left* and on the midline (arrow) and different from the localization of activation in Fig. 2, *A* and *B*. *B*: neural activity in response to positive images was greater when the positive face was more attractive than the neutral face.

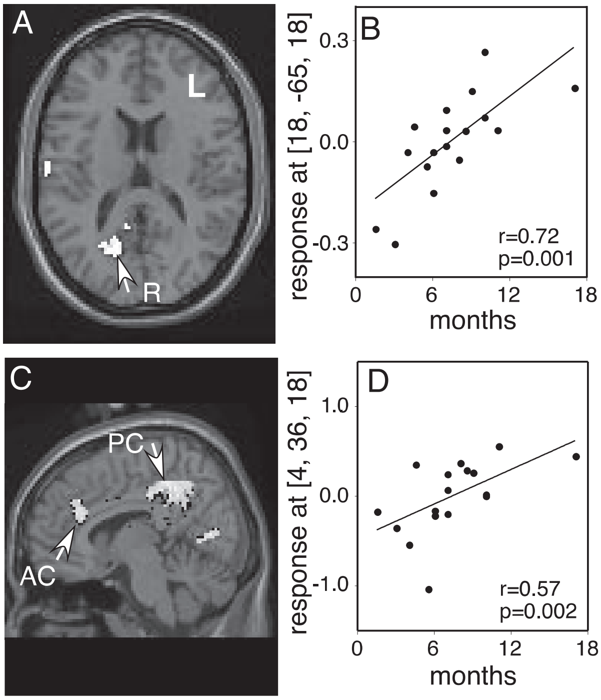

FIG. 5. Length of time in love correlated with activation in specific regions. Regions are indicated on axial (*A*) and sagittal (*C*) sections. *A*: cluster location for the retrosplenial cortex correlation (arrow) is similar to a region correlated with satiation while eating chocolate (Small et al. 2001). *B*: correlation for the peak voxel in the cluster labeled R in *A*. *C*: location of voxel clusters correlated with relationship length in the AC and PC (arrows). *D*: graph of the correlation between the BOLD response and months in love for the AC. AC, anterior cingulate cortex; PC, posterior cingulate cortex; R, posterior cingulate/BA30 retrosplenial cortex.

Cortical areas associated with emotion were involved, also, such as the insular and cingulate cortex. However, as expected for a goal-directed state with diverse outcomes, activation of emotion-associated areas varied among individuals depending on their general affect intensity, passion score, and the length of the relationship. Two subcortical areas associated with emotion were affected: the amygdala and the septum. Amygdala activity was decreased relative to the neutral stimulus, whereas septal activity was correlated with the PLS score. Deactivation was seen in the amygdala by Bartels and Zeki (2000, 2004), also. They suggested that love reduces fearful responses. However, amygdala activity plays a role in the recognition of faces in general, and it is not clear why it was specifically involved in this study (Kosaka et al. 2003). The septum was one of the first regions found to be rewarding during electrical self-stimulation (Olds and Milner 1954). It is activated by VTA self-stimulation reward and medial forebrain bundle self-stimulation reward, and it is involved in several emotional responses in animals, including relief from aversive emotional states (Esposito et al. 1984; Porrino et al. 1984, 1990; Yadin and Thomas 1996). Thus it is consistent with a

TABLE 3. *Regional changes in brain activity that were correlated with the length of the relationship*

	Left				Right			
	x	*y*	*z*	*P*	*x*	*y*	*z*	*P*
The longer the relationship, the greater the difference between the positive and neutral stimuli								
Mid-insula BA 13					42	−2	2	0.013
Anterior cingulate					4	36	28	0.002
Posterior cingulate*					9	−50	15	0.001
Posterior cingulate/retrosplenial cortex					18	−65	18	0.001
Parietal/precuneus					12	−70	40	0.004
Inf. frontal gyrus	−40	52	1	0.001				
Middle temporal gyrus	−51	−60	3	0.002				
Ventral putamen/pallidum	−28	−2	−7	0.013				
The shorter the relationship the greater the difference between positive and neutral stimuli								
Posterior cingulate/BA30/retrospletrial cortex	−22	−38	9	0.005				

Talairach and Tourneau (1988) coordinates (*x,y,z*) for the voxel with the highest correlation. *Cluster for positive-minus-neutral contrast overlapped at least partially with the cluster in the same region for the positive-minus-countback contrast.

large body of data that the septum would be active during a reward state. Finally, the lateral septum has also been implicated in pair-bonding in prairie voles (Liu et al. 2001).

Regional heterogeneity of ventral tegmental area reward functions

To establish whether the VTA activation occurred because our participants were feeling romantic passion or were stimulated by an esthetically pleasing face, we correlated facial attractiveness (as rated by others) with neural activation. This correlation showed that those with more esthetically pleasing partners compared with the neutral stimulus showed greater neural activity in the *left* VTA than those with less attractive partners compared with the neutral stimulus. Several fMRI studies indicate that the *right* VTA, where we found activation for our basic positive-minus-neutral contrast, is associated with rewards and/or working for rewards (Aharon et al. 2001; Breiter et al. 2001; Elliott et al. 2000, 2004; Small et al. 2001); others showed bilateral activation of the VTA (Breiter et al. 1997; O'Doherty et al. 2002). Importantly, Aharon et al. (2001) showed that the *left* VTA activation was specifically associated with a face deemed esthetically pleasing (liking), whereas *right* VTA activation increased during presentation of a face that participants would work to see longer (wanting). Thus several fMRI studies corroborate reward effects in the human VTA (Table 1), but this is the second fMRI study to show a localization effect within the VTA for two aspects of reward, wanting and liking (Berridge and Robinson 2003) and to show that this effect is lateralized. Caudate effects for the positive-minus-neutral contrast were on the right, providing more evidence that the lateralized VTA effect is not spurious.

The localization of the VTA activation appears to be quite specific in the figures, given the size of the original voxels (3.75 × 3.75 × 4.0 mm) and the size of the smoothing filter (8 mm). The specificity appearance is enhanced by the normalized images (2 × 2 × 2 mm). However, the human VTA is ~8 mm across, from anterior to posterior, and 4 mm dorsoventral, well within the area covered by several voxels. In addition, by smoothing the data, which tends to enhance effects in large regions of cortex, we probably diluted the observed effect in this small region. The VTA is a small region, however, and given the variability inherent in the brains of subjects and the normalization procedures, we cannot be sure that the activation does not include other surrounding areas.

Regional caudate effects implicate emotion and visual attention functions

Participants who scored higher than others on the PLS showed greater activation in the right antero-medial caudate body. This region is rich in limbic-associated membrane protein, calbindin, and medial cortical afferents, each of which is associated with higher-order cognitive and emotional functions (Parent et al. 1995). The specific region where activation correlated with the PLS in our study was activated during anticipation of a monetary reward (Knutson et al. 2001), reward-based stochastic learning (Haruno et al. 2004), attention (Zink et al. 2003), a spatial and temporal somatosensory discrimination task (Pastor et al. 2004), and simple passive visual processing (Bleicher et al. 2003). Recently, this same right-sided region showed increased dopamine release for a predictable money reward (Zald et al. 2004). In addition, our countback task (when compared with the neutral stimulus) activated this region. Thus this area of the antero-medial body of the caudate is most likely associated with rewarding, visual, and perhaps attentional aspects of romantic love. Intense, focused attention on an individual is one of the cardinal behavioral signs of romantic love (Fisher 1998; Hatfield and Sprecher 1986). Visual attention, reward, motivation, and motor planning are often related to caudate function (Dagher et al. 1999; Hikosaka et al. 2000; Lauwereyns et al. 2002; Zink et al. 2003). In addition, there is one report of electrical stimulation of the caudate through a chronically indwelling electrode in a human epilepsy patient (Delgado et al. 1973). The patient's words expressing love toward the investigator were stimulus-bound (J. Delgado and E. E. Coons, personal communication), providing evidence that caudate activation could be causally related to feelings of romantic love.

Months in love: cortical and subcortical effects

One of the most interesting findings of this study is regional effects related to the number of months in love. Notably, several limbic cortical regions showed a correlation with the length of the relationship: anterior and posterior cingulate, mid-insula, and retrosplenial cortex; but also, parietal, inferior frontal, and middle temporal cortex. One small region of the left ventral putamen and pallidum was associated with time in love. The ventral pallidum has been implicated in attachment in prairie voles (Lim and Young 2004; Lim et al. 2004). In their fMRI study of longer-term romantic love, Bartels and Zeki (2000) found activation in the anterior cingulate and mid-insula. Thus we confirm the results of Bartels and Zeki (2000) that these brain regions are involved; but in addition, our results suggest that the activation is dependent on time factors. The time-related activations may be related to memory, familiarity, motivation, and attention functions (Velanova et al. 2003; Yamasaki et al. 2002) or an emotional internal state factor such as heart rate (Critchley et al. 2003; Porro et al. 2003). The correlation in the anterior cingulate is notable because it is implicated in a cardinal trait of romantic love: obsessive thinking; it is also involved in cognition and emotion (Bush et al. 2000; Rauch et al. 2001; Ursu et al. 2003). The right retrosplenial cortex correlation with length of relationship is of special interest because metabolic activity there increased during satiation for chocolate (Small et al. 2001) and was correlated with level of thirst (Denton et al. 1999). In any case, these results highlight the importance of these cortical regions for processing stimulus/internal state change, and the importance of taking time factors into account in future studies of human relationships. At the same time, these results must be interpreted cautiously because they are cross-sectional, so that, for example, it is possible they represent differences in the kinds of people that remain intensely in love over a longer period rather than changes over time.

Evolution of romantic love and its distinction from the sex drive

Studies of prairie voles show that D2 dopamine and oxytocin receptor stimulation in the nucleus accumbens is associated with mate preference in females (Gingrich et al. 2000; Liu and Wang 2003), and recent studies of male voles focus on the ventral striatum/pallidum and the distribution of vasopressin and oxytocin receptors; however, oxytocin receptors are found throughout the striatum as well as in the accumbens in both males and females (Lim and Young 2004; Lim et al. 2004). A comparison with our findings leads us to speculate about the evolution of romantic love: with the development of the human cerebral cortex, ancestral hominids employed the phylogenetically newer cortex and dorsal caudate to initiate partner preference. Romantic love may be a *developed* form of a general mammalian courtship system, which evolved to stimulate mate choice, thereby conserving courtship time and energy (Fisher 1998). Also, previous fMRI studies of human sexual arousal show regional activation largely different from the pattern we saw for our participants (Arnow et al. 2002; Redoute et al. 2000), consistent with romantic love being distinct from the sex drive (Aron and Aron 1991; Fisher 1998).

Comparison with a study of longer-term romantic love

Bartels and Zeki (2000) reported findings of an fMRI study on the neural correlates of romantic love and reanalyzed their data in relation to another study they carried out on maternal love (Bartels and Zeki 2004). As previously stated, their participants were in love longer and were not as intensely in love as in this study [28.8 vs. 7.3 mo; $t(32) = 4.28$, $P < 0.001$; PLS scores of 7.55 vs. 8.54; $t(31) = 3.91$, $P < 0.001$]. Both studies used 17 participants and a photograph of the beloved as the positive stimulus. In this study, we used a familiar acquaintance as a control, whereas Bartels and Zeki used photographs of friends. Also, we used a distraction task that served as a second control condition, the countback task. Many of the basic results are remarkably similar. The ventral midbrain region/VTA and dorsal caudate nucleus were activated by romantic love in both studies (Bartels and Zeki 2000, 2004); the amygdaloid region was deactivated in both studies; the mid-insula, anterior, and posterior cingulate were affected in both studies, but in this study, activation in the cortex was found to be correlated with relationship length. The fact that all of the above regions were affected in both studies strongly suggests that they are involved in romantic love in important ways and that reward and motivation systems are critical.

In addition, there were differences between the two studies for the positive-minus-neutral contrast. Among them, this study showed effects in several regions of the caudate, in the septum, and the retrosplenial cortex, and no effect in the dorsal hippocampus or putamen, as was seen by Bartels and Zeki (2000). These differences may be caused by the difference between early-stage and longer-term romantic love that could not be assessed with the limited time range in our study, but could also be caused by individual characteristic responses that differed between the two samples or by the differences in experimental methods.

Technical considerations and assumptions

The BOLD responses that we measured were relatively sustained during the presentation of the stimuli and also limited by the hemodynamic response function model that we used. If we had employed other models of response, we might have detected other areas that could be involved. For example, Moritz et al. (2000) reported that caudate-putamen BOLD responses to finger-tapping had a short duration, quite different from the cortex. Also, we base our interpretation of the data on the assumption that a BOLD response largely reflects axon terminal activity and field potentials rather than cell body activity, although the two can be correlated (Arthurs et al. 2004; Logothetis et al. 2001; Mata et al. 1980; Sokoloff 1999, 1993). In an animal study using metabolic mapping of natural somatosensory corticostriate activity, increased metabolism was associated with corticostriate axon terminal fields (Brown et al. 2002). Thus we interpret the measured activation in the caudate to be largely the result of afferent activity from the cortex, VTA, and intrinsic caudate cell axon collaterals. Likewise, the BOLD response in the VTA may reflect afferent activity from the caudate or accumbens or other region, not necessarily activity of local cells.

The BOLD response reflects venous blood flow and volume (e.g., Arthurs and Boniface 2002). Thus activation from the medial caudate and tail that appeared to be in or lining the ventricle may be a signal change in the large draining veins on the surface of the caudate that forms the ventricular borders (Netter 1983). Such a signal still reflects nearby parenchymal activity, however. Other studies have seen lateral "ventricular activation" that follows the curved surface of the caudate (Bleicher et al. 2003; Haruno et al. 2004). We ascribe this activation to the caudate because we expect activity there based on known cortical projection patterns, the activation is localized and on one side, the caudate protrudes into the ventricle and could produce a partial volume effect, and ventricular activation that might be caused by an artifact such as movement is not seen in other ventricular regions.

The 30-s trial period to look at faces was relatively unconstrained, although instructions were given. Also, differences between the positive and neutral conditions may have been caused by different eye movements or different habituation effects. If number of eye movements had been a major factor, we expect that the frontal eye fields would have shown an effect. It is possible that a difference in habituation is an inextricable factor.

In conclusion, the results lead us to suggest that early-stage, intense romantic love is associated with reward and goal representation regions, and that rather than being a specific emotion, romantic love is better characterized as a motivation or goal-oriented state that *leads to* various specific emotions such as euphoria or anxiety. With this new view of romantic love as a motivation state, it becomes clearer why the lover expresses an imperative to be with a preferred individual (the beloved) and to protect the relationship. Moreover, our results suggest to us that romantic love does not use a functionally specialized brain system. Romantic love may be produced, instead, by a constellation of neural systems that converge onto widespread regions of the caudate where there is a flexible combinatorial map representing motivating stimuli and memories dependent on the individual and the context (Brown 1992; Brown et al. 1998; Lidsky and Brown 1999). As such, it would be an example of how a complex human behavioral state that includes emotions is processed. Taken together, our results and those of Bartels and Zeki (2000, 2004) with longer-term in love participants show similar cortical, VTA, and caudate localization, suggesting that these regions are consistently and critically involved in this aspect of human reproduction and social behavior, romantic love. Further experiments will be needed to determine whether a circumscribed caudate region and specific afferents are necessary to the experience and behaviors of romantic love. Importantly, we found potential regional heterogeneity for different aspects of reward in the VTA and identified some cortical regions whose neural activation was different for individuals who had been in love over a time scale of months or who showed affect trait differences.

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