Romantic Love, Pair-bonding, and the Dopaminergic Reward System

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Romantic love is a fundamental human experience. It is a force that provides bi-parental care for children and can create great joy for lovers, bring peace to the heart, and inspire creation. On an evolutionary level, romantic love has enabled humanity to survive and flourish. At the individual level, it can create a feeling of aliveness, connection, and inspiration like no other. Indeed, romantic love is one of the greatest natural rewards. When things are going well in romantic love relationships individuals experience euphoria, well-being, and elevation. At the same time, pair-bonds provide couples with support, a sense of calm, ease, and that "all is right in the world". However, romantic love often involves challenges, of varying degrees, which may be associated with a host of negative outcomes including depression, anxiety, pain, intrusive thinking about the beloved, and even suicidal tendencies; as well as being a disruptive force for persons and family networks when it is experienced for someone other than a romantic partner. Nevertheless, that humans experience great joy and suffering as a result of "the drive to be united with a beloved" seems quite adaptive when we consider its involvement in reproduction, regulatory processes related to emotions and motivation, self-expansion, and the stability of pair-bonds and families.

Humans (and other mammals) are wired for love, and although varying configurations of attachment relationships exist (e.g., parent-infant bonds and pair-bonds) they seem to share common behaviors and biological substrates (e.g., Hazan & Shaver, 1987; Fisher 1992; Carter, 1998; Mikulincer & Shaver, 2007). This idea has been supported by neuroimaging work showing overlapping patterns of neural activation for an “attachment system” (e.g., Bartels & Zeki, 2004; Acevedo, Aron, Fisher, & Brown, 2011). However, pair-bonds are unique in that they include attraction and the drive to mate. They support reproduction and growth of the couple, familial stability, relationship happiness, and overall well-being (Simpson, Campbell, & Berscheid, 1986; Aron & Henkemeyer, 1995; Masuda, 2003; Riehl-Emde Thomas, & Willi, 2003; O’Leary et al., 2011).

Increasingly over recent decades scientists have started to investigate romantic love— a phenomenon that was once relegated to poets and mystics, and that is still deemed “mysterious” and “magical” by many—using sophisticated methodologies. The most common methods used in close relationships research are functional magnetic resonance imaging (fMRI) and evoked response potentials (ERP). Other methods involve use of neurobiological markers (e.g., hormones) and animal models (testing relationship processes in animals such as non-human primates and rodent mammals (e.g., Bales et al., 2007).

In this chapter we will review research using fMRI methods to examine romantic love and human pair-bonds. We will discuss findings in relation to the brain’s mesolimbic dopamine system, involved in reward processing and implicated in a variety of behaviors from feeding, to responding to monetary rewards, and addictive compulsions. Finally, we discuss how integrating knowledge of reward system processes that mediate romantic love and addiction may elucidate applications for substance abuse.

Research on the Neural Correlates of Romantic Love

In recent decades human studies investigating the neural basis of romantic love and related relationship processes have increased rapidly. Studies utilizing fMRI have consistently shown that romantic love—both early-stage and long-term, and even in the context of love remaining after being rejected—is associated with activation of the brain's dopaminergic reward system (e.g., Aron et al., 2005; Bartels & Zeki, 2000, 2004; Ortigue et al., 2007; Acevedo et al., 2011; Fisher et al., 2011; Xu et al., 2011).

In one of the first fMRI studies to investigate the neural correlates of early-stage romantic love, researchers in London examined brain activations of 17 female and male participants intensely in-love with an opposite-sex partner of about 2.4 years on average (Bartels & Zeki, 2000). Participants were shown face images of their romantic partners and three friends matched to the partner on gender, age, and relationship length as comparisons. The results showed activations specific to viewing the partner in key areas of the brains dopaminergic reward system (the caudate nucleus and putamen) and an area commonly involved in memory (the posterior hippocampus). A few years after, the same team published a re-analysis of the data (Bartels & Zeki, 2004), but adding a comparison to a study on maternal love. Results from the 2004 study revealed neural activations specific to romantic love in key areas of the brain's dopamine reward system (in the mid-brain regions of the ventral tegmental area region, caudate nucleus, and putamen). Additional activations were found in the globus pallidus, an important reward center rich in opiate receptors that mediates the "liking"and pleasure associated with rewards (e.g., Smith et al., 2010); an area important for emotional functioning (the mid-insula); areas involved in attention, arousal, and pain regulation (anterior and posterior cingulate), (e.g., Brooks et al., 2005; Petrovic et al., 2002; Logno et al., 2012), memory (the hippocampus), and hormonal behaviors and functions, such as sex, stress, and feeding (the hypothalamus).

The second study published on early-stage romantic love, was conducted by our group in the US (Aron et al., 2005; Fisher et al., 2005). We investigated the neural activations of 17 female and male participants in-love for about 7 months on average while viewing face images of their beloved. The controls included a familiar, neutral person (such as the local drycleaner or grocer) and a numerical countback task as an attentional control for thinking about the beloved (individuals report this is a very desirable experience and often have a hard time stopping). Our results showed significant activations in key areas associated with the dopaminergic reward system (the ventral tegmental area (VTA) and several sites of the caudate), and the posterior cingulate (implicated in attention and autobiographical memory).

In yet another fMRI study of early-stage romantic love, Ortigue and colleagues (2007) measured the brain activity of 36 heterosexual female participants in the US reporting intense passionate love (confirmed with interviews and scores on a standard passionate love questionnaire measure) for romantic partners of about 15 months on average (Ortigue et al., 2007). However, this study employed a different paradigm. While being scanned, participants were shown subliminal stimuli representing their beloved, a life passion (e.g., a hobby), and a male friend (of around the same age and relationship length as the partner). Results showed activations specific to viewing the partner (versus the friend) in major reward centers of the VTA, and caudate nucleus. Additional activations included the insula (important for emotional and visceral processing), occipitotemporal/fusiform region (involved in face processing), parahippocampal gyrus (involved in memory), and the angular gyrus (involved in self-processing and representation). Neural activations in response to beloved primes (versus the passionate hobby primes) were found in the angular gyrus and the occipitotemporal/fusiform region. It is important to note the activation of the VTA and caudate (key areas of the dopaminergic reward system) replicated results from the other studies of early-stage intense romantic love utilizing a different experimental procedure. Moreover, Ortigue et al. (2007) displayed stimuli subliminally, suggesting that processing of information related to the beloved may occur rapidly and below awareness

The fourth study to investigate early-stage romantic love (Xu et al, 2010) was led by a researcher from our team and in collaboration with researchers in Beijing, China. In the study, 18 females and males in relationships of about 7 months on average (ranging from 1 to 13 months) underwent fMRI scanning, replicating procedures used by Aron et al. (2005) where participants viewed face images of their beloved and a familiar, neutral person. Once again, the data showed activation of the VTA and caudate tail in response to the beloved (versus the familiar, neutral acquaintance). Additional activations were seen in the mid-orbitofrontal cortex and areas of the cerebellum in response to the beloved.

In a fifth study of early-stage romantic love researchers at Stanford University in the US investigated the neural activations of fifteen individuals in relationships of nine months or less undergoing periods of moderate and high thermal pain while they viewed images of their partners, a familiar acquaintance, or a word task (Younger et al., 2010). Results showed that even in the context of thermal pain, viewing images of a romantic partner was associated with greater analgesic effects reflected by activation of reward systems (such as the caudate, nucleus accumbens, orbitofrontal cortex). Additional activations were found in areas involved in emotion-processing and emotion regulation, namely the amygdala and dorsolateral prefrontal cortex.

In yet another study of early-stage romantic love researchers in Germany compared brain activations of twelve individuals in-love for about 6 months on average with those of twelve individuals experiencing grief from a recent break-up with a romantic partner (Stoessel et al., 2010). Participants were shown face images of the beloved, erotic pictures, autobiographical pictures, and neutral pictures (e.g., landscape). When viewing face images of the beloved (versus erotic images), the happily in-love group showed significant neural activation in areas found in other studies of romantic love such as the caudate (associated with the dopaminergic reward system) and the posterior cingulate, implicated in autobiographical memory of socially relevant stimuli such as partner names (e.g., Maddock et al., 2001). Other activations were shown in areas related to retrieval of memories (such as the precuneus and parahippocampal gyrus). Also, findings showed that unhappy lovers showed less activation in areas related to emotion, attention, and reward circuits (insula, anterior and posterior cingulate). Unlike previous studies of early-stage romantic love, this study did not report on activation of the VTA.

In addition to romantic love in its early stages, our team in the US also investigated brain activations for long-term relationships. We sampled a group of 17 individuals from the New York City area reporting intense romantic love for a spouse of around 20 years (Acevedo et al. 2011). We implemented the paradigm as in Aron et al. (2005), Fisher et al. (2011), and Xu et al. (2010) where participants were shown face images of a beloved, a familiar neutral acquaintance, and a numerical countback task. Using the same procedures was beneficial for directly comparing results as we were mainly interested in whether long-term romantic love would show the same pattern of neural activation found for early-stage romantic love. This was important for sorting out differing theoretical perspectives about the course of love over time, but also for therapists and lay people that often question, “Can love last?”.

In addition, in the study of long-term romantic love we included a control for closeness (a close friend of the same-sex and known about as long-term partner), an important component of established and lasting bonds (Aron, Mashek, & Aron, 2004). We compared our results (brain responses to the partner images versus neutral acquaintance and the close friend) with previous studies of early-stage romantic love and maternal love (e.g., Aron et al., 2005; Bartels & Zeki, 2004). Activations common with early-stage romantic love were found in dopaminergic reward processing regions of the VTA and caudate nucleus; the mid-insula (involved in emotion and visceral processing); and the posterior hippocampus, and area implicated in memory of primary rewards, hunger and satiation (e.g., Fernandez & Kroes, 2010). Activations common with maternal love were found in key areas of the reward system, including the substantia nigra (a site of dopamine production) caudate, putamen, and globus pallidus; an area rich in serotonin receptors (dorsal raphe region) important for mood regulation (such as anxiety, stress, and intrusive thinking); areas involved in emotion and visceral processing (the mid-insula and insular cortex); and areas important for attention, arousal, and pain regulation (the anterior and and posterior cingulate).

Acevedo et al. (2011) also conducted correlations with several relationship measures and found that a standard measure of closeness, the inclusion of other in the self scale, IOS) was associated with dopaminergic reward system activity in neural regions of the VTA and SN. Also, consistent with the definition of "including the other in the self," IOS scores were positively associated with activation in areas reflecting self-referential processing, emotions, and attention, namely the middle insula and anterior cingulate (e.g., Craig, 2009; Kurth et al., 2010, meta-analysis; Enzi et Northoff et al., 2006, meta-analysis).

Zeki and Romaya (2010) investigated neural activations of 24 individual in same-sex and opposite-sex relationships reporting intense romantic love for their partners of about 3.7 years, ranging from 4 months to 23 years. Participants underwent fMRI scanning while viewing images of their beloved and a neutral friend. Two major activation patterns were reported in response to the beloved (versus neutral), in the tegmentum, caudate, hypothalamus, hippocampus, the superior parietal lobe, and in the cerebellum. Results did not reveal differenced by gender or sexual orientation. PLS scores were found not correlated to subject age or relationship length; however, there was a significant negative correlation found between loved>neutral condition and relationship length due to an outlier, the participant with a relationship length of 23 years, the correlations was not significant when the subject was excluded.

In addition to individuals in romantic love within an established pair-bond, researchers have also investigated the neural correlates of lovers that had recently experienced a break-up (e.g., Najib et al., 2004; Fisher et al., 2011). We will not go into these studies into great deal. However, what is important to note is that even in the context of dissolved relationships some individuals continued to show neural activation of the dopaminergic reward system. This is consistent with common knowledge and case studies showing that even in the context of rejection or loss, humans may experience continued “longing for union” with the beloved, they continue to crave their presence, hear their voice, and feel their touch. This is often associated with suffering and dysregulated mood, emotions, and physiological states as the systems involved in reward and social bonding (the “attachment” system) readjust to the absence of the beloved (e.g., Sbarra & Hazan, 2008). In some cases when loss is unresolved, suffering and other psychological complications may arise (such as depression). We will discuss this in greater depth in sections that follow integrating it with research on addiction.

Romantic Love, Dopamine, and Reward

As outlined above, numerous studies examining the neural basis of romantic love have shown evidence of activation of the brain's reward system. Our reward system orchestrates behaviors needed for basic needs and survival—such as feeding and sex (e.g., Camara et al., 2009). The mammalian reward system is also involved in processing of other types of rewarding stimuli, such as monetary rewards, food intake, and addictive substances such as alcohol and cocaine (e.g., Pfaus et al., 1990; D'Ardenne et al., 2008; Dominguez & Hull, 2005; Heinz et al., 2004; Matthew et al., 2010; Risinger et al., 2005; Saal et al., 2003; Xue-Ying et al., 2011).

Dopamine release in the reward system is associated with rewarding and approach-related behaviors associated with stimuli (e.g., Schultz, 2010). This involves a variety of processes such as learning associations between stimuli and responses, and motivation to seek out a given reward and work for it regardless of whether it is affectively pleasant or unpleasant. Research by Berridge and Robinson (1998, 2003) suggests that brain mechanisms involved in "liking or disliking" something (implicit emotion) and "wanting" something (implicit motivation) are distinct, and that "liking" is not necessary for "wanting." Thus, even when lovers experience obstacles, challenges, or rejection, they may keep coming back for more, continuing to crave and work to be united with their beloved.

Areas implicated in learning and memory, such as the hippocampus and parahippocampal gyrus, were also recruited in most of these studies. The hippocampus is involved in the encoding and retrieval of memories and is linked with motivation, emotion, executive, and sensorimotor functions through connections with other brain regions. Specifically, the intermediate and temporal areas of the hippocampus are linked to the VTA, via projections to the prefrontal cortex and subcortical sites (e.g., Bast, 2007).

Finally, the insula (activated in numerous fMRI studies of early stage romantic love, the study on long-term romantic love, and in the fMRI studies of the buffering effects of romantic love to pain and marriage to stress) is involved in processing pain and caress-like touch between individuals (Olausson, et al., 2002). Studies have confirmed the insula as a visceral sensory area, visceral motor area (autonomic), motor association area, vestibular area, and language area (e.g., Klein et al., 2007; Craig, 2009). The middle insula has been found in numerous studies involving emotion and is thought to be important for social behaviors, emotional and social behaviors (e.g., Dapretto et al., 2006; Kurth et al., 2010, meta-analysis).

Correlations with Measures of Passionate Love

Aron et al. (2005) found that intensity of consciously experienced passionate love correlated significantly with activation of the right antero-medial caudate body and the septum/fornix. Self-reported passionate love was assessed with the standard, well validated questionnaire measure, the Passionate Love Scale (PLS: Hatfield & Sprecher, 1986). Ortigue et al. (2007) also conducted correlations of PLS scores and found activation in response to the beloved (versus a friend) in the VTA, caudate nucleus, angular gyrus, insula, parahippocampal gyrus and frontal gyrus. Acevedo et al. (2011) found that greater ratings on PLS scores were positively associated with activation in medial caudate body, septum fornix, putamen, posterior cingulate and poster hippocampus. Fisher et al. (2011) also found a correlation between passionate love scores and activation of the caudate and septum/fornix. The correlations found in these studies were substantial, which is especially striking given the limited range of PLS scores (in each study, participants were selected being highly in love and all had very high scores on the PLS).

Activation of the septum/fornix activation, found in three of the four studies, provides good evidence that it is important for passionate love. Acevedo et al. (2011) carried out further analyses, separating obsession-related items (e.g., “I feel I can’t control my thoughts, they are obsessively on my partner.”) from romantic love items (“I will love my partner forever.”) and found that activation of the septum-fornix was distinctly related to obsession-related items of the PLS. Lesion studies with rats suggest that it is implicated in anxiety reduction (e.g., Decker et al., 1995; Degroot & Treit, 2004).

Romantic Love, Dopamine, and Oxytocin

Findings from diverse fMRI studies of romantic love we have reviewed here— across different samples, relationship stages, heterosexual and homosexual relationships, and paradigms (ranging from face images, name primes, hand-holding procedures, and responses to pain)— provided strong evidence that the dopaminergic reward system, namely the regions of the VTA and caudate, is associated with romantic love. Additional evidence that dopaminergic reward areas are implicated in romantic love was provided by several studies correlating standard measures of romantic love, such as the PLS and Eros subscale scores, with brain activations (e.g., Aron et al., 2005; Ortigue et al., 2007; Acevedo et al., 2011; Fisher et al., 2011). All studies correlating the PLS with brain activity found activation of the caudate, and some found activation of the VTA.

Numerous studies have shown the important role of the VTA and caudate nucleus in motivation, reinforcement learning, and decision making (e.g., Carter et al., 2009; Delgado et al., 2003; O’Doherty et al., 2004). The VTA is centrally placed in a wider motivational/reward network associated with behaviors necessary for survival (e.g., Camara et al., 2009). It is widely accepted that activation of dopamine-rich sites, such as the VTA and caudate, are evoked in response to rewards such as food (e.g., Hare et al., 2008), monetary gains (e.g., Carter, Macinnes, Huettel, & Adcock, 2009; Delgado et al., 2003; D'Ardenne et al., 2008), cocaine and alcohol (e.g., Heinz et al., 2004; Risinger et al., 2005), and overall highly motivational stimuli (e.g., Carter et al., 2009; Knutson & Greer, 2008). Recruitment of the mesolimbic dopamine reward system is consistent with notions of romantic love as a "desire for union with another."

The caudate (or dorsal part of the striatum) is a key structure in the mesolimbic dopamine system, associated with motor and cognitive control, and goal-directed behavior (e.g., Doherty et al., 2004). Goal-directed behavior, necessary to attain rewarding stimuli, is consistent with characteristics of pair-bonds and romantic love as being a motivational associated with a specific set of behavioral characteristics, such as proximity-seeking, working to make the partner happy, and rejection of unfamiliar conspecifics state (e.g., Fisher, 1998; Aron et al., 2005). These behaviors serve to initiate, maintain, and protect the pair-bond as eveidenced by research using animal models (e.g., Aragona et al., 2003; Carter, DeVries, & Getz, 1995; Wang, Hulihan, & Insel, 1997; Winslow et al., 1993).

Caudate response has been linked with expecting monetary rewards, showing increased dopamine release in response to the monetary reward (e.g., Zald et al., 2004; Knuston et al., 2001). Release of dopamine is associated with euphoric states, ingestion of drugs such as cocaine, and monogamous pair-bonding in non-human mammals (e.g. Curtis et al., 2006; Young et al., 2001; Young & Wang, 2004). Dopamine is produced mainly in the VTA and SN of the brain and it has many functions ranging from reward learning, motivation, movement, attention, sleep, and mood.

The caudate also responds to information regarding visual stimuli (e.g., Hikosaka et al., 2000; Lauwereyns et al., 2002). This is particularly important for romantic love as the beloved takes on special meaning with focused attention and attraction, particularly for the face (e.g., Fisher 1998; Zeki, 2007). Research with rodent mammals has also shown that monogamous prairie voles versus promiscuous ones (montane voles) have greater densities of oxytocin receptors in the caudate. Oxytocin is stored in the pituitary gland and released during orgasm in both sexes (e.g., Burri et al., 2008; Blaicher et al., 1999; Carmichael et al., 1987; Murphy et al., 1987) and during childbirth and lactation in females (e.g.,Bosch, 2011; Kendrick et al., 1997). Oxytocin has come to be known as the "trust" hormone as it has stress and fear-reducing effects (e.g., Knobloch et al., 2012) and has been linked with increased trust in humans (e.g., Keri & Kiss, 2011; meta-analysis, VanIzendoorn & Bakermans-Kranenburg, 2012).

Correlations with Marital Satisfaction

Numerous studies carried out over the past few decades have shown significant links between relationship/marital satisfaction and health (e.g., Kiecolt-Glaser et al., 1998; Proulx, Helms & Buehler, 2007, meta-analysis). Responsiveness to a close other's needs involves attending to and empathizing with them; approaching them; responding appropriately to their emotional or cognitive states; and deriving a sense of reward from such interactions (this enables learning and continuation of the behavior).

Imaging research has started to show how brain processes may mediate the various functions needed to respond to a relationship partner's needs. For example, in a study of giving support to a loved one twenty racially diverse females in long-term were scanned using fMRI while their male partners stood beside them while receiving periodic signaled electric shocks. The female subjects were also given shocks at the start of the experiment to familiarize them with the level of shock their partner would receive. The results showed that participants providing support to their loved one showed greater activation of the ventral striatum region of the reward system. Additional analyses showed that activation of the ventral striatum was positively correlated to higher reported support effectiveness.

Studies have shown how the perceived quality of a relationship, generally referred to as marital or relationship satisfaction in the context of pair-bonds, is actually reflected in brain regions associated with reward and pleasure (Acevedo et al., 2011). In addition to providing a sense of reward, perceived relationship quality also has measurable benefits for the couple. For example, relationship quality is associated with physical health, life satisfaction, stress-buffering, self-esteem, and psychological well-being (e.g.,Kiecolt-Glaser & Newton 2001, review; Proulx, Helms, & Buehler, 2007, meta-analysis; Saxbe, Repetti, & Nishina; Coan et al., 2006; Riehl, Thomas & Willi, 2003). On the negative side, discord in romantic relationships is linked with depression, stress, negative emotions, partner aggression, and divorce (e.g., Whisman, 2001, meta-analysis; Beach, Arias, & O'Leary, 1986; Cohen, Klein, & O'Leary, 2007; Heyman & Slep, 2001; Kiecolt-Glaser et al., 2005).

Several studies have investigated the neural mechanisms mediating the link between pair-bond quality and health, and provide a new lens to understand human health and functioning. For example, in a seminal study researchers assessed neural activations among 16 women in highly-satisfied marriages, responding to threat cues (shocks) and safety cues while holding their husbands' hand, a stranger's hand, or no hand-holding (Coan, Schaefer, & Davidson, 2006). Results showed that responses to threat cues were significantly attenuated while holding the husband's hand, as evidenced by lower neural activation in the anterior cingulate, posterior cingulate, superior colliculis, and post-central gyri. Also, wives' with greater marital satisfaction scores showed decreased activation of areas interpreted by the authors as reflecting the attenuation of threat/stress (namely, less activation of the anterior insula, superior frontal gyrus, and the hypothalamus) while holding a partner's hand. Thus, perceived relationship quality moderates the stress-buffering effects provided by pair-bonds.

Acevedo, Aron, Fisher, and Brown (under review) also examined the neural correlates of marital satisfaction among a group of 17 individuals in happy and stable marriages. They found positive correlations with neural regions implicated in reward and motivation (e.g., the VTA), stress control (e.g., bed nucleus of the stria terminalis), emotion regulation (prefrontal cortex), and empathy (e.g., anterior insula), and the mirror system (e.g. inferior frontal gyrus). The idea that relationship partners elicit activation of areas related to empathy has been observed in other fMRI studies (e.g., Singer et al., 2004, 2006), and they appear to be moderated by relationship satisfaction.

Acevedo et al. (under review) also reported that relationship satisfaction was negatively correlated with brain activity in the subcallosal cingulate gyrus, an area that shows less activity in response to satiation (e.g., Small et al., 2001) and greater activity in major depression (e.g., Lozano et al., 2008). This finding has been replicated in at least two other samples of pair-bonded individuals, newlyweds and individuals in early-stage romantic love (Acevedo et al., 2010; Xu et al., under review).

Neural Correlates of Pair-bonding Over Time

Several studies of romantic love have reported correlations with relationship length, reflecting the establishment and maintenance of pair-bonds. Aron et al. (2005) found that length of time in-love for their newly in-love sample of 17 individuals correlated significantly with several regions, most notably the mid-insula, the ventral putamen/pallidum, right anterior and posterior cingulate cortex, and right posterior cingulate/retrosplenial cortex.

Acevedo et al. (2011) found a different pattern of time-related neural activity with the long-term romantic love sample. They reported correlations with years married in areas of the accumbens and the periaqueductal gray. Activations in nearby regions of the accumbens were also found in studies of individuals grieving from break-up (e.g., Fisher et al., 2011; Najib et al., 2004) or death of a loved one (O'Connor et al., 2008). Also, activation in this area was found to be associated with cocaine-induced "high" (Risinger et al., 2005).

It is interesting to note that Fisher et al. (2011) and Aron et al. (2005) both reported time-related activation of the anterior cingulate associated with rejected and newly in-love individuals, respectively. The anterior cingulate is implicated in focused attention related to cognition and emotion (Bush et al., 2000; Rauch et al., 1999; Ursu et al., 2003) and cocaine-craving (e.g., Risinger et al., 2005).

In the study of rejected lovers (Fisher et al., 2011 greater number of days since the break-up was associated with less activation of the ventral pallidum s, but it was positively associated with length of relationship for individuals in early-stage romantic love (Aron et al., 2005). The ventral pallidum (VP) is particularly interesting as it is an area that integrates sensory, emotional, and cognitive information and appropriate motor responses. It is rich in receptors for vasopressin, a target site associated with monogamous pair-bonding as shown with numerous studies with rodents (e.g., Insel et al., 1994; Young et al., 2001). It has also been linked with ethanol consumption and cocaine-seeking behavior (e.g., Childress et al., 2008; Kemppainen et al., 2010; Root et al., 2010); hunger and satiation signals (e.g., Berridge et al., 2010; Smith et al., 2008); and mood disorders and dysregulated emotion regulation (e.g., e.g., Murrough et al., 2011; Prossin et al., 2010; Zubieta et al., 2003, 2003). This suggests the VP may be a key target site for addiction and social bonding research.

Pair-bonding and Addiction

Collectively, the results with time-related responses are important for pair-bonding research. They provide seeds for understanding the unfolding of human pair-bonding as bonds are created (e.g., Bartels & Zeki, 2000; Aron et al., 2005, Xu et al., 2011), dissolved (e.g., Fisher et al., 2011; Najib et al., 2004) and sustained over time (e.g., Acevedo et al., 2011). Moreover, by integrating knowledge of the neural underpinnings of the human attachment system with new discoveries in addiction research scientists gain important insights and guiding principles for alleviating problems related to addiction and suffering from the loss of a loved one. For example, as described above, some key neural sites—such as the ventral pallidum, accumbens, and anterior cingulate—are both critical for attachment bonding (both romantic and parental) and addiction functions. Thus, they may be targeted specifically in future research.

Finally, by highlighting the shared neural circuitry between attachment and addiction we revisit a hypothesis that substance-use in mammals may be a repair attempt to replace natural neurobiological processes provided by attachment bonds (e.g., Flores, 2004; Lewis et al., 2000; MacLean 1990). This may explain how the in the presence of distressed attachment relationships or insecure attachment styles, individuals may develop ineffective styles of coping to stress and social challenges leaving them susceptible to addictive compulsions. However, by understanding the close tie in neural circuitry for attachment bonds and addiction, program developers and the like may utilize this knowledge to make strides in helping individuals overcome unwanted addictions. In other words, by increasing awareness and knowledge of the close tie between addiction and attachment, health-care providers, therapists, researchers, funding-agencies, and intervention and treatment program developers may put “close relationships” front-and-center in their practices to more effectively help individuals overcome unwanted addictions and recover from loss.

Conclusions

In the current chapter we reviewed published studies to date examining the neural correlates of romantic love in humans. Results from a variety of studies across the globe, using varying procedures, relationship stages, both opposite and same-sex relationships, in the context of new love (e.g., Aron et al., 2005; Bartels & Zeki, 2000), lasting love (e.g., Acevedo et al., 2011), and even romantic rejection (Fisher et al., 2011), all show involvement of the brain's dopaminergic reward system important for motivation and approach-related behaviors. This supports the idea that romantic love is a basic human motivation, a driving force associated with wanting and longing to be united with a beloved (e.g., Aron & Aron, 1986; Hatfield & Sprecher, 1986; Fisher, 1998; Acevedo et al., 2010). Romantic love is multi-faceted. It is associated with behaviors necessary for survival and propagation of the species, such as reproduction and pair-bonding. It also involves complex phenomenon, such as relationship-satisfaction and inclusion of other in the self.

We also reviewed several studies examining the neural mechanisms mediating the link between pair-bond quality and health. These studies suggest that providing support to a loved one is associated with reward-related brain activity (Inagaki & Eisenberg, 2012), a good indicator for continuation of the behavior. Also, receiving support from a loved one is associated with the attenuation of stress and threat response neural responses and the effects seem to be moderated by perceived relationship quality, such that individuals in more satisfying relationships experience stronger buffering (e.g., Coan et al., 2006). Finally, relationship quality is associated with brain regions involved in reward and motivation, stress, emotion regulation, empathy, and mood disorders (Acevedo et al., under review). These studies provide a new lens to understand human health, and highlight mediating processes linking attachment bond quality with physiological, emotional, and psychological health, supporting decades of research linking marital quality and health (e.g., Kiecolt-Glaser et al., 1998) and observational research conducted decades earlier with orphan children and primates deprived of social bonds (e.g., Spitz, 1951; Harlow, 1965; Robertson, 1971; Bowlby, 1977).

In addition to romantic love, relationship satisfaction, and pair-bonding, the dopaminergic reward system is also implicated in behaviors related to feeding (Hare et al., 2008), monetary gains (D'Ardenne et al., 2008), and consumption of addictive substances such as cocaine and alcohol (e.g., Heinz et al., 2004; Risinger et al., 2005). By highlighting and understanding the shared neural circuitry between human attachment bonds and addiction health-care providers, therapists, researchers, funding-agencies, and intervention and treatment program developers may be better able to serve individuals overcome unwanted addictions and recover from loss.

References

Acevedo, B.P., & Aron, A. (2009). Does a long-term relationship kill romantic love? *Review of General Psychology, 13,* 59-65.

Acevedo, B.P., Aron A, Fisher H, Brown, L.L. (2011). Neural correlates of long-term intense romantic love. *Social Cognitive and Affective Neuroscience Journal, doi: 10.1093/scan/nsq092.*

Acevedo, B.P., Aron, A., Gross, J.J., Xu, X., & Ralte, Z. (2010). *Is love different from "basic" emotions? Valence, complexity, and emotion regulation.* Manuscript submitted for publication.

Amato, P., & Sobolewski, J. (2001). The effects of divorce and marital discord on adult children's psychological well-being. *American Sociological Review 66*, 900-921.

Amodio, D.M., & Frith, C.D. (2006). Meeting of minds: the medial frontal cortex and social cognition. *Nature Review 7*, 268–277.

Anderson, K.L., Umberson, D., Elliott, S., & Vangelisti, A.L. (2004). Violence and abuse in families. *Handbook of family communication,* 629-645. Lawrence Erlbaum Associates Publishers, Mahwah, NJ, US.

Aragona, B. J., Liu, Y, Curtis, J.T., Stephan, F.K., & Wang, Z. (2003). A critical role for nucleus accumbens dopamine in partner-preference formation in male prairie voles. *Journal of Neuroscience, 23*(8), 3483-3490.

Aron, A., & Aron, E. (1986). Love and the expansion of self: Understanding attraction and satisfaction. New York: Hemisphere.

Aron, A., Aron, E. N., & Smollan, D. (1992). Inclusion of other in the Self Scale and the structure of interpersonal closeness. *Journal of Personality and Social Psychology*, *63*, 596-612.

Aron, A., Fisher, H., Mashek, D., Strong, G., Li, H., & Brown, L. (2005). Reward, motivation and emotion systems associated with early-stage intense romantic love. *Journal of Neurophysiology*, *93*, 327-337.

Aron, A., & Henkemeyer, L. (1995). Marital satisfaction and passionate love. *Journal of Social and Personal Relationships*, *12*, 141-149.

Aron, A., Norman, C. C., Aron, E., McKenna, C. & Heyman, R. E. (2000). Couples' shared participation in novel and arousing activities and experienced relationship quality. *Journal of Personality and Social Psychology, 78*(2), 273-284.

Aron, A., & Westbay, L. (1996). Dimensions of the prototype of love. *Journal of Personality and Social Psychology*, 70, 535-551.

Arzy, S., Seeck, M., Ortigue, S., Spinelli, L., & Blanke, O. (2006). Induction of an illusory shadow person. *Nature, 443,* 287.

Bales, K. L., Mason, W. A., Catana, C., Cherry, S. R., & Mendoza, S. P. (2007). Neural correlates of pair-bonding in a monogamous primate. *Brain Research, 1184*, 245-253.

Bartels, A., & Zeki, S. (2000). The neural basis of romantic love. *NeuroReport: For Rapid Communication of Neuroscience Research 11*(17), 3829-3834.

Bartels, A., & Zeki, S. (2004). The neural correlates of maternal and romantic love. *NeuroImage, 21*(3), 1155-1166.

Bartels, A., & Zeki, S. (2004). Functional Brain Mapping During Free Viewing of Natural Scenes. *Human Brain Mapping 21,* 2, 75-85.

Barry, R.A., & Kochanska, G. (2010). A longitudinal investigation of the affective environment in families with young children: From infancy to early school age. *Emotion 10,* 2, 237-249.

Baxter, M.G., Parker, A., Lindner, C.C., Izquierdo, A.D., & Murray, E.A. (2000). Control of response selection by reinforcer value requires interaction of amygdala and orbital prefrontal cortex. *Journal of Neuroscience 20*, 4311– 4319.

Baumeister, R.F., & Bratslavsky, E. (1999). Passion, intimacy, and time: Passionate love as a function of change in intimacy. *Personality and Social Psychology Review, 3*(1), 49-67.

Baumgarten, H.G., & Grozdanovic, Z. (1995) Psychopharmacology of central serotonergic systems. *Pharmacopsychiatry*, 2, 73-9.

Beach, S.R.H., & O'Leary, K.D. (1993). Marital discord and dysphoria: For whom does the marital relationship predict depressive symptomatology. *Journal of Social and Personal Relationships 10,* 405-420.

Berridge K.C., & Robinson, T.E. (1998). What is the role of dopamine in reward: hedonic impact, reward learning, or incentive salience?. *Brain Research Reviews*, 28, 309-69.

Berscheid, E., & Hatfield [Walster], E. H. (l969). Interpersonal attraction. New York: Addison-Wesley.

Bittar, R.G., Kar-Purkayastha, I., Owen, S.L., Bear, R.E., Green, A., Wang, S., & Aziz, T.Z. (2005). Deep brain stimulation for pain relief: a meta-analysis. *Journal of Clinical Neuroscience*, 5, 515-9.

Blanke, O., Ortigue, S., Landis, T., & Seeck, M. (2002). Stimulating illusory own-body perceptions. *Nature 419,* 269-270.

Botvinick, M., Jha, A., Bylsma, L., Fabian, S., Solomon, P., & Prkachin, K. (2005). Viewing facial expressions of pain engages cortical areas involved in the direct experience of pain. *NeuroImage 25,* 1, 312-319.

Bowlby, J. (1969). Attachment and Loss (Volume 1) Attachment. London: Hogarth.

Bray, S., Shimojo, S., & O'Doherty, J. (2010). Human medial orbitofrontal cortex is recruited during experience of imagined and real rewards. *Journal of Neurophysiology 103*, 2505-2512.

Bragulat, V., Dzemidzic, M., Bruno, C., Cox, C.A. Talavage, T., Considine, R.V., & Kareken, D.A. (2010). Food-related odor probes of brain reward circuits during hunger: A pilot fMRI study. *Obesity,* doi:10.1038/oby.2010.57.

Bunge, S.A., Dudukovic, N.M., Thomason, M.E, Vaidya, C.J., & Gabrieli, J.D. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron 33,* 301-311.

Buss, D. M. (1989). Sex differences in human mate preferences: Evolutionary hypotheses tested in 37 cultures. *Behavioral & Brain Sciences*, *12*, 1-49.

Buss, D.M. (2006). The evolution of love. In R. Sternberg and K. Weis (Eds.), *The new psychology of love* (pp. 65-86). New Haven: Yale University Press.

Cacioppo, J., & Patrick, W. (2008). Review of human: The science behind what makes us unique. *Nature Neuroscience 11*, 10, 1008-1119.

Camara, E., Rodriguez-Fornells, A., Ye, Z., & Munte, T.F. (2009). Reward networks in the brain captured by connectivity measures. *Frontiers in Neuroscience, 3,* 350-362.

Carlson. (2000). Children exposed to intimate partner violence: Research findings and implications for intervention. *Trauma Violence Abuse 1,* 321-342.

Carter, C.S. (1998). Neuroendocrine perspectives on social attachment and love. *Psychoneuroendocrinology, 23,* 779-818.

Carter, C.S., DeVries, A.C., & Getz, L.L. (1995). Physiological substrates of mammalian monogamy: The prairie vole model. *Neurosci. Biobehav. Rev., 19,* 303-314.

Carter, R.M., MacInnes, J.J., Huettel, S.A., Adcock, R.A. (2009). Activation in the VTA and nucleus accumbens increases in anticipation of both gains and losses. *Frontiers in Behavioral Neuroscience,* 3(21).

Casey, B.J., Galvan, A., & Hare, T.A. (2005). Changes in cerebral functional organization during cognitive development. *Current Opinions Neurobiology 15*, 239-244.

Casey, B.J., Getz, S., & Galvan, A. (2007). The adolescent brain. *Developmental Review 28,* 62-77.

Coan, J. A., Schaefer, H. S., & Davidson, R. J. (2006). Lending a hand: Social regulation of the neural response to threat. *Psychological Science, 17*(12), 1032-1039.

Colasanti, A., Rabiner, E.A., Lingford-Hughes, A., & Nutt, D.J. (2010). Opioids and Anxiety. *Journal of Psychopharmacol*ogy.

Collins, N., & Ford, M.B. (2010). Responding to the needs of others: The caregiving behavioral system in intimate relationships. *Journal of Social and Personal Relationships 27,* 235-244.

Craig, A.D. (2009). How do you feel—now ? The anterior insula and human awareness. *Nature Review Neuroscience, 10,* 59-70.

Cristopoulos, G.I., Tobler, P.N., Bossaerts P, Dolan RJ, Schultz W (2009). Neural correlates of value, risk, and risk aversion contributing to decision making under risk. *Journal of Neuroscience 40,* 12574-83.

Cromwell, H.C., Berridge, K.C. (1993). Where does damage lead to enhanced food aversion : the ventral pallidum/sunstantia innominata or lateral hypothalamus ? *Brain Research, 624,* 1-10.

Cross, E.S., Hamilton, A., & Grafton, S.T. (2006). Building a motor simulation de novo: Observation of dance by dancers. *NeuroImage 31*, 1257–1267.

Curtis, J. T., Liu, Y., Aragona, B. J., & Wang, Z. (2006). Dopamine and monogamy. *Brain Research, 1126(1)*, 76-90.

D'Ardenne, K., McClure, S.M., Nystrom, L.E., & Cohen, J.D. (2008). BOLD responses reflecting dopaminergic signals in the human ventral tegmental area. *Science 319,* 1264-1267.

Davidson, T.L., & Jarad, L.E. (1993). A role for hippocampus in the utilization of hunger signals. *Behav. Neural Biol., 59,* 161-171.

Davila, J., Karney, B.R., Hall, T.W., & Bradbury, T.N. (2003). Depressive symptoms and marital satisfaction: Dynamic associations and the moderating effects of gender and neuroticism. *Journal of Family Psychology 17*, 557-570.

Decety, J., Grèzes, J., Costes, N., Perani, D., Jeannerod, M., Procyk, E., Grassi, F., & Fazio, F. (1997). Brain activity during observation of actions. Influence of action content and subject’s strategy. *Brain 10,* 1763-1767.

Decker, M.W., Curzon, P., & Brioni, J.D. (1995). Influence of separate and combined septal and amygdala lesions on memory, acousticstartle, anxiety, and locomotor activity in rats. *Neurobiol Learn Mem*, 64, 156-168.

Degroot, A., & Treit, D. (2004). Anxiety is functionally segregated within the septo-hippocampal system. *Brain Research*, 1001,60-71.

Delgado, M.R., Locke, H.M., Stenger, V.A., & Fiez, J.A. (2003) Dorsal striatum responses to reward and punishment: Effects of valence and magnitude manipulations. *Cognitive* Affective & *Behavioral Neuroscience*, 3, 27–38.

Drevets, W.C., Price, J.L., & Furey, M.L. (2008). Brain structural and functional abnormalities in mood disorders: Implications for neurocircuitry models of depression. *Brain Structure Function 213,* 93-118.

Drevets, W.C., Savitz, J.,& Trimble, M. (2008). The subgenual anterior cingulate cortex in mood disorders. *CNS Spectrums 13,* 663-681.

Eastwick, P. W. & Finkel, E. J. (2008). The attachment system in fledgling relationships: An activating role for attachment anxiety. *Journal of Personality and Social Psychology*, *95*, 628-647.

Eisenberg, N., & Miller, P. (1987). The relation of empathy to prosocial and related behaviors. *Psychological Bulletin*, *101,* 1, 91-119.

Elliott, R., Dolan, R.J., & Frith, C.D. (2000). Dissociable functions in the medial and lateral orbitofrontal cortex: evidence from human neuroimaging studies. *Cerebral Cortex 10*, 308 –317.

Enzi, B., Greck, M., Prosch, U., Templemann, C., Northoff, G. (2009). Is our self nothing but reward? Neuronal overlap and distinction between reward and personal relevance and its relation to human personality. *PLoS ONE, 4.*

Fan, Y., Duncan, N.W., de Greck, M.,& Northoff, G. (2010). Is there a core neural network in empathy? An fMRI based quantitative meta-analysis. *Neuroscience & Biobehavioral Reviews 35,* 903-911.

Fernandez, G., & Kroes, M.C. (2010). Protecting endangered memories. *Nature Neuroscience, 13,* 408-410.

Fisher, H.E. (1992). Anatomy of love: The natural history of monogamy, adultery, and divorce. New York: W.W. Norton.

Fisher, H.E. (1998). Lust, attraction, and attachment in mammalian reproduction. Human Nature, 9, 23-52.

Fisher, H. (2004). Why we love: the nature and chemistry of romantic love. New York: Henry Holt.

Fisher, H.E. (2006). The drive to love. In R. Sternberg and K. Weis (Eds.), *The new psychology of love* (pp. 87-115). New Haven: Yale University Press.

Fisher, H.E., Brown, L.L., Aron, A., Strong, G., Mashek, D. (2010). Reward, addiction, and emotion regulation systems associated with rejection in love. *Journal of Neurophysiology*, doi:10.1152/jn.00784.2009.

Frascella J, Potenza MN, Brown LL, Childress AR. Shared brain vulnerabilities open the way for nonsubstance addictions: carving addiciton at a new joint? *Ann N Y Acad Sci., 1187*, 294-315.

Frech, A.,& Williams, K. (2007). Depression and the psychological benefits of entering marriage. *Journal of Health and Social Behavior 48,* 2, 149-163.

Freud (1921) Group Psychology and the Analysis of the Ego" (1921) [SE, XVIII, 90-91].

Fromm, Erich. (1956). The art of loving. New York: Harper Perennial.

Gable, S., Reis, H., Impett, E., & Asher, E. (2004). What do you do when things go right? The intrapersonal and interpersonal benefits of sharing positive events. *Journal of Personality and Social Psychology 87,* 2, 228-245.

Gallese, V., & Goldman, A. (1998). Mirror neurons and the simulation theory of mind reading. *Trends in Cognitive Science 2,* 493-501.

Genovese, C.R., Lazar, N.A., & Nichols, T. (2002). Thresholding of statistical maps in functional neuroimaging data using the false discovery rate. *NeuroImage 15*, 870-878.

Gingrich, B., Liu, Y, Cascio, C, Wang, Z, Insel, TR. (2000). Dopamine D2 receptors in the nucleus accumbens are important for social attachment in female prairie voles (Microtus ochrogaster). *Behavioral Neuroscience, 114*(1), 173-183.

Glenn, N., & Weaver, C. (1981). The contribution of marital happiness to global happiness. *Journal of Marriage & the Family 43,* 2, 161-168.

Glimcher, P., & Rustichini, A. (2004). The consilience of brain and decision. *Science 306*, 447–452.

Gonzaga, G.C., Turner, R.A., Keltner, D., Campos, B., & Altemus, M. (2006). Romantic love and sexual desire in close bonds. *Emotion*, 6, 163–179.

Gross, J.J., & John, O.P. (2003). Individual differences in two emotion regulation processes: Implications for affect, relationships, and well-being. *Journal of Personality and Social Psychology 85,* 348-32.

Grote, N. K. Frieze, I. H. (1994). The measurement of friendship-based love in intimate relationships. *Personal Relationship, 1*, 275-300.

Guitart-Masip, M., Bunzeck, N., Stephan, K.E., Dolan, R.J., & Düzel, E. (2010) Contextual novelty changes reward representations in the striatum. *Journal of Neuroscience*, 30(5), 1721-6.

Hare, T.A., O'Doherty, J., Camerer, C.F., Schultz, W., Rangel, A. (2008). Dissociating the role of the orbitofrontal cortex and the striatum in the computation of goal values and prediction errors. *Journal of Neuroscience, 28,* 5623-5630.

Hatfield, E., & Sprecher, S. (1986). Measuring passionate love in intimate relations. *Journal of Adolescence, 9*, 383-410.

Ha, T., Overbeek, G., Vermulst, A.A., & Engels, R.C. (2009). Marital quality, parenting, and adolescent internalizing problems: A three-wave longitudinal study. *Journal of Family Psychology 23,* 263-267.

Hammack, S.E., Roman, C.W. et al (2010). Roles for pituitary adenylate cyclase-activating peptide (PACAP) expression and signaling in the bed nucleus of the stria terminalis (BNST) in mediating the behavioral consequences of chronic stress. *J. Molecular Neuroscience 42,* 327-340.

Hazan, C., & Shaver, P. R. (1987). Romantic love conceptualized as an attachment process. *Journal of Personality and Social Psychology*, 52, 511-524.

Hazan, C., & Zeifma, D. (1999). Pair-bonds as attachments: Evaluating the evidence. In J. Cassidy & P.R. Shaver (Eds.), *Handbook of attachment: Theory, research, and clinical applications* (336-354). New York: Guilford Press.

Heinz, A., Siessmeier, T., Wrase, J. et. al. (2004). Correlation between dopamine D2 receptors in the ventral striatum and central processing of alcohol cues and craving. *The American Journal of Psychiatry, 161,* 1783-1789.

Hendrick, C., & Hendrick, S. S. (1986). A theory and method of love. *Journal of Personality and Social Psychology*, 50, 392-402.

Hendrick, S. & Hendrick, C. (1992). Romantic Love. Newbury Park, CA: Sage Publications, Inc.

Iacoboni, M., Woods, R.P., Brass, M., Bekkering, H., Mazziotta, J.C., & Rizzolatti, G. (1999). Cortical mechanisms of human imitation. *Science 286*, 2526–2527.

Insel, T. R., Wang, Z. X., & Ferris, C. F. (1994). Patterns of brain vasopressin receptor distribution associated with social organization in microtine rodents. *Journal of Neuroscience*, *14*, 5381-5392.

Izquierdo, A., & Murray, E.A. (2010). Functional interaction of mediodorsal thalamic nucleus but not nucleus accumbens with amygdala and orbital prefrontal cortex is essential for adaptive response selection after reinforcer devaluation. *The Journal of Neuroscience 30*, 661-669.

Jabbi, M., & Keysers, C. (2008). Inferior frontal gyrus activity triggers anterior insula response to emotional facial expressions. *Emotion 8,* 775-80.

Jenkins, J.S., Ang, V.T., Hawthorn, J., Rossor, M.N., & Iversen, L.L. (1984). Vasopressin, oxytocin and neurophysins in the human brain and spinal cord. *Brain Res*. 291 (1), 111–117.

Kampe, K., Frith, C.D., & Frith, U. (2003). "Hey John": Signals conveying communicative intention towards the self activate brain regions associated with mentalising regardless of modality. *Journal of Neuroscience*, 23, 5258-5263.

Karama, S., Lecours, A.R., Leroux, J.-M., Bourgouin, P., Beaudoin, G., Joubert, S., & Beauregard, M. (2002). Areas of brain activation in males and females during viewing of erotic film excerpts. *Human Brain Mapping* 16, 1–13.

Karney, B. R. & Bradbury, T. N. (2005). Contextual influences on marriage: Implications for policy and intervention. *Current Directions in Psychological Science, 14*, 171-174.

Kiecolt-Glaser, J.K., Glaser, R., Cacioppo, C., & Malarkey, W.B. (1998). Marital stress: Immunologic, neuroendocrine, and autonomic correlates. *Annals of the New York Academy of Sciences 840*, 656–63.

Kiecolt-Glaser, J., & Newton, T. (2001). Marriage and health: His and hers. *Psychological Bulletin 127,* 4, 472-503.

Kiecolt-Glaser, J., Loving, T., Stowell, J., Malarkey, W., Lemeshow, S., & Dickinson, S., et al (2005). Hostile marital interactions, proinflammatory cytokine production, and wound healing. *Archives of General Psychiatry 62,* 12, 1377-1384.

Kilner, J.M., Neal, A., Weiskopf, N., Friston, K.J., & Frith, C.D. (2009). Evidence of mirror neurons in human inferior frontal gyrus. *Journal of Neuroscience 29,* 10153-10159.

Kirouc, G.J., Li, S., Mabrouck, G. (2004). GABAergic projections from the ventral tegmental area and substantia nigra to the periaqueductal gray region and the dorsal Raphe nucleus. *The Journal of Comparative Neurology, 469,* 170-184.

Klein, T.A., Endrass, T., Kathmann, N., et al., (2007). Neural correlates of error awareness. *Neuroimage, 34,* 1774-1781.

Knutson, B., & Cooper, J. (2005). Functional magnetic resonance imaging of reward prediction. *Current Opinion Neurology 18*, 411-417.

Knutson, B., Fong, G.W., Adams, C.M., Varner, J.L., & Hommer, D. (2001). Dissociation of reward anticipation and outcome with event-related fMRI. *NeuroReport 12*, 3683–3687.

Knutson, B., & Greer, S.M. (2008). Anticipatory affect: Neural correlates and consequences for choice. *Philosophical Transactions of the Royal Society B*, 363, 3771-3786.

Knutson, B., Rick, S., Wimmer, G.E., Prelec, D., & Loewenstein, G. (2007). Neural predictors of purchases. *Neuron, 53,* 147-156.

Kringelbach, M., O'Doherty, J., Rolls, E., & Andrews, C. (2003). Activation of the human orbitofrontal cortex to a liquid food stimulus is correlated with its subjective pleasantness. *Cerebral Cortex 13,* 10, 1064-1071.

Kringelbach ML, Rolls ET (2004). The functional neuroanatomy of the human orbitofrontal cortex: evidence from neuroimaging and neuropsychology. *Prog Neurobiol 72,* 341–372.

Kurth, F., Ziles, K., Fox, P.T., Laird, A.R., Eickhoff, S.B. (2010). A link between the systems: Functional differentiation and integration within the human insula revealed by meta-analysis. *Brain Structure and Function, 214,* doi: 10.1007/s00429-010-0255-z.

LaBar, K.S., Gitelman, D.R., Mesulam, M.M., & Parrish, T.B. (2001). Impact of signal-to-noise on functional MRI of the human amygdala. *Neuroreport,* 12, 3461-3464.

Lamm C, Decety J, Singer T (2011). Meta-analytic evidence for common and distinct neural networks associated with directly experienced pain and empathy for pain. *NeuroImage 54,* 2492-2502.

Le Maître, E., Vilpoux, C., Costentin, J., & Leroux-Nicollet, I. (2005). Opioid receptor-like 1 (NOP) receptors in the rat dorsal Raphe nucleus: evidence for localization on serotoninergic neurons and functional adaptation after 5,7-dihydroxytryptamine lesion. *Journal of Neuroscience Research*, *81*, 488-96.

Lee, John A. (1977). A Typology of Styles of Loving. *Personality & Social Psychology Bulletin*, *3*, 173-182.

Leibenluft, E., Gobbini, M. I., Harrison, T., & Haxby, J. V. (2004). Mothers' neural activation in response to pictures of their children and other children. *Biological Psychiatry, 56*(4), 225-232.

Liakakis G, Nickel J, Seitz RJ (2011). Diversity of the inferior frontal gyrus—A meta-analysis of neuroimaging studies. *Behavioural Brain Research, doi: 10.1016/j.bbr.2011.06.022.*

Lim, M.M., Young, L.J. (2004). Vasopresson-dependent neural circuits underlying pair-bond formation in the monogamous prairie vole. *Neuroscience, 125, 35-45.*

Loup, F.E., Triboll**et,** E., Dubois-Dauphin, M., & Dreifuss, J.J. (**1991**). Localization of high-affinity binding sites for oxytocin and vasopressin in the human brain. An autoradiographic study. *Brain Research*, 555, 220-232.

Loup, F. E., Tribollet, E., Dubois-Dauphin, M., Pizzolato, G., & Dreifuss, J.J. (1989). Localization of oxytocin binding sites in the human brainstem and uppoer spinal cord: An auto radiographic study. *Brain Research 500,* 223-230.

Lozano A, Mayberg H, Giacobbe P, Hamani C, Craddock R, Kennedy S (2008). Subcallosal cingulate gyrus deep brain stimulation for treatment-resistant depression. *Biological Psychiatry 64,* 6, 461-467.

Maddock, R. J., Garrett, A. S., & Buonocore, M. H. (2001). Remembering familiar people: the posterior cingulate cortex and autobiographical memory retrieval. *Neuroscience, 104*(3), 667-676.

Mai, J.K., Paxinos, G., & Voss, T. (2008). *Atlas of the human brain*, 3rd Edn. San Diego, Elsevier Academic Press.

Maner, J. K., Rouby, D. A., & Gonzaga, G. C. (2008). Automatic inattention to attractive alternatives: the evolved psychology of relationship maintenance. *Evolution and Human Behavior, 29,* 343-349.

Mar AC, Walker LJ, Theobald DE, Eagle DM, Robbins TW (2011). Dissociable effects of lesions to the orbitofrontal subregions on impulsive choice in the rat. *The Journal of Neuroscience 31,* 6398-6404.

Master, S.L., Eisenberger, N.I., Taylor, S.E., Naliboff, B.D., Shirinyan, D., & Lieberman, M.D. (2009). A picture's worth. Partner photographs reduce experimentally induced pain. *Psychological Science, 20,* 1316-1318.

Masuda, M. (2003). Meta-analyses of love scales: Do various love scales measure the same psychological constructs? *Japanese Psychological Research, 45*(1), 25-37.

Mazzola V, Latorre V et al (2010). Affective responses to a loved one's pain: Insula activity as a function of individual differences. *PLoS One 5*, 1-10.

McClure SM, Ericson KM, Laibson DI, Loewenstein G, Cohen JD (2007). Time discounting for primary rewards. *Journal of Neuroscience 27*, 5796 –5804.

Menzies, L., et al., (2008). Integrating evidence from neuroimaging and neuropsychological studies of obsessive-compulsive disorder: The orbitofrontal-straitel model revisited. *Neuroscience and Behavioral Reviews, 32,* 525-549.

Meyers, S.A., & Berscheid, E. (1997). The language of love: the difference a preposition makes. *Personality and Social Psychology Bulletin*, 23, 347.

Mikulincer, M., Shaver, P.R. (2007). Attachment in adulthood: Structure, dynamics, and change. New York, The Guilford Press,.

Miller, R.S. (1997). Inattentive and contented: Relationship commitment and attention to alternatives. *Journal of Personality and Social Psychology, 73,* 758-766.

Mitchell JP, Ames DL, Jenkins AC, Banaji MR (2009). Neural correlates of stereotype application. *Journal of Cognitive Neuroscience 21*, 594–604.

Mitchell J, Macrae N, Banaji M (2006). Dissociable medial prefrontal contributions to judgments of similar and dissimilar others. *Neuron 50,* 4, 655-663.

Mobini S, Body S, Ho MY, Bradshaw CM, Szabadi E, Deakin JF, Anderson IM, Mayberg H, Lozano A, Voon V, McNeely H, Seminowicz D, Hamani C, Kennedy S (2005). Deep brain stimulation for treatment-resistant depression. *Neuron, 45,* 5. 651-660.

Najib, (XXX)

Napier, T.C., Mitrovic, I. (1999). Opiod modulation of ventral pallidal inputs. *Ann NY Acad Sci, 877,* 176-201.

Nelissen K, Luppino G, Vanduffel W, Rizzolatti G, Orban GA (2005). Observing others: multiple action representation in the frontal lobe. *Science, 310*, 332–336.

Northoff, G., Heinzel, A., deGreck, M., Bermpohl, F. Dobrowolny, H., et al. (2006). Self-referential processing in our brain—a meta-analysis of imaging studies on the self. *Neuroimage, 31*, 440-457.

Ochsner, K.N., & Gross, J.J. (2005). The cognitive control of emotion. *Trends in Cognitive Science 9,* 242-249.

Ochsner, K. N., Knierim, K., Ludlow, D. H., Hanelin, J., Ramachandran, T., Glover, G., et al. (2004). Reflecting upon feelings: An fMRI study of neural systems supporting the attribution of emotion to self and other. *Journal of Cognitive Neuroscience*, 16, 1746-1772.

O'Connor, M.-F., Wellisch, D. K., Stanton, A. L., Eisenberger, N. I., Irwin, M. R., & Lieberman, M. D. (2008) Craving love? Enduring grief activates brain's reward center. *NeuroImage,* 42, 969-972.

O'Doherty, J., Dayan, P., Schultz, J., Deichmann, R., Friston, K., & Dolan, R.J. (2004). Dissociable roles of ventral and dorsal striatum in instrumental conditioning. *Science, 304,* 452-454.

O'Doherty J, Deichmann R, Critchley H, Dolan L (2002). Neural responses during anticipation of a primary taste reward. *Neuron 33,* 5, 815-826.

O'Doherty J, Kringelbach ML, Rolls ET, Hornak J, Andrews C (2001). Abstract reward and punishment representations in the human orbitofrontal cortex. *Nature Neuroscience 4,* 95–102.

O'Doherty J, Winston J, Critchley H, Perrett D, Burt DM, Dolan RJ (2003). Beauty in a smile: the role of medial orbitofrontal cortex in facial attractiveness. *Neuropsychology 41*, 147–155.

O'Leary KD, Acevedo BP, Aron A, Huddy L, Mashek D (in press). Is long-term love more than a rare phenomenon? If so, what are its correlates*? Social Psychology and Personality Science*.

O'Leary KD, Slep AM, O'Leary SG (2000). Co-occurrence of partner and parent aggression: research and treatment implications. *Behavior Therapy 31*, 631-648.

Olive, M.F., Anton, B., Micevych, P., Evans, C.J., Maidment, N.T. (1997). Presynaptic vs. Postsynaptic locoalization of opioid receptors in dorsal and ventral striatopallidal pathways. *J Neuroscience, 17,*7471-7479.

Ortigue, S., Bianchi-Demicheli, F., Hamilton, A.F.,& Grafton, S. T., (2007). The neural basis of love as a subliminal prime: An event-related fMRI study. *Journal of Cognitive Neuroscience, 19,* 1218-1230.

Paxinos G, Watson C (1998). The rat brain in stereotaxic co-ordinates

Peckys, D., & Landwehrmeyer, G. B. (1999). *Neuroscience,* 88, 1093–1135

Pelchat, M,L., Johnson, A., Chan, R., Valdez, J., & Ragland, J.D. (2004). Images of desire: food-craving activation during fMRI. *Neuroimage*, 23, 1486-1493.

Plassmann H, O'Doherty J, Rangel A. (2010). Appetitive and aversive goal values are encoded in the medial orbitofrontal cortex at the time of decision making. *Journal of Neuroscience, 30,* 10799–808.

Proulx C, Helms H, Buehler C (2007). Marital quality and personal well-being: A meta-analysis. *Journal of Marriage and Family*, *69*(3), 576-593.

Riehl-Emde, A., Thomas, V., & Willi, J. (2003). Love: An important dimension in marital research and therapy. *Family Process*, *42*, 253-267.

Risinger, R. C., Salmeron, B. J., Ross, T. J., Amen, S. L., Sanfilipo, M., Hoffmann, R. G., et al. (2005). Neural correlates of high and craving during cocaine self-administration using BOLD fMRI. *NeuroImage, 26*(4), 1097-1108.

Rizzolatti G, Craighero L (2004). The mirror-neuron system. *Annu Rev Neurosci 27,* 169 –192.

Rusbult, C.E., Van Lange, P.A.M., Wildschut, T., Yovetich, N.A., Verette, J. (2000). *Perceived superiority in close relationships: Why it exists and persists. Journal of Personality and Social Psychology*, *79*, 521-545.

Sabatinelli D, Fortune EE, Li Q, Siddiqui A, Kraftt C, Oliver WT, Beck S, Jeffries J (2011). Emotion perception: Meta-analyses of face and natural scene processing. *NeuorImage, 54,* 2524-2533.

Savine AC, Braver TS (2010). Motivated cognitive control: Reward incentives modulate preparatory neural activity during task-switching. *Journal of Neuroscience, 30,* 10294-10305.

Sbarra D, Hazan C (2008). Coregulation, dysregulation, self-regulation: An integrative analysis and empirical agenda for understanding adult attachment, separation, loss, and recovery. *Personality and Social Psychology Review*, *12*(2), 141-167.

Schulz D, Canbeyli RS (2000). Lesion of the bed nucleus of the stria terminalis enhances learned despair. *Brain Research Bulletin, 52*, 83-87.

Schultz, W. (2001). Reward signaling by dopamine neurons. *The Neuroscientist, 7,* 293-302.

Silk J (2007). Social components of fitness in primate groups. *Science*, *317*(5843), 1347-1351.

Singer T, Seymour B, O'Doherty J, Kaube H, Dolan R, Frith C (2004). Empathy for Pain Involves the Affective but not Sensory Components of Pain. *Science, 303*(5661), 1157-1162.

Small DM, Gregory MD, Mak YE, Gitelman D, Mesulam MM, Parrish T (2003). Dissociation of neural representation of intensity and affective valuation in human gustation. *Neuron, 39*, 701–711.

Smith, K.S., Tindell, A.J., Aldridge, J.W., Berridge, K.C. (2009). Ventral pallidum roles in reward and motivation. *Beh Brain Res., 196 (2),* 155-167.

Sroufe, L.A., & Waters, E. (1977). Attachment as an organizational construct. *Child Development, 48,* 1184-1199.

Sternberg, R. J. (1986). A triangular theory of love. *Psychological Review*, 93, 119-135.

Strathearn, L., Li, J., Fonagy, P., & Montague, P. (2008). What's in a smile? Maternal brain responses to infant facial cues. *Pediatrics*, 122(1), 40-51.

Sullivan K, Pasch L, Johnson M, Bradbury T (2010). Social support, problem solving, and the longitudinal course of newlywed marriage. *Journal of Personality and Social Psychology*, *98*(4), 631-644. *doi:10.1037/a0017578.*

Tamir D, Mitchell J (2010). Neural correlates of anchoring-and-adjustment during mentalizing. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, *107*(24), 10827-10832.

Tennov, D. (1979). *Love and limerence: The experience of being in love*. New York: Stein & Day.

TW (2007). Shifting and stopping: Frontostriatal substrates, neurochemical modulation and clinical implications. *Phil Transactions of the Royal Society fir Biological Sciences, 362,* 917-932.

Van Overwalle F, Baetens K (2009). Understanding others' actions and goals by mirror and mentalizing systems: A meta-analysis. *NeuroImage, 48,* 564-5584.

Voss K, Markiewicz D, Doyle A (1999). Friendship, marriage and self-esteem. *Journal of Social and Personal Relationships*, *16*(1), 103-122.

Waldinger R, Schulz, M, Hauser, S, Allen, J, Crowell, J (2004). Reading others' emotions: The role of intuitive judgments in predicting marital satisfaction, quality, and stability. *Journal of Family Psychology*, *18*(1), 58-71.

Walker DL, Miles LA, Davis M (2009) Selective participation of the bed nucleus of the stria terminalis and CRF in sustained anxiety-likeversus phasic fear-like responses. *Prog Neuropsychopharmacol Biol Psychiatry 33(8),* 1291–1308.

Walter A, Mai JK, Lanta L et al (1991) DifferentialWhisman, M. (2001). The association between depression and marital dissatisfaction. *Marital and family processes in depression: A scientific foundation for clinical practice*, 3-24. American Psychological Association, Washington DC.

Walum, H., Westberg, L., et al. (2008). Genetic variation in the vasopressin receptor 1a gene (AVPR1A) associates with pair-bonding behavior in humans. *Proceedings of the National Academy of Sciences, 105,* 14153-14156.

Wang, Z.X, Hulihan, T.J., & Insel, T. R. (1997). Sexual and social experience is associated with different patterns of behavior and neural activation in male prairie voles. *Brain Research, 767(2),* 321-32.

Whisman M, Bruce M (1999). Marital dissatisfaction and incidence of major depressive episode in a community sample. *Journal of Abnormal Psychology*, *108*(4), 674-678.

Winslow, J., Hastings, N., Carter, C. S., Harbaugh, C., & Insel, T.R. (1993) A role of central vasopressin in pair bondings in monogamous prairie voles. *Nature*, 365, 545-548.

Wunderlich, K., Rangel, A., & O'Doherty, J.P. (2009). Neural computations underlying action-based decision making in the human brain. *Proc Natl Acad Sci U S A*, 106, 17199-17204.

Xu, X., Aron, A., Brown, L., Cao, G., Feng, T., & Weng, X. (2010). Reward and motivation systems: A brain mapping study of early-stage intense romantic love in Chinese participants. *Human Brain Mapping*. doi: 10.1002/hbm.21017

Xu X, Brown L, Aron A, Acevedo B, Cao G, Feng T, Weng, X (in press). Regional brain activity during early-stage intense romantic love predicted relationship outcomes after 40 months: an fMRI assessment. *Social Psychology and Personality Science, doi:*

Young, L. J., Lim, M. M., Gingrich, B. & Insel, T. R. (2001). Cellular mechanisms of social attachment. *Hormones and Behavior, 40*(2), 133-138.

Young, L.J., Wang, Z. (2004). The neurobiology of pair-bonding. *Nat Neuro, 7(10),* 1048-1054.