AN EXPLORATION OF THE TRANSITION FROM ROMANTIC INFATUATION TO ADULT ATTACHMENT

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Though every person has relationships that affect us our entire lives, the process of forming an attachment in adulthood is still largely unknown. Taking the two identified and well-documented phases of relationships in adulthood, romantic infatuation and adult attachment, this dissertation investigates the transition from the attachment-in-the-making infatuation phase to a fully-fledged attachment relationship with a romantic partner. First, a theoretical argument is presented presenting a speculative hypothesis of how this transition happens neurochemically. Through interactions with oxytocin and endocannabinoid receptors and heterodimers, the reward system is shifted to favor familiar and satisfying reward over novel and exciting rewards. Because of this, the reward of attachment is maintained indefinitely and encoded in mu-opiate receptor activation, while infatuation reward, driven by dopamine, ultimately fades over time. This results in the observed phenomenology of each of these phases across individuals, time, and culture. Based on this theoretical model of neurological change between infatuation and attachment, a study was conducted to identify a possible biological marker of attachment formation through pupillary reactions to partner mental representations. Because norepinephrine, identified as high during infatuation and low during attachment, can affect the contraction of iris muscles, it is hypothesized that bringing the partner to mind would cause pupil dilation during infatuation and pupil constriction during attachment. While there was little constriction, there was significantly greater pupil dilation during infatuation than attachment, as

well as before many relationship milestones including relationship length. It is possible that this could be used as an unconscious marker of infatuation, and subsequently attachment formation, in adults. Finally, in order to better understand the phenomenology and timing of this transition, a large survey was distributed to examine current and past relationships. Using a classification analysis, the time between eighteen months and thirty months was identified as a time of transition, which aligns with earlier research. However, these data point to the time not being a clean transition, but a gradual one where aspects of both infatuation and attachment are simultaneously experienced. Thus, this dissertation provides a foundation for building further theoretical and empirical work investigating the transition into adult romantic attachment.

BIOGRAPHICAL SKETCH

Sarah Merrill is currently working towards her Ph.D. in Developmental Psychology in the Human Development department at Cornell University. She received Bachelor of Arts degrees in both Psychology and Neuroscience from Wellesley College before beginning her doctoral degree at Cornell.

DEDICATION

Thank you to my committee, Ritch Savin-Williams and Richard Depue, without whom this would not be possible, and especially to Cindy Hazan, my mentor and my idol who I am more grateful to know every day.

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Chapter 1: Introduction

Humans are innately social and sexual creatures, and though people have been engaging in platonic, caring, romantic, and sexual relationships for millennia, science has only recently begun to understand the dynamics of these relationships. Bowlby's (1979) theory of attachment is the gold standard in our understanding of the formation and dynamics of close social bonds. This theory proposed that infants form a connection to a caregiving primary attachment figure, and this connection is driven chiefly on the spatial and emotional relationship between them, characterized in four ways: proximity maintenance, safe haven, separation distress, and secure base. Bowlby theorized that the main features of attachment relationships are to stay close to the attachment figure (proximity maintenance), reach out to them for comfort when you are afraid or upset (safe haven), be distressed if you are unable to reach them (separation distress), and know that you will always have their support in trying new things and exploring (secure base). Bowlby's theory (1979) also required that attachment is a monotropic hierarchy in that you can have multiple attachment bonds (e.g., parents, friends, siblings; Baldwin, Keelan, Fehr, Enns, & Koh-Rangarajoo, 1996), but only one will ever be a primary attachment bond. However, the attachment process is "from the cradle to the grave" (Bowlby, 1979, p. 129) in that it is natural, inborn, and operates from birth until the end of life.

The life-long duration of attachment bonds coupled with their monotropic nature necessitate the shift from childhood parental attachments to the prototypical instantiation of attachment in adulthood, romantic partners (Bowlby, 1979; Trinke & Bartholomew, 1997). Therefore, it was theorized that the attachment orientations typified in our early experiences are translated to our adult attachment through a conservation of systems, compelling adult attachment to

mechanistically resemble infant-parental attachment (Hazan and Shaver, 1987; Zeifman and Hazan, 1997). There are some important differences, however, such as the contrast between the complementarity of infant-caregiver relationships and the reciprocity of adult romantic relationships; adult relationships typically sexual in nature and partners serve as both recipients and providers of security and comfort. Sex appears to be the primary motivating force behind proximity seeking in adult attachment, as opposed to the felt security of an infant drawn to a caregiver (Hazan & Zeifman, 1994)

A great deal of the research on adult attachment has focused on attachment styles, as outlined by the research of Mary Ainsworth (1978). However, the inquiry into the process of forming an adult attachment has more recently come to the forefront in the field (e.g. Hazan & Zayas, 2015; Zayas, Merrill, & Hazan, 2015; Birnbaum & Finkle, 2015). One basis for this line of research was begun long ago by Dorothy Tennov (1979) who focused on infatuation, or limerence, a phase of relationships before a true attachment bond forms. Tennov (1979) discovered that infatuation was an ubiquitous period of relationships distinguished by reliable "symptoms": acute onset, physiological arousal, mental preoccupation, mood dependency, idealization, and direction towards only a single target. She found that infatuation symptoms begin abruptly, yet memorably (acute onset), and for only one person at a time (single target); that people experiencing infatuation ate less, slept less, and yet were more energized and aroused (physiological arousal); people experiencing infatuation also were completely obsessed with thinking and speaking about their partner, to the point of the thoughts of the partner intruding into their lives involuntarily (mental preoccupation); that those thoughts were unequivocally positive to the point where every aspect of the person is perfect or near perfect (idealization); and the positivity or negativity of their mood stemmed from their latest interaction with the partner,

resulting in mood swings (mood dependency). This period of the relationship does not last forever, though, and generally leads either to a break-up or the establishment of an adult attachment relationship (Tennov, 1979). This is a critical moment in the development of an adult attachment bond, and where most bonds end before they begin.

This process by which two individuals go from being relative strangers to having developed a full-fledged attachment bond is still not well understood (Zayas & Hazan, 2014). Therefore, this dissertation proposes a neurochemical theory of the transition from infatuation to attachment at the synaptic and systems level. To this point, there has been a plethora of research on the formation of pair bonds and their formation, but the majority of this research has been done in animals. Specifically, most major contributions have come from a single species of pair bonding rodent, the monogamous prairie vole (Microtus ochrogaster) (Johnson & Young, 2015). However, recent literature has examined pair bonding titi monkeys (Callicebus cupreus) as a possible primate model as well (Bales et al., 2017). The animal literature highlights the importance of oxytocin, arginine vasopressin, dopaminergic activity at D2-type receptors, and mu-opiate receptor activation for pair bond formation to take place, while dopaminergic activity at D1-type receptor and kappa opiate activation inhibit bond formation and are indicative of a shift to pair bond maintenance (Aragona et al., 2006; Aragona & Wang, 2007; Burkett & Young, 2012; Carter, 1998, 2005, 2014; Resendez et al, 2016). Some of these findings have been supported by human research as well. OT in particular has consistently been found to be associated with all mammalian pair bonding (Feldman, 2017), and fMRI studies have found functionally different patterns of activity for long and short term relationships (Acevedo et al., 2012; Feldman, 2017; Fisher, Aaron & Brown, 2005).

Using the wealth of research findings from both animal and human literature, we put forth a neurochemical theory of adult attachment formation. We then attempt to support this theory with empirical research examining the biological and experiential changes that take place in this transition, using our theoretical framework as a foundation.

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Chapter 2:

Making Love:

A Neurobiological Model of Romantic Infatuation and Implications for Adult Attachment Formation

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Abstract

Neurochemical research into human pair bonding is largely based on models of monogamous animal behavior, but few have presented a comprehensive correlation of these findings to the process of pair bond and attachment formation in humans. We aim to synthesize the animal neurochemical and human behavioral literatures into an integrated theory of human pair bond formation from infatuation to the shift into attachment. Infatuation is characterized by desire and arousal, which are driven by the interaction of high dopamine activity at D2 receptors, mu-opiate receptors, oxytocin, norepinephrine, arginine vasopressin, testosterone, low global serotonin, and the endocannabinoid system. Over time and as uncertainty decreases, D2 and norepinephrine receptor activity decreases and serotonin activity increases, decreasing appetitive reward processing, arousal, and testosterone levels. Oxytocin and vasopressin also decrease slightly. However, because oxytocin remains present and prevents mu-opiate habituation through endocannabinoid interactions, mu-opiate reward and feelings of consummatory reward do not habituate over time. Unlike dopaminergic activity, global serotonin and prolactin levels increase, which, along with oxytocin and mu-opiates, are associated with attachment-related feelings of satiety, safety, and comfort. D1 receptor activity and kappa-opiates also increase during the attachment phase, presumably to keep the bond intact. This change in neurochemical activity from excitement and appetitive desire to safety and contentment is theorized to underlie the transition from romantic infatuation to pair bond attachment in humans.

Keywords: Attachment, Infatuation, Neuroendocrine, Oxytocin, Reward, Serotonin

Introduction

It is a truism that romantic relationships change over time. In free-choice mating societies, such relationships typically begin with high levels of passion and excitement but then—if they endure—evolve into a bond characterized more by feelings of comfort and security. This transition from infatuation to attachment is the focus of our theoretical model. Our goals are to explain 1) *how* this normative change occurs in terms of the conditioning of basic neuroendocrinological systems and 2) in evolutionary terms, *why* it occurs. We start by describing the "symptoms" of the infatuation and attachment phases of romantic relationship development. Next we detail the relevant and interacting roles of oxytocin, arginine vasopressin, dopamine, norepinephrine, serotonin, opiates, endocannabinoids, testosterone, and prolactin in this process. We conclude by discussing from an evolutionary perspective why, in this neurochemical environment, it makes adaptive sense that sexual attraction and repeated sexual encounters with the same person facilitates the development of a pair bond.

"Symptoms" of Infatuation and Attachment

When the spark of sexual attraction initially draws two people together they are far from being attached, and they may never become attached. Though this sexual desire and the romantic love associated with attachment are governed by distinct biological processes, they are also intimately intertwined (Diamond, 2004). This initial attraction motivates the desire for close contact that promotes the development of an attachment bond. This early phase, referred to as infatuation, limerence, or being "in love", is repeatedly characterized by a constellation of "symptoms"—specifically physiological arousal, mental preoccupation, mood dependency, focus on a single target, and idealization (Fisher, 1998; Fisher, 2000; Fisher, Xu, Aron, & Brown, 2016; Langeslag, Muris, & Franken, 2013; Tennov, 1979; Wakin & Vo, 2008; Willmott &

Bentley, 2015). Infatuation feels as though it comes on all at once, leaving you breathless and your heart racing; you feel as though you don't need to eat or sleep; every moment you think about that one special someone, whether you'd like to or not; your every move and mood is dependent on whether they look your way or give you a smile; you have an insatiable lust for them; they seem absolutely perfect in your eyes. While this intense period of emotion and uncertainty is important for bond formation, it is not a state that is sustainable over the long-term. Over time, romantic infatuation fades. In this way, infatuation is not identical to the concept of "passionate love" (Hatfield & Sprecher, 1986; Langeslag, Muris & Franken, 2013; Wakin & Vo, 2008), which can be maintained over time in a relationship without uncertainty and obsession (Acevedo & Aron, 2009), but a unique state that wanes as an attachment bond forms (Hazan & Zeifman, 1994).

Not all romantic infatuations develop into attachment bonds, but those that do undergo significant qualitative change. According to Bowlby's ethological theory, attachment is integral to human behavior "from the cradle to the grave" (Bowlby, 1979). In infancy the preferred attachment figure is the primary caregiver, whereas in adulthood it is typically a mate or romantic partner. Importantly, the defining features—or "symptoms" of attachment—are essentially the same across the lifespan. We stay in close contact with attachment figures ("proximity maintenance"), turn to them for comfort and reassurance when distressed ("safe haven"), are upset by unexpected or protracted separations ("separation distress"), and derive confidence from the knowledge that they are available if needed ("secure base"). Two obvious differences between infant-caregiver attachments and pair bonds is that the latter tend to be reciprocal (i.e., each partner both provides and receives care) and, importantly, engage the sexual mating system.

Although each phase of romantic relationship development is fundamentally and qualitatively different from the other, one thing they have in common is that they are equally, though differentially, *rewarding*. Many approaches and models of romantic infatuation and the shift to an attachment focus primarily or exclusively on the role of dopamine and the bonding peptides oxytocin and vasopressin (see Feldman, 2017); however, as the symptomology of early relationship formation illustrates, a more comprehensive conceptualization of the neurochemistry of relationship formation is warranted. The theoretical model that follows aims to comprehensively explain how and why—in neuroendocrinological terms—the rewards of infatuation and attachment differ.

Oxytocin & Vasopressin

The underlying theory of bonding must begin with the peptide hormone most identified with pair bond formation and attachment: oxytocin (Carter, 1998, 2005, 2014). Oxytocin (OT) is also known as the "cuddle hormone" for its role in both infant and adult attachment formation, as well as its release during physical affection, sex, orgasm, lactation, and childbirth (Carter, 1992, 2005, 2014; Insel, 1992). OT is necessary for pair bond formation. OT receptor (OTR) antagonists prevent pair bonding in prairie voles, and affect the speed at which bonding occurs (Liu & Wang, 2003; Ross et al, 2009; Ross & Young, 2009). OT facilitates the appetitive value of sex and can even induce partner preferences without sex in monogamous prairie voles (Carter, 1998; Carter & Porges, 2011; Cho, DeVries, Williams & Carter, 1999; Melis & Argiolas, 2011). In humans, OT is higher in infatuated couples than in long-term couples, and higher plasma OT in new couples is predictive of staying together (Schneiderman et al, 2012). OT's role in attachment formation and maintenance is most likely through a four-fold action: down-regulating threat-related reactivity of the hypothalamic-pituitary-adrenocortical axis (HPA) and the

autonomic nervous system (ANS); promotion of positive, socially-salient memory formation; sensitizing indirect dopaminergic receptor interactions in the reward pathway; and preventing the tolerance to and withdrawal symptoms from mu-opiate receptor activation.

An external or internal threat triggers a cascade of neurological and physiological responses to signal potential danger in the HPA axis, releasing cortisol and activating ANS response (Aguilera & Liu, 2012; Karelina & DeVries, 2011; Kovács, 2013; Yee et al., 2016). OT serves as an anxiolytic by downregulating this HPA activation, possibly through exciting inhibitory γ-amino butyric acid (GABA) receptors (Carter, 1998, 2005, 2014; Carter & Porges, 2011, 2013; DeVries et al., 2007; Kareline & DeVries, 2011; Neumann et al., 2000; Ochedalski, Subburaju, Wynn, & Aguilera, 2007). OT is released and circulates centrally through the paraventricular nucleus (PVN) of the hypothalamus, having a negative influence on a number of areas involved in the detection and processing of threat, such as the anterior cingulate cortex, implicated in paid, stress and emotional processing; the bed nucleus of the stria terminalis; amygdala and hippocampus (Martínez-Lorenzana et al., 2008; Windle et al., 2004). This subsequently reduces the amount of corticotropin-releasing hormone (CRH) produced, and thus its downstream product cortisol, effectively reducing the stress response (Aguilera & Liu, 2012; Liberzon & Young, 1997; Windle, Shanks, Lightman, & Ingram, 1997). In addition to decreasing feelings of anxiety, OT may also reduce pain (Martinez-Lorenzana et al., 2008), although OT's antinociceptive abilities appear to be opioid-dependent, as the animal literature has shown the pain attenuation is blocked by opioid antagonism (Kirsch, 2005; Petersson, Alster, Lundeberg, & Uvnäs-Moberg, 1996; Wang, Lundeberg, & Yu, 2003). Along with arginine vasopressin (AVP), OT also regulates the ANS – effectively leading to immobilization and maintained propinquity to a partner without fear, and important component of attachment formation (Carter & Porges,

2011; Feldman, 2017; Porges, 1998).

In addition to OT's anxiolytic capabilities, OT can have profound effects on memory. Normally, OT is an amnesiac and enhances forgetting and long-term depression, for example, rats given OT forgot the noxious experience associated with an active avoidance task (Kovács & Telegdy, 1982). However, OT enhances memory encoding selectively for *positive social* stimuli (Guastella, Mitchell & Matthews, 2008; Rimmele et al, 2009; Ross & Young, 2009), and can improve memory for socially relevant stimuli when administered in humans, but only with a positive bias (Heinrichs et al, 2004). OT and AVP action at the V1a receptor (V1aR) has been shown to be necessary for normative social recognition memory, a crucial aspect of attachment formation (Bielsky et al., 2004; Carter, 2005; Winslow et al., 1993). This is most likely through their action in the lateral septum, which is an intermediary between the CA3 area of the hippocampus and the reward hub ventral tegmental area and is implicated in linking context and reward (Albers, 2012; Luo, Tahsili-Fahadan, Wise, Lupica, & Aston-Jones, 2011). This is especially likely because V1aR antagonism in the lateral septum prevented pair bonding in male prairie voles (Liu, Curtis, & Wang, 2001). AVP is also necessary for pair bond formation and mate guarding in male prairie voles, though not necessary for female prairie voles who have more OT than male prairie voles (Carter, 2006; Lim & Young, 2006). AVP prolongs memory, regulates social discrimination, and blocks forgetting; AVP treated rats had memory prolonged by days (DeWied, 1980; Nair & Young, 2006). The combination of long-term social recognition from AVP and OT promoting memory encoding for positive social stimuli, while otherwise acting as an amnesiac, may be the root of infatuation's idealization and seeing only the good and not the less desirable aspects of a partner.

Though many stimuli activate the reward system, the processing of affiliative and sexual

stimuli differs due to the action of oxytocin (OT) (Burkett & Young, 2012; Depue & Morrone-Strupinsky, 2005; Kovács, Sarnyai & Szabo, 1998). Fundamentally, OT's role in bonding depends on its interaction with dopamine (DA), specifically the action at the indirect pathway, inhibitory g-protein coupled D2 dopamine receptors (D2R). D2R activation is the beginning of the indirect pathway of striatal influence reducing thalamic activity (Meyer & Quenzer, 2013). D2R also are g-protein coupled receptors that preferentially bind their alpha unit to Gi/Go inhibitory g-proteins. Through this pathway, D2R reduce cyclic adenosine monophosphate (cAMP) and reducing the overall activity of the cell. Because of this, D2R act as both inhibitory autoreceptors presynaptically on DA neurons, as well as inhibitory postsynaptic receptors on cells that DA neurons synapse on to (Meyer & Quenzer, 2013).

When researchers administered D2R antagonists to monogamous prairie voles, pair bond formation was prevented, even when OT was available (Liu & Wang, 2003). Both OTR and D2R activation are necessary for the formation of a pair bond (Numan & Young, 2016). OT innervates the dopaminergic neurons in the reward pathway between the ventral tegmental area (VTA) and the nucleus accumbens (NAcc) shell, which increases the appetitive reward response in the D2R pathways (Succu et al., 2007; Melis et al., 2009; Shahrokh et al., 2010). How this sensitization occurs is still unclear, but one possibility is through interactions with endocannabinoid heterodimers.

Heterodimers are complexes formed of two different receptors that physically interact and can have different effects than the activation of one receptor alone (Meyer & Quenzer, 2013). A receptor that is fairly promiscuous at forming heterodimers is the cannabinoid receptor CB1 (CB1R). CB1R are the g-protein coupled receptors for naturally produced endocannabinoids and exogenous cannabinoids from the cannabis plant that preferentially activate the Gi/Go pathway,

reducing cAMP levels like D2R (Wenzel & Cheer, 2017). Unusually, the endocannabinoid natural ligands, anandamide and 2-Arachidonoylglycerol (2-AG), for the CB1 receptor are so lipophilic, they cannot be stored in vesicles, and are therefore usually produced by activity in the postsynaptic cell and diffuse through the synaptic cleft to interact with the with CB1Rs presynaptically (Meyer & Quenzer, 2013). Because of this, endocannabinoids are not stored, but made on demand and are dependent on high internal stores of calcium, often being triggered by the Gq g-protein pathway that releases internal stores of calcium via inositol trisphosphate (IP3) and creates the precursor for 2-AG, diacylglycerol (DAG) (Hoare et al., 1999; Ohno-Shosaku, Hashimotodani, Maejima, & Kano, 2005).

The endocannabinoids, especially the at CB1R, have been found to interact and affect the reward system similar to OT (Solinas, Goldberg, & Piomelli, 2008; Wenzel & Cheer, 2017). This is most likely because both OTR and V1aR are g-coupled protein receptors that preferentially activate the Gq pathway, increasing intracellular calcium and releasing endocannabinoids (Hoare et al., 1999; Ku, Qian, Wen, Anwer, & Sanborn, 1995; Terrillon, Barberis, & Bouvier, 2004; Wei et al., 2015). Wei and colleagues (2015) found that blocking OTR prevents endocannabinoid mobilization and prevents preference formation in a social conditioned place preference task. However, increasing endocannabinoids restored some of OTs place preference effects. Their conclusion, was that oxytocin affects social reward through endocannabinoid interaction with CB1 in the NAcc (Wei et al., 2015). Naturally following these findings, there has been recent work on endocannabinoids in social reward and social anxiety, yet not in regards to pair bond formation (Karhson, Hardan, & Parker, 2016; Schechter et al., 2013; Wei et al., 2015; Wei, Allsop, Tye, & Piomelli, 2017).

A hypothesis as to how D2R and OTR are facilitatory and simultaneously necessary for pair

bond formation in the NAcc shell is through heterodimeric interactions with CB1R. In the NAcc shell, there are facilitatory D2-OT heterodimers (Romero-Fernandez, Borroto-Escuela, Agnati, & Fuxe, 2013). In these heterodimers, D2Rs still activate the Gi/Go pathways, reducing cAMP and overall activity in the cell, and OTRs activate the Gq pathway, increasing intracellular calcium and releasing endocannabinoids into the synapse (Romero-Fernandez et al., 2013). When this happens, there will be both DA and endocannabinoids in the synaptic cleft to interact pre- and post-synaptically. Normally, when there is a large amount of DA in the synapse, DA binds presynaptically to the D2 autoreceptor that activates Gi/Go in the presynaptic cell, reducing cAMP and DA release (Meyer & Quenzer, 2013). However, when both CB1R and D2R are simultaneously activated, they form a heterodimer complex that activates the Gs pathway instead (Glass & Felder, 1997; Kearn, 2005). The Gs pathway has the opposite effect of the Gi/Go pathway and increases cAMP in the presynaptic cell, thus increasing DA release from the presynaptic neuron. The hypothesis is then, since D2R and OTR are physically localized on the same neuron in the NAcc, OTRs are able, through endocannabinoid signaling, to bias increased DA release to only D2 and *not* D1 DA receptors (illustrated in Figure 1).

However, OT does not sensitize all reward in this way. Opiates, specifically mu-opiates, are also part of the reward pathway, and OT can prevent mu-opioid tolerance formation and attenuate symptoms of opiate withdrawal, most likely also through the endocannabinoid interaction (Burkett & Young, 2012; Damiano et al., 2014; Kovacs, Sarnyai & Szabo, 1998; Shahrokh et al., 2010). In essence, the shift from infatuation to attachment is also the shift from the experience of exciting, appetitive reward of the combined effects of DA and OT in infatuation to the lasting, satisfying consummatory reward combination of OT and endocannabinoids interacting with and mu-opiates in attachment.

Dopamine

The reward system begins first with the appetitive, or incentive, reward system that triggers feelings of *wanting* or desire. It is activated *before* a reward is enjoyed and thereby propels approach (Berridge, 2007). Appetitive reward is dependent on dopaminergic release to predictive error in the mesolimbic reward centers, whose importance in pair bond formation and selective partner preference has been replicated many times over in animals and humans (e.g. Acevedo & Aron, 2014; Atzil et al., 2017; Liu & Wang, 2003; Smeltzer, Curtis, Aragona, & Wang, 2006; Young & Wang, 2004; Wang et al., 1999). Of course, not all incentive rewards are created equal; there is magnitude differentiation between rewards based on the perceived enticements involved, with sex being one of the most rewarding unconditioned experiences (Meston & Buss, 2007; Pfaus, 1995). DA contribution to pair bond formation, however, is localized at the D2Rs that OT biases towards (Cibrian-Llanderal et al., 2012; Humphries & Prescott, 2010; Zhou, Wilson & Dani, 2003). These D2R have been repeatedly shown to be necessary in partner formation (see review Burkett & Young, 2012). While there are excitatory DA receptors able to use direct or indirect pathways that have a low affinity for DA and fire only phasically, known as D1 receptors (D1R), they *prevent* bond formation with high activation, not enhance it (Aragona et al., 2006; Aragona & Wang, 2007; Burkett & Young, 2012; Humphries & Prescott, 2010). This is ultimately because, in the NAcc shell, increased cAMP, caused by D1R binding to Gs, inhibits pair bond formation in prairie voles, while decreasing cAMP, caused by D2R binding to Gi/Go, increases pair bond formation (Aragona & Wang, 2007). Therefore, by OT and endocannabinoids biasing DA release to D2R in the NAcc, they are able to reduce cAMP and overall activity. Without OTR and CB1R activation, however, we would see no bias towards D2R; likewise, we would see no receptor to bias towards in order to reduce cAMP if D2R are not present. This is likely why *both* OTR and D2R, and we hypothesize CB1R, in the

NAcc shell are necessary for pair bond formation (Young, Gobrogge, Liu, & Wang, 2011; Young & Wang, 2004).

Anticipatory DA reward occurs in order to propel an individual towards a rewarding stimulus, but not to receive the reward itself (Depue & Collins, 1999). Thus, appetitive reward prizes novelty and habituates with repeated exposures to the same stimulus, such as having sex with the same person multiple times (Depue & Collins, 1999). A loss of desire is the ultimate downside of familiarity. This is because, as a reward becomes more consistent and predictable, preemptive DA release reduces, since DA release depends on predictive error in reward receipt (Hart, Rutledge, Glimcher, & Phillips, 2014). Thus, once the pair bond is formed, the role of the dopaminergic system in bonding changes. Instead, of D2R activation to a socially relevant stimulus, novel rewards, such as a sexually attractive alternative to your partner, would result in a phasic burst of D1R activation (Aragona et al., 2006).

Attachment formation alters neural architecture, including increasing D1R proliferation in the NAcc. Aragona and colleagues (2006) found that a male, pair-bonded prairie vole cohabitating with a partner had 60% more D1Rs in the NAcc than male prairie voles cohabitating with a brother. Resendez and colleagues (2016) also found that pair-bonded voles had substantially increased mRNA expression for the gene encoding D1R, but not D2Rs. This is presumably because D1Rs are upregulated through natural homeostatic compensation to increase cAMP levels in the, at this point, chronically inhibited NAcc shell. Because of this modification, some have hypothesized that D1Rs are crucial in pair bond maintenance (Aragona & Wang, 2007; Carter & Porges, 2011; Resendez & Aragona, 2013; Yawata et al., 2012). D1R activation does not result in the passionate feelings of D2Rs, instead D1R activation is associated with aversive feelings through formation of its product, dynorphin (Burkett & Young, 2012). This

results in novel, attractive partner alternatives initiating a phasic burst of DA that, instead of acting on D2Rs, will act on D1Rs and associate the novelty with unpleasant feelings. The resulting selective avoidance, and possibly selective aggression, has been hypothesized to maintain pair bonds by rejecting novel potential partners and preventing new pair bond formation (Aragona et al., 2006; Insel, Preston & Winslow, 1995; Resendez & Aragona, 2013). This D1R action may contribute to the monotropic hierarchy of attachment, with only one paramount and primary bond (Trinke & Bartholomew, 1997).

The ratio of D1Rs to D2Rs in brain areas related to reward between infatuation and attachment is primarily caused by D1R proliferation in the NAcc (Aragona et al., 2006; Aragona & Wang, 2007). However, the D1:D2 ratio can also be affected by a proliferation of D2Rs. A study by Graham and colleagues (2015) found that an estrogen equivalent increased the number of D2Rs in the medial preoptic area (mPOA), a brain area with oxytocinergic projections to reward areas (Shahrokh et al., 2010). However, when progesterone was added with the estrogen, the mPOA returned to a higher D1:D2 ratio (Graham et al., 2015). Interestingly, estrogen has been found to stimulate the synthesis of OT and increase OT binding affinity (Gimpl & Fahrenholz, 2001; Nomura et al., 2002), while progesterone reduces the availability of OTRs (Grazzini, Guillon, Mouillac & Zingg, 1998). These data not only point to the importance of the D1:D2 ratio in multiple brain regions connected to the reward system on potential pair bond formation, but also the close interaction between OT and D2Rs. Appetitive reward is only one piece of the reward system, though; both D2Rs' role in pair bond formation and D1Rs' role in pair bond maintenance have a compliment in the action of mu- and kappa- opiates in the consummatory reward system.

Opiates

With familiarity and the loss of passion comes comfort and satiation in relationships. This is the realm of the consummatory reward system that in sex and bonding is acting upon mu-opiate receptors (MOR) (Depue & Morrone-Strupinsky, 2005). Where appetitive reward is associated with wanting, consummatory reward is associated with *liking* and *enjoying* (Smillie, 2013). Therefore, these receptors are activated when a reward becomes proximally accessible, and is the feedback mechanism that helps determine the magnitude of future dopaminergic rewards (Depue & Morrone-Strupinsky, 2005; Herbert & Howes, 1993). Similarly, where appetitive reward triggers approach-oriented action, consummatory reward triggers a cessation of approach behavior—namely, sedation and rest (Hilliard, Domjan, Nguyen, & Cusato, 1998). Thus, consummatory reward also reinforces attachment through immobilization without fear (Porges, 2001).

The involvement of this system in bonding, both maintenance and formation, in nonhuman animals has been confirmed and replicated, and may serve an even more important role in humans (Burkett et al., 2011; Burkett & Young, 2012; Machin & Dunbar, 2011; Nelson & Panksepp, 1998; Saltzman & Maestripieri, 2011). Specifically, MORs in the caudate-putamen have proven to be integral to partner preference formation (Burkett et al., 2011). Burkett and colleagues (2011) tested the importance of MORs in the caudate-putamen region by injecting a selective MOR antagonist, which prevented the formation of a partner preference. Additionally, the injection of a non-selective opioid antagonist resulted in partner aversion (Burkett et al., 2011). This is most likely because the dorsal striatum, containing the caudate-putamen, is responsible for goal-oriented behavior (Robinson, Sotak, During, & Palmiter, 2006).

In the case of sociosexual interactions, beta-endorphins are released, usually through D2R action, and interact preferentially with mu-opioid receptors (MOR) creating the satisfying experience of consummatory reward (Hilliard, Domjan, Nguyen, & Cusato, 1998; Irnaten et al., 2003; Machin & Dunbar, 2011; Steiner & Gerfen, 1998). This opiate receptor activity also increases pain thresholds, and may be partially responsible, along with OT, for the elevated pain thresholds that are seen in concert with romantic relationships and during orgasm (Whipple & Komisaruk, 1985; Younger, Aron, Parke, Chatterjee, & Mackey, 2010). The magnitude of opiate receptor activation is encoded along with the sensory cues of the immediate surroundings, associated feelings, and distinct characteristics of the partner in the hippocampus (Depue & Morrone-Strupinsky, 2005). This information is then used to determine the expected magnitude of the reward the next time this contextual ensemble takes place, and the subsequent appropriate anticipatory reward to incentivize individuals toward the partner. The integration of hedonic preference allows reward learning, effectively encoding that this partner is rewarding and approach behaviors should be rewarded (Depue & Morrone-Strupinsky, 2005).

Mu-opiates, just like DA, normally habituate over time, but this leads to the question: if both reward systems habituate over time, what would make an enduring attachment bond pleasurable? The answer is in the interaction between OTRs, CB1Rs, and MORs. OT attenuates the development of a tolerance to opiates (Burkett & Young, 2012; Kovács, Sarnyai, & Szabó, 1998). This has the vital effect of preventing the magnitude of the consummatory reward from substantially decreasing over time, and the satisfying pleasure associated with long-term partners can continue indefinitely as long as OT is also present.

One hypothesis of how OT prevents opiate tolerance is through releasing endocannabinoids that interact with the MOR-CB1 heterodimer found in the reward system

(Corcoran, Roche, & Finn, 2015; Le Naour et al., 2013; López-Moreno, López-Jiménez, Gorriti, & de Fonseca, 2010; Manduca et al., 2016). Endocannabinoids directly interact with opiate reward (Fattore et al., 2000; Mahler, Smith, & Berridge, 2007; Wenzel & Cheer, 2017). In fact, CB1R knockout mice prevented morphine reward while MOR knockout prevented endocannabinoid reward in rats (Fattore et al., 2000; Ghozland et al., 2002), and opiates and cannabinoids reciprocally stimulate the other's release (Caille, Alvarez-Jaimes, Polis, Stouffer, & Parsons, 2007; Valverde et al., 2001). Although the exact mechanism is currently unknown, the receptors are co-localized and form heterodimers that, when co-activated, do not change their similar Gi/Go functions, but prevent tolerance development (Hojo et al., 2008; Rios, Gomes, & Devi, 2006; Schoffelmeer, Hogenboom, Wardeh, & De Vries, 2006). Therefore we hypothesize that, OTR, and most likely V1aR, release endocannabinoids to activate MOR-CB1 heterodimers in the reward pathway and prevent consummatory reward tolerance indefinitely. Thus, while infatuation is characterized by the passion and excitement of dopamine, attachment is experienced as the gratifying satiety of mu-opiate reward. This mu-opiate reward persistence may be why the symptoms of partner separation distress have many similarities to morphine withdrawal symptoms (Burkett & Young, 2012).

Similarly to DA, though, there is an additional function of opiates during attachment that was not present during infatuation. While D2Rs lead to MOR activation, D1Rs lead to kappa-opiate (KOR) activation through its ligand, dynorphin, in the NAcc-VTA direct, excitatory dopaminergic pathways (Resendez et al., 2012; Resendez & Aragona, 2013; Steiner & Gerfen, 1998). KOR activation has been associated with depersonalization, derealization, feelings of disgust, profound dysphoria, and negative affect (Land et al., 2008; Walsh et al, 2001). Via its relationship with D1Rs, KOR activity has been implicated in pair bond maintenance through

selective avoidance and aggression, as well as negative response to partner separation (Resendez et al., 2012; Resendez & Aragona, 2013). For example, blockade of KOR, but not MOR, in the NAccshell resulted in the reduction of selective aggression in pair bonded prairie voles (Resendez et al., 2012). The relationship between D1 and KOR action is inseparable, much like D2Rs and MOR cause positive affect, satisfaction, approach, and encode the context of positive events (Depue & Morrone-Strupinsky, 2005), D1Rs and KOR cause negative affect, promote aversion and aggression, and serve to encode stressful events (Aragona & Wang, 2007; Land et al., 2008; Resendez & Aragona, 2013). Therefore, the purpose of KOR appears to be similar to D1Rs in that they promote aversion or aggression towards potentially sexually attractive stimuli and prevent bonding to another. KOR activation may also be at least partially responsible for the end of idealization in infatuation by promoting dysphoria, disgust, and memory for negative events.

Serotonin

Another neurochemical integral to relationship development, despite the relative lack of research about its role, is Serotonin (5-HT). Though 5-HT has been hypothesized to play a role in the obsessive nature of infatuation before (Fisher, Aron, Mashek, Li, & Brown, 2002), the reason for the delay into fully investigating the role of 5-HT in bond formation is most likely related to the very complicated nature of this monoamine transmitter with 14 receptors unique receptor types (Malenka, Nestler, & Hyman, 2009). The behavioral and neurochemical evidence indicate that infatuation is characterized by low global 5-HT (Fisher, Aron, Mashek, Li, & Brown, 2002), while attachment is characterized by higher, normative levels of global 5-HT. Lower global 5-HT has been shown to increase DA release and impulsive behavior. Low 5-HT is also associate with higher global norepinephrine (NE) from the locus coeruleus, which is

associated with physiological arousal and hypervigilant attention (Boulougouris, Glennon, & Robbins, 2008; Hirata, Aguilar & Castro-Alamancos, 2006; Moore & Depue, 2016). Low 5-HT has also been hypothesized to be a main contributor in reducing the threshold for emotional lability through a reduction of regulatory capacity in the prefrontal cortex (Cools, Roberts & Robbins, 2008; Moore & Depue, 2016; Nelson & Trainor, 2007; Winstanley, Theobald, Dalley, & Robbins, 2005). A defining feature of infatuation is mood dependency – extreme responses to even small, and often unintentional, signals from the object of affection. The strong emotional behaviors elicited by normally inconsequential stimuli, regardless of valence, may be due to the low global 5-HT environment lowering the threshold for emotional mutability in the presence of an emotionally rewarding stimulus, as illustrated by the Moore and Depue's (2016) threshold model of neurobiological reactivity to environmental stimuli. The lower the global 5-HT concentrations are, the lower the necessary threshold of a stimuli to elicit an emotional response and the broader the range of stimuli the infatuated person would react to. It follows then, that the inverse is true in attachment; as global 5-HT increases, emotional stability should also increase, leading to mood regulation in attachment, which is also in line with Moore & Depue's theory (2016).

While the empirical evidence has yet to be uncovered, a hypothesized mechanism of action for 5-HT change during infatuation and into attachment will be proposed. In response to the emotionally salient cues and chronic stress of infatuation, high release of cortiotropin-releasing factor (CRF) causes internalization of the CRF_{R1} receptor, leading to CRF binding to the lower affinity CRF_{R2}. This CRF_{R2} activation causes exaggerated release of 5-HT in the dorsal raphe nuclei (DRN) (Moore & Depue, 2016; Valentino, Lucki & Bockstaele, 2010; Wood et al., 2013). However, this influx of 5-HT is reacted to by presynaptic $5\text{-}HT_{1A}$ autoreceptors,

located throughout the brain (Albert & Lemonde, 2004; Haddjeri, Ortemann, de Montigny, & Blier, 1999; Zimmer et al., 2004). These presynaptic 5-HT1a autoreceptors hyperpolarize potassium channels that attenuate the firing of action potentials, which inhibits the firing of neurotransmitters from the synaptic ends of 5-HT producing neurons, causing an inhibition of global 5-HT (Barnes & Neumaier, 2011). This is similar to the acute action of selective serotonin reuptake inhibitor (SSRI) antidepressants in the first weeks on medication (Burghardt & Bauer, 2013). This hypothesis is supported by the low dorsal raphe nuclei, where 5-HT is produced, activation found in early relationships that gradually increases with relationship length (Acevedo et al., 2011; Fisher, Aron & Brown, 2005), as well as the finding that 5-HT_{1A} receptor agonism in monogamous pair bonded titi monkeys lowered affiliative behaviors between mates (Larke et al., 2016). Additionally, infatuated partners in the early stage of their relationship had low 5-HT transporter, similar to obsessive-compulsive patients, in their blood plasma, which increased as the relationship progressed (Marazziti, Akiskal, Rossi, & Cassano, 1999). Harmer and colleagues (2003) also found that acute administration of SSRIs to healthy volunteers better recognized and more quickly responded to happy and fearful faces faster than controls, which may indicate 5-HT's role in mood dependency. Simultaneously, 5-HT_{1A} receptors located in the PVN increase OT production, and increase NE and DA activity (Barnes & Neumaier, 2011; Jørgensen, Riis, Knigge, Kjaer, & Warberg, 2003; Levy & Van de Ker, 1992; Osei-Owusu et al., 2005; Van de Kar et al., 1995). The lowered global 5-HT, coupled with increased DA, OT, and NE would contribute to feelings of excitement and motivation, as well emotional lability and hypervigilance (Moore & Depue, 2016).

Another 5-HT receptor interaction may be contribute to the obsessive and intrusive thinking that also accompanies infatuation: 5-HT_{2A}. In low 5-HT environments, such as those

created by 5-HT_{1A} autoreceptor activation, the 5-HT_{2A} receptor is primed towards dopaminergic agonism, giving DA ten times the ability to activate 5-HT_{2A} (Bhattacharyya et al., 2002; Bhattacharyya et al., 2006). In this environment DA causes 5-HT_{2A} receptor activation and internalization, which is recycled continuously (Bhattacharyya et al., 2002). 5-HT_{2A} receptor activity has been shown to associate with the severity of symptoms of obsessive compulsive disorder, especially when interacting with D2R activation (Adams et al., 2005; Perani et al., 2008; Serretti, Drago, & De Ronchi, 2007). 5-HT_{2A} also has projections from the prefrontal cortex to the VTA and within the NAcc shell that have excitatory and facilitating effects on DA and NE as well (Barnes & Neumaier, 2011).

However, this state cannot be maintained, and sustained activation of the 5-HT_{1A} autoreceptor causes internalization without recycling of the presynaptic 5-HT_{1A} autoreceptors in the DRN, thus causing termination of 5-HT_{1A} signaling in the presnaptic neurons and resumption of 5-HT release from the raphé neurons at the synapse (Haddjeri, Ortemann, de Montigny, & Blier, 1999; Zimmer et al., 2004), similar to chronic SSRI administration (Burghardt & Bauer, 2013). Thus, the presynaptic 5-HT_{1A} autoreceptor, in a low 5-HT environment eventually inhibits itself, thus allowing for 5-HT to gradually return to normal (Albert & Lemonde, 2004; Haddjeri, Ortemann, de Montigny, & Blier, 1999; Zimmer et al., 2004). Once there is again high global 5-HT, then the receptor 5-HT_{2C} can be activated. This receptor can be found in the VTA and NAcc shell and inhibits DA and NE directly. It also releases OT, AVP, and prolactin (PRL) in the PVN (Barnes & Neumaier, 2011), and was found to mediate the depolarization of bed nucleus of stria terminalis neuronal responses, a key area in anxiety and stress (Guo et al., 2009; Somerville, Whalen & Kelley, 2010). While many other 5-HT receptors are also active, due to 5-HT_{2C}'s proliferation in brain areas associated with attachment and pair bond formation, it is

reasonable to assume this receptor has a role in relationships (Acevedo et al., 2011; Fisher, Aron & Brown, 2005; Barnes & Sharp, 1999; Diamond & Dickerson, 2012). Through high global 5-HT, and 5-HT_{2C} activation especially, attachment is characterized by emotional stability and positive mood.

Prolactin & Testosterone

Adding to the dichotomy in the passion of the infatuation phase and the satiety of the attachment phase are the actions of the hormones testosterone (T) and prolactin (PRL). Though not always mentioned in discussions of attachment formation, these hormones react in a contrasting manner. T is a steroid hormone more prevalent in men, but present in both sexes, and positively correlated with aggression, competition, stubbornness, sexual interest, and sexual pursuit (Farrelly et al., 2015). There is evidence from animal models that T is integral for pair bond formation due to its motivational role in partner preference formation, likely through its positive association with DA (DeVries, DeVries, Taymans, & Carter, 1995; 1996). This may be why infatuated men have higher T than their long-term relationship counterparts (Farrelly et al., 2015). Additionally, men who are new fathers and in long-term relationships have significantly lower T than single men and non-fathers, respectively (e.g., Alvergne, Faurie, & Raymond, 2009; Gettler, McDade, Feranil, & Kuzawa, 2011; Gray, 2003; Gray et al., 2002; Jasienska, Jasienski, & Ellison, 2012; van Anders & Watson, 2006). New mothers have also been found to have lower T than non-mothers or mothers of older children, though less research has been done on female T levels (van Anders & Watson, 2006). Lower T has been hypothesized to promote pair bonding in parents by reducing the urge to seek new mating opportunities (Farrelly et al., 2015). This is congruous with the finding that T is negatively associated with relationship satisfaction, commitment, and fidelity in both men and women (Edelstein et al., 2014).

Infatuation may be characterized by high T, congruent with the high level of sex drive often found during the infatuation phase (Klusmann, 2002).

Whereas T has a positive correlation with DA and motivation, prolactin or luteotropin, has a negative one. PRL is a hormone involved in the regulation of maternal behavior and lactation (Riddle, Lahr, & Bates, 1935). It is present in both sexes, but women generally have higher PRL levels. PRL is a D2R gated hormone, meaning that when D2R activation is higher, PRL is lower (Fitzgerald & Dinan, 2008). As infatuation wanes and action at the D2Rs decreases through habituation, PRL release increases. PRL also acts in a short-loop negative feedback manner to decrease its own levels by stimulating the release of DA, which may be responsible for the larger phasic bursts in DA seen during attachment that trigger D1R activation (Fitzgerald & Dinan, 2008). PRL secretion is also increased through 5-HT_{2C} receptor activation in the PVN, and, in a feedback loop, increases 5-HT release as well. The effect of PRL secretion inhibits T in two ways: directly through desensitizing receptors at the gonads and disrupting gonandotropin releasing hormone (GnRH), a precursor to sex hormone production (Bernard et al., 2015). PRL is released during lactation, nipple sucking, and orgasm, as well as being associated with sexual refractory periods, sexual gratification, and hippocampal neurogenesis – the main effect of all currently available antidepressant medication (Meston & Frohlich, 2000; Torner, 2016). In fact, PRL has recently been found in tamarins to be similar within pairs and correlated to the amount of sexual behavior and contact affiliation within the pair (Snowdon and Ziegler, 2015). Moreover, the amount of PRL produced during a partnered sexual interaction predicts subsequent satisfaction and relaxation, indicating a sensitizing of consummatory reward magnitude (Brody & Krüger, 2006). It is worth noting that the magnitude of PRL increase following partnered sexual intercourse is 400% greater than following solitary masturbation

(Brody & Krüger, 2006). Therefore, it is clear both neurochemically and behaviorally that the relationship between T and PRL not only mirrors the motivation versus satisfaction elements of the reward system in infatuation and attachment, but also contributes to their sensitization, especially in regards to sex.

A Neuroendocrinological Model of Attachment Formation

In theory, the process of pair bond formation unfolds as follows. Encountering a sexually attractive potential partner triggers an increase in T, DA, AVP, NE, OT, and MOR (Carter, 2014; Carter & Porges, 2011; Johnson & Young, 2015; Numan & Young, 2015; Meston & Frohlich, 2000; Young & Wang, 2004). These neurochemicals act together to motivate approach towards a sexually attractive other. Activation at D2Rs propels toward the rewarding stimulus, OT and CB1 activation sensitize this system and OT promotes memory for the event. T increases sexual arousal and motivation, while AVP promotes social recognition and memory encoding, and high NE in a low 5-HT environment directs hypervigilant attention and increases physiological arousal (Guastella, Mitchell & Matthews, 2008; Meston & Frohlich, 2000; Rimmele et al., 2009). Upon interaction, the consummatory reward of MOR activation provides hedonic value feedback (Depue & Morrone-Strupinksy, 2005). This combination of high T, D2R, MOR, OTR, and V1aR activation, coupled with the subsequent lower activation of their counterparts, PRL, D1R, KOR, and 5-HT, promotes the feelings associated with the "symptoms" of infatuation: Mental preoccupation and mood dependency from low global 5-HT causing emotional lability, high NE causing hypervigilance, and dopaminergic 5-HT_{2A} activation causing obsessive and intrusive thinking; motivation and physiological arousal from DA and NE; positive memory encoding and idealization from OTR; and increased social recognition and memory from AVP; increased libido from T interacting with OT and DA. These neurochemical interactions act in

concert to create the ideal environment for selective and robust encoding of positive emotional memories and an elaborated, rewarding mental representation of the partner (Kovacs, Sarnyai & Szabo, 1999; Meston & Frohlich, 2000; Pietromonaco & Feldman Barrett, 2000; Selcuk et al., 2012; Shohamy & Adcock, 2010; Zayas, Gunaydin, & Shoda, 2014).

Once the mental representation of the partner is established, its hedonic value changes as infatuation shifts into attachment. DA, NE, and T decline, and there is a smaller reduction in OT (Burkett & Young, 2012; Carter & Porges, 2011; Johnson & Young, 2015; Numan & Young, 2016). Simultaneously, MOR activation in MOR-CB1 heterodimers within the reward system remains relatively stable and becomes the predominate reward associated with the partner – replacing the excitement of infatuation with the contentment of attachment. PRL, 5-HT, D1R, and KOR activation increase during this shift from infatuation to attachment: PRL increases feelings of satiety and partner sensitivity, 5-HT increases feelings of emotional stability and positive mood, and D1 and KOR prevent the establishment of another bond through selective aggression. Also, MOR, OT, PRL, and 5-HT act together as an anxiolytic force to reduce stress and pain.

This blend of neurochemical effects mirrors the core features of attachment: separation distress related to the dysphoria of KOR activation and MOR withdrawal, proximity seeking promoted through OT and DA social motivation, safe haven-related pain mediation and anxiolytic effects of OT and MOR activation sensitized by PRL and 5-HT, and secure base mood stabilization effects of OT and 5-HT. Whereas the primary function of neuroendocrine action during the infatuation phase of romantic relationship development is to propel you toward and create a mental representation of the partner, the primary function of neuroendocrine action

during the attachment phase is to use the mental representation for affect regulation and pair bond maintenance.

Conclusion & Future Directions

It is no accident of nature that the same hormones that trigger labor in pregnant women and milk letdown in lactating mothers are released at high levels during sexual orgasm and during feelings of romantic love. In all these cases, the neurochemical milieu facilitates bonding. Humans are drawn into attachment promoting interactions with because it either helps ensure survival of themselves or their offspring. If human infants, as members of an altricial species, did not maintain proximity to adult caregivers and protectors, they simply would not survive. In contrast, what draws adults into attachment promoting interactions is the motivational reward of sexual attraction, which is followed by the consummatory reward of relationship maintenance, yet the function in both cases is theorized to be the same.

This theoretical outline of the cause and function of neurochemical changes from infatuation to attachment relationships provides an empirical framework to test this process. Future research should be sure to consider not only oxytocin, vasopressin, and dopamine, but also the integral and intersecting effects of opioids, endocannabinoids, serotonin, norepinephrine, prolactin, and sex hormones. The interaction between the bonding peptides and endocannabinoids in the reward system is only now coming to light and provides relationship science a new scaffold for future studies. Prolactin, as well, is relatively understudied in the realm of adult relationships, yet has significant neurological effects and, along with testosterone, sex specific consequences for the experiences during relationship formation and maintenance. Future studies should endeavor to use a comprehensive neurochemical lens when considering the

types of rewards and reactions partners experience in the process of forming, establishing, and maintaining relationships.

Chapter 2 References

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Chapter 2 Tables and Figures

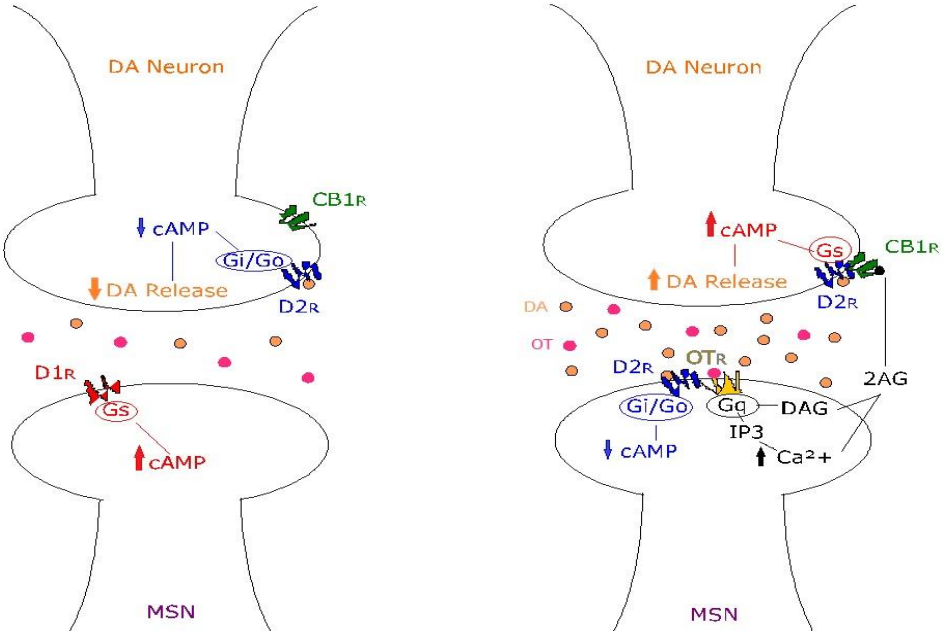

Figure 1. A theoretical representation of the synaptic consequence of oxytocin receptor (OTR) bias. OTR biases dopamine (DA) release towards D2 dopamine receptor (D2R) and not D1 dopamine receptor (D1R) activation through endocannabinoids. On the left is a dopamine (DA) neuron synapsing onto a medium spiny neuron (MSN) in the nucleus accumbens shell that has a D1R. This D1R activates the Gs protein pathway increasing cAMP in the MSN, but as DA is released into the synapse, it binds to the D2R presynaptic autoreceptor. The D2R presynaptically activates Gi/Go, reducing cAMP in the DA neuron and reducing DA released into the cleft. However, the right MSN has a D2-OT heterodimer activating Gi/Go and Gq, respectively. While D2R reduces cAMP in the MSN, OTR increase calcium and catalyzes the creation of endocannabinoids, which diffuse out into the synapse and bind to presynaptic endocannabinoid receptor (CB1R). The co-activation of D2R and CB1 causes them to form a heterodimer, which activates Gs instead of Gi/Go. This increases cAMP in the DA neuron and increases DA release only from the neuron synapsing onto D2-OT heterodimers.

Chapter 3:

Adult Attachment Differences in Pupil Reactions to Partner Mental Representations

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Abstract

Recent work has begun to distinguish the reward biology of infatuation from attachment relationships. The current study hypothesized a major difference between these stages was the dominance of the appetitive and consummatory reward systems, respectively. Dopamine, driving the appetitive reward system, causes pupil dilation, and mu-opiates, driving the consummatory reward system, cause pupil constriction. Using this theoretical framework, the pupil area changes of 48 participants in response to self-produced mental representations of the partner were measured. Participants were asked to bring their partner to mind for two minutes while measuring pupil area via an infrared camera. Pupil area was z-transformed. Standard deviations above the mean were interpreted as dilation, while below the mean were constriction. As hypothesized, when thinking of their partner, the infatuated participants exhibited significant pupil dilation, yet attached participants did not differ from baseline. Participants were also asked to imagine their partner as a source of support and as a source of sexual desire. There was significant dilation to the representation of a partner as sexual and no dilation to the representation of a partner as supportive. The pupil constriction while thinking of the partner as supportive was significantly correlated with relationship length, cohabitation, and the frequency of emotionally close behaviors. Pupil area differences to a general partner representation acted as an unconscious marker of the secure base feature of attachment, while pupil area differences to thinking of the partner specifically as an attachment figure acted as an unconscious marker of relationship progression. Interpretations of the study as a measurement of reward or arousal are discussed.

Keywords: Attachment, Infatuation, Reward, Arousal, Relationships, Pupillometry

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Introduction

The desire for human connection is fundamental and often exhibited in adulthood through romantic relationships. Though there have been a profusion of studies focused on these relationships, relatively little is known about normative adult relationship development and progression (Hazan & Zayas, 2014). One framework for understanding this process is an attachment formation process perspective (Hazan & Shaver, 1987; Hazan & Zeifman, 1999). Couples begin as relative strangers, propelled towards each other by the powerful feelings of infatuation during the nascent stages of the relationship that, over time, wanes and may evolve into a full-fledged adult attachment bond (Fisher et al., 2002; Hazan & Zeifman, 1994; Zayas, Merrill & Hazan, 2015).

The first phase of this process, infatuation, is characterized by intense feelings of excitement, desire, and physiological arousal, along with obsessive and intrusive thinking, longing, emotional lability, and uncertainty (Fisher et al., 2002; Langeslag, Muris, & Franken, 2013; Tennov, 1979; Wakin & Vo, 2008; Willmott & Bentley, 2015). Over time these feelings generally wane and either the couple ends the relationship or it evolves into an attachment bond (Fisher et al., 2002; Hazan & Zeifman, 1994). The features of attachment remain the same across the lifespan, and as such, these adult attachments are defined by proximity seeking, separation distress, safe haven, and secure base (Bowlby, 1979; Hazan & Shaver, 1987). Partners in these relationships maintain closeness (proximity seeking), are upset by being apart (separation distress), find comfort in each other in times of stress (safe haven), and feel supported in a way that allows them to explore (secure base). The affective feelings of attachment relationships are generally associated with a feeling of calm, security, trust, and contentment.

Though the quality of the relationship changes, this does not mean that one phase is more rewarding than the other. Many people discuss infatuation as extremely rewarding, motivating, and passionate. Though this spark does generally fade through relationship progression, most people continue to find relationships they remain in rewarding and enjoyable. One approach to understanding this shift in relationships is to understand its phenomenological overlap with the two major components of the neurochemical reward system: the appetitive and the consumatory. Zayas, Merrill, and Hazan (2015) theorized that a shift from the prevalence of the appetitive (wanting and desire) to the consummatory (liking and satisfaction) reward system during normative relationship progression could underlie the shift from infatuation to attachment in humans.

The experience of infatuation is consistent with appetitive reward motivation driven by the neurochemical dopamine (Tennov 1979; Fisher et al., 2002). Meanwhile, the experience of adult attachment bonds is more consistent with the liking, enjoyment, and contentment of consummatory reward driven by mu-opiate receptor activation (Burgdorf & Panksepp, 2006; Hazan & Shaver, 1994). Essentially, the purpose of reward during infatuation is to motivate you towards forming a bond with a partner, whereas the purpose of reward during attachment is keep you in the bond you have already created. This theoretical framework for, and the ecological experiences of, infatuation and attachment therefore posit that there is a distinct reward biology differentiating the two phases (Zayas, Merrill, & Hazan 2015). One way to test this theory is to examine biological markers of reward system.

Due to the conflicting effects of mu-opioids and dopamine on pupillary reactions, the current study measured pupil area change in order to assess if this method could act as a biological marker differentiating infatuation from attachment in romantic relationships. It is well

documented that both dopamine, and its antecedent noradrenaline, cause significant pupil dilation, or mydriasis, in humans (Einhäuser, Stout, Koch, & Carter, 2008; Spiers, 1969). Similarly, the dose-dependent pupil constriction, or miosis, associated with mu-opiates is also well documented (Pickworth, 1989). Therefore, we hypothesize that, while thinking about their partner, participants who are attached should experience pupillary constriction via a prevalence of mu-opiate receptor activation, while infatuated individuals should experience pupillary dilation via a prevalence of dopaminergic and noradrenergic receptor activation.

To test this hypothesis two findings must be established: there is a discernable difference in pupil area between a scenario known to release dopamine and a scenario known to release opiates, and there is a discernable difference in pupil area between directed appetitive conceptualizations of the partner and directed consummatory conceptualizations of the partner. The first establishes that it is possible to test for opiate and dopaminergic rewards with this paradigm, while the second establishes that there is a difference in biological reactions to appetitive and consummatory processes regarding the partner specifically.

In regards to the first, the current study used a memory of social rejection as the scenario that results in mu-opiate receptor activation, as this activation is consistently implicated in social rejection and isolation (Burkett & Young, 2012; MacDonald & Leary, 2005; Panksepp, 2003, 2005; Resendez & Aragona, 2013). The dopaminergic and noradrenergic equivalent used was a sexual fantasy, as increases in both neurochemicals are associated with arousal (Krüger, Hartmann & Schedlowski, 2005). Additionally, sexual arousal is correlated with pupil dilation (Rieger et al., 2015). If this methodology is capable of detecting these differences, the pupil area during a memory of social rejection would be less than the pupil area during a sexual fantasy. Specifically, the pupil would constrict during the memory and dilate during the fantasy.

In regards to the second, the current study compared the average pupil area when participants were asked to think of their partner as someone who is sexually exciting and as someone who will always have their back. The partner as a sexual figure stimulus was chosen because of its unique ability to address the motivational aspect of desire for the partner. Therefore, this condition assesses appetitive reward specifically in relation to the partner. Importantly, though there is considerable overlap between sex and attachment processes, the systems are distinct and independent (Diamond, 2004; Diamond & Dickerson, 2012). Alternatively, the partner as an attachment figure stimulus was chosen to prompt thoughts of support, calm, and contentment in order to assess the more consummatory reward elements of attachment. Therefore, the second hypothesis was that there is a significant difference in pupil area between thinking about the partner as exciting and sexually attractive and thinking about the partner as a supportive and secure attachment figure. Specifically, the former should result in pupil dilation, while the later should result in pupil constriction.

After establishing these findings, the third hypothesis was that there is a significant difference in pupil area to thinking about the partner in general between participants who were infatuated and attached, as determined by the partner's presence or primacy for the defining features of attachment. Similarly, just as attachment increases over the course of the relationship, pupil area to thoughts of the partner should decrease with relationship length and emotionally intimate relationship progression milestones.

Method

Participants.

Participants in this study included 48 people in romantic relationships. 31 participants were Cornell University students and 17 were recruited through Cornell University staff emails.

Student participants were compensated with course credit, while staff participants were paid $25 for their time. The study lasted approximately 100 minutes. Participants included 33 females and 15 males between the ages of 18 and 54 with an average age of 21 (*SD*= 5.05). More than half (67%) of the sample identified as exclusively heterosexual and about half (44%) identified as white/Caucasian. The majority of the sample (57%) was not at all or only a little bit religiously observant.

All but one (98%) of our participants were sexually active with their partner and all were monogamous. Approximately one third (35%) were in a long distance relationship at the time of participation, and one quarter were cohabitating (25%). The participants were generally attracted to their partner, (on a scale from 1 to 5, *M*=1.38, SD=0.67), satisfied with their partner (*M*= 4.33, *SD*=0.78), satisfied with their relationship (*M*=4.29, *SD*=0.85), and committed to their relationship (*M*=4.54, *SD*=0.62). Participants' relationships ranged from 1 month to 25 years in length (*M*= 44.69 months, *SD*= 48.68).

Materials.

Research assistants obtained informed consent from all participants, who were knowledgeable about the procedures, benefits and risks of participating, voluntary participation, and contact information of the researchers before beginning. Non-aggregate self-report materials included relationship questions about monogamy, cohabitation, long distance status, and length. Participants answered questions about relationship satisfaction, commitment, attraction, and desire on a Likert scale from 1 to 5. Participants also answered questions about their sexual experiences in the relationship including if they had engaged in sex with their partner, if they had orgasmed with their partner, and the likelihood they orgasm when having sex with their partner.

Measure of Attachment. The WHOTO measure (Hazan & Zeifman, 1994; Fraley &Davis, 1997) is a measure of the four defining features of attachment: proximity seeking, separation distress, safe haven, and secure base (Bowlby, 1979; Hazan & Shaver, 1987). The measure presents a series of statements that represent one of the four features of attachment, and all four features are represented in the measure. The instructions require participants to indicate, in order, their relationship to the person, or persons, who fulfill each statement. Example statements include, ‘‘person(s) you know always wants the best for you” and “person(s) whose absence makes you feel like something is not quite right”. Participants may name up to four relationships per statement. These data were coded with the position of the romantic relationship partner for each statement. These data were then split into the partner’s presence for each statement and partner’s primacy for each statement (Hazan & Zeifman, 1994; Freeman & Simons, 2018).

Closeness and Intimacy. A series of questions about relationship closeness were developed based on consensus among researchers in the lab. These questions were intended to have ecological validity to common experiences in relationship progression that indicate intimacy, familiarity, and vulnerability. All questions and response scales are listed in Appendix A.

Demographics. Participants were asked to provide a number of demographics including sex, gender, age, sexual orientation, relationship status, and race.

Location.

The study took place in a booth inside of a laboratory on the Cornell University campus in Ithaca, NY. This booth allowed for the participant to have increased privacy and decreased

distraction during the study. The enclosed environment also allowed for the room to be maintained at a constant 49 lux of ambient light for all participants throughout the study. Maintaining the same light level for all participants at all stages of the study is necessary due to the normal pupillary light reflex (Ellis, 1981).

Stimuli.

Participants saw a sepia-toned screen that maintained approximately 27 lux emission throughout the experiment. The specific stimuli presented is available in Appendix B. Included in this is the crosshair screen used for baseline and mental representation pupil area measurements, instructions for which mental representation to bring to mind (partner, partner as an attachment, partner as sexually exciting, a sexual fantasy, and a memory of social rejection). Not included are the Sternberg Working Memory task (Sternberg, 1969), and a sepia-toned "cloud" video.

Equipment.

Inquisit presentation software showed stimuli to participants and collected written responses. An SR Research Remote infrared gaze tracker recorded pupil data per millisecond with a 35 mm lens focused on participants' right eye. An ophthalmologist head mount kept participants' heads steady and at a consistent 500mm from the lens throughout the paradigm. The program EyeLink 1000 used the monocular setting to compute pupil area as the number of pixels occluded by the infrared light reflected by the right pupil. Qualtrics web-based survey tool recorded survey responses. MATLAB was used for pupil area data processing, including removing blinks, head movements, and saccades.

Design and Procedure.

Participants received an email with the instructions and prompts for the study before attending the session. This was to reduce cognitive effort in bringing the partner or scenarios to mind, which can cause pupil dilation (Kahneman, 1973). Upon reaching the lab, researchers obtained informed consent, led participants into the booth, and had them sit in front of the camera. The researcher calibrated the participant's eye movements and pupil threshold at this time (see Rieger et al., 2015 for description). Participant then began the paradigm.

Participants were first asked to think about their partner for 2 minutes, during which a crosshair was on the screen (see Appendix B). The crosshair was present for all stimulus conditions and all baselines. The crosshair's purpose was to help the participant keep their eyes open and toward the middle of the screen. This was followed randomly by thinking of the partner either the as "someone who always has your back" or as someone who was "sexually exciting". Then prompts for a memory of social rejection and an arousing sexual fantasy followed in a random order. All presentations were also counter-balanced to prevent order effects. Between each representation period, participants engaged with the Sternberg Working Memory Task as a distractor. After the task, participants were shown a 30 second video of sepia-toned clouds and told to clear their minds. This was also done to reduce cognitive effort. Following the clouds was a 25 second crosshair, which served as a baseline, before the instructions for the next stimulus condition were presented. After the 2 minutes of thinking about the prompt, participants wrote about their thought process in the immediately preceding condition. After completing all stimulus conditions in the booth, the participant returned to the lab and completed the questionnaire on a laboratory computer.

The reasoning behind using mental representations as the stimulus was twofold. First, mental representations are not visual, do not require eye movements, and are not necessarily

focused on the partner's physical appearance. Second, there are robust data on the function of mental representations as elaborated internal working models of the partner that implicitly influence behavior and affective states (Collins et al., 2004; Günaydin, Zayas, Selcuk, & Hazan, 2012; Mikulincer, Gillath, & Shaver, 2002; Pietromonaco & Feldman Barrett, 2000; Pietromonaco, Feldman Barrett, & Powers, 2006; Selcuk, Zayas, Günaydin, Hazan & Kross, 2012; Zayas, Günaydýn, & Shoda, 2015; Zayas & Shoda, 2005). All participants in the sample agreed with the question "It is easy for me to conjure up an image of my partner in my mind."

Data Standardization.

Pupil area data was averaged for each stimulus in the paradigm. In order to compare pupil area scores across participants, the procedures from Rieger et al., 2015 were used. The average and standard deviation of all baseline and mental representation stimuli were used to z-transform each individual's pupil area data. Therefore, all pupil area data was analyzed in terms of standard deviations above or below the mean. Standard deviations above the mean indicated an increase in pupil area, or pupil dilation, while standard deviations below the mean indicated a decrease in pupil area, or pupil constriction.

Results

Standardizing pupil data into z-scores makes it possible to conduct intergroup comparisons. In order to determine if the paradigm was effective, the average pupil area during the memory of social rejection was compared to the average pupil area during the sexual fantasy using a paired t-test. The hypothesis is that a memory of social rejection will cause opiates to be released and, thus, result in pupil constriction, while a sexual fantasy will cause dopamine and norepinephrine to be released and, thus, result in pupil dilation. The hypothesis was supported

with a significant difference in pupil area between the memory (*M*=-.*20*, *SD*=.71) and fantasy conditions (*M*=.23, *SD*=.93), *t*(45) = -3.15, *p* = .003, 95% CI [-.71, -.15]. The sexual fantasy did result in pupil dilation and the memory did result in pupil constriction (Figure 1).

The second hypothesis was that thinking about the partner as exciting and sexually attractive would cause pupil dilation, while thinking about the partner as a supportive and secure attachment figure would cause pupil constriction. This hypothesis was somewhat supported with a significant difference in average pupil area between thinking about the partner as a sexual figure (*M*=.*29*, *SD*=.59) and as an attachment figure (*M*=-.*02*, *SD*=.65), *t*(45) = -3.25, *p* = .002, 95% CI [-.50, -.11]. Thinking of the partner as sexually exciting did result in pupil dilation, and though thinking of the partner as someone who has your back did not result in substantial pupil constriction, it also did not result in pupil dilation (Figure 2).

Independent sample t-tests were used to test the third hypothesis: there is a significant difference in average pupil area between participants who did and did not list their partner on each feature of attachment. There were no significant differences in pupil dilation to the mental representation of the partner for any proximity seeking (e.g. "person you make sure to see or talk to frequently", *t*(45) = -.94, *p* = .350, 95% CI [-.81, .29]) or safe haven measures (e.g. "person you seek out when worried or upset", *t*(45) = -.553, *p* = .583, 95% CI [-.66, .37]). However, there were significant differences in average pupil area depending on the partner's position on statements representing separation distress and secure base.

In regards to the statement the "person you know always wants the best for you", a secure base statement, there was a statistically significant difference between the pupil area of participants who listed their partner as their primary secure base (*M*=-.34, *SD*=.69) and those

that did not (*M*=.39, *SD*=.83), *t*(45) = -2.66, *p* = .011, 95% CI [-1.29, .18] (Figure 3). Further, Cohen's effect size value (*d* = .96) suggested a high practical significance (Cohen, 1988). For this same statement, there was a significant different between the pupil area of participants who listed their partner at all on this measure (*M*=.12, *SD*=.84) and those that did not (*M*=.89, *SD*=.63) *t*(45) = -2.14, *p* = .038, 95% CI [-1.49, -.04]. Participants that didn't list their partner on this secure base item experienced significantly more dilation than those that did. This was a large effect (Cohen's *d* = 1.03).

For the secure base statement focusing on capitalization, "person you are most likely to tell when something good happens to you," there was a significant difference in average pupil area to the partner representation between participants who listed their partner first (*M*=-.01, *SD*=.78) and those that did not (*M*=.59, *SD*=.84), *t*(45) = -2.51, *p* = .016, 95% CI [-1.10, -.12]. This was a medium to large effect (Cohen's *d* = .74). All participants in the sample listed their partner in some position on this statement and so no analysis could be done on partner presence.

Partner primacy on the secure base item, "person you can hardly imagine your life without," was only marginally significant, *t*(45) = -1.84, *p* = .073, 95% CI [-.99, .05]. However, the ordinal position of the partner on the list for this statement significantly negatively correlates with pupil area during partner mental representation *r*(40)=-.371, p=.04. Participants that listed their partner higher exhibited a lower average pupil area when thinking about their partner than participants that listed their partner further down on the list. Therefore, the more primary a partner is for the secure base statement "person you can hardly imagine your life without", the smaller the participant's pupil area when thinking about them. In total, pupil area differences are significant across secure base statements on the WHOTO.

For the separation distress statement, “person whose absence makes you feel like something is not quite right,” there was a significant difference in average pupil area to the partner mental representation between participants who listed their partner first (*M*=-.03, *SD*=.78) and participants who did not (*M*=.58, *SD*=.86), *t*(45) = -2.54, *p* = .015, 95% CI [-1.09, -.13]. Participants who did not have their partner as primary on this statement experienced significantly more dilation. This was a medium to large effect (Cohen’s *d* = .75). There was no significant difference in pupil area to partner mental representation between partner presence and absence on this statement *t*(45) = -.65, *p* = .515, 95% CI [-1.08, .55].

In addition to aspects of the WHOTO, pupil reaction to partner mentalizing showed significant difference in other relationship domains as well. In the items assessing general anxiety and worry in the company of the partner, average pupil area to the partner condition was negatively correlated with high ratings of anxiousness *r*(47)=-.296, p<.05 and worry *r*(47)=-.293, p<.05, while average pupil area while thinking of the partner as an attachment figure negatively correlated with nervousness *r*(47)=-.390, p<.01. Overall, the less anxiety and uncertainty experienced while around a partner, the smaller the participant’s pupil area was when thinking about them.

Differences in average pupil area to partner representations pertained to the sexual relationship as well. Participants who had a high percentage of sexual encounters with their partner that resulted in orgasm had a significantly smaller pupil area while thinking about their partner *r*(41)=-.310, p<.05. In a similar vein, there were some significant differences in participants’ pupil area when specifically thinking about their partner as sexually exciting. For example, participants who said they had never had an orgasm with their partner (*M*=-.41,

SD=.35) had a significant pupil constriction to imagining their partner sexually in comparison to those who had (*M*=.341, *SD*=.58), *t*(43) = .84, *p* = .015 6, 95% CI [.16, 1.35]. Understandably, pupil area while sexually thinking of their partner was positively correlated with how much sexual desire the participant felt for their partner overall *r*(45)=.301, p<.05. For the safe haven statement, "person you immediately think of contacting when something bad happens", there was a significant difference in average pupil area to thinking of the partner as sexually exciting between presence (*M*=.38, *SD*=.58) and absence (*M*=-.32, *SD*=.26), *t*(45) = 2.87, *p* = .006, 95% CI [.21, 1.18]. Participants who did not list their partner was someone they would turn to immediately for comfort experienced significant pupil constriction to the partner as sexually exciting prompt (Figure 4). This was a large effect with a high practical significance (Cohen's *d* = 1.54).

A series of questions were devised to assess a participant's comfort level sharing personal items and spaces (see Appendix A). The average pupil area during the condition where participants are thinking about their partner sexually was negatively correlated with the participant's level of comfort sharing these personal things *r*(46)=-.385, p<.01 (Figure 5). Most specifically, comfort sharing a plate of food *r*(45)=-.347, p<.02, a bathroom *r*(45)=-.421, p=.004, or a bar of soap *r*(45)=-.392, p=.007 were significantly correlated with reduced pupil dilation to thinking of the partner as sexually exciting.

There were several illuminating differences in pupil area during the prompting to think of the partner as an attachment figure. First, a series of questions were asked about how often certain comfortable scenarios play out in the relationship (see Appendix A). None of these items correlated with average pupil area while thinking of the partner generally or while thinking of the

partner as sexually exciting. However, average pupil area while thinking of the partner as an attachment significantly negatively correlated with the frequency of sharing a bed without having sex $r(48)=-.589$, $p<.0005$ (Figure 6), feeling comfortable hanging around without talking to each other $r(48)=-.288$, $p<.05$, sleeping well while sharing a bed $r(48)=-.321$, $p=.026$, and expressing thoughts even when the partner disagrees $r(48)=-.347$, $p<.02$. All of these items are correlated with increased pupil constriction while thinking of the partner as an attachment figure.

While there was no significant correlation between average pupil area while thinking of the partner and relationship length $r(48)=.02$, $p=.884$, average pupil area when thinking about the partner as an attachment figure was negatively correlated with relationship length $r(47)=-.403$, $p=.005$ (Figure 7). The longer a participant was in a couple, the more constriction they experienced when thinking of them as someone who has their back. Additionally, participants who were living with their partner ($M=-.32$, $SD=.80$) experienced more constriction than participants who were living separately from their partner ($M=.15$, $SD=.62$), $t(45) = -2.09$, $p < .05$, 95% CI [-.92, -.02]. This was a moderate effect (Cohen's $d = .66$). Expectedly, participants who were cohabitating were together longer ($M=68.66$, $SD=82.87$) than participants who were not ($M=19.85$, $SD=14.40$), $t(46) = 3.38$, $p = .001$, 95% CI [19.35, 76.29]. Finally, a forced-choice question was presented to the participants: is "home" with your parents/where you grew up or with your partner? Participants who said home was with their partner ($M=-.73$, $SD=.61$) experienced significantly more pupil constriction than those who said home was with their parents ($M=.21$, $SD=.62$) $t(41)=3.67$, $p=.001$, 95% CI [.08, 1.13] (Figure 8). This was a large effect with high practical significance (Cohen's $d = 1.53$).

Discussion

The current study examined whether self-report measures of attachment and relationship progress are associated with changes in pupil area to mental representations of a romantic partner. First, the manipulation control comparing a memory of social rejection to a sexual fantasy showed significant differences in the predicted direction, suggesting the paradigm may be effective in measuring differences between dopaminergic and opiate activity via pupil area (Figure 1).

The second hypothesis that the pupil area while thinking about the partner as an attachment would be less than thinking about the partner as sexual was also confirmed. However, while the sexual condition did result in pupil dilation, the partner as an attachment condition did not result in constriction or dilation (Figure 2). One possible reason for this is that, based on participant reports, thinking about the partner as sexually exciting was sometimes a memory and sometimes an imaginary fantasy, whereas the partner as an attachment figure was almost exclusively a memory. Previous research found that retrieving memories can increase pupil dilation, however, we did not see this effect for the memory of social rejection condition (Goldinger & Papesh, 2012). Alternatively, it is possible that thinking of the partner as an attachment is not an effective prompt for activating the consummatory reward system, but also did not activate the appetitive reward system.

The third hypothesis, that the primacy and presence of a partner on the features of attachment would result in smaller pupil area, had some support and some conflict within these data. There were significant differences for separation distress and robust and consistent differences for secure base, including primacy, presence, and ordinal effects (Figure 3). However, there were no differences for proximity seeking or safe haven items. Both separation distress and secure base are defining features while away from the partner, but not actively

seeking the partner like proximity seeking and safe haven. It is possible that the motivational aspect of proximity seeking and safe haven prevents this measure from discerning differences in attachment status according to these features. A future study conducting a similar paradigm while the partner is present and acting as stimuli, instead of a mental representation, could elucidate these differences. However, though not statistically significant, all features of attachment followed the same trends for partner primacy, with dilation for those who did not list their partner first and no dilation for those who did list their partner first. It may be possible that the differences between the attachment features is due to the small sample size.

Similar to the partner as an attachment condition, the presence or primacy of the partner did not result in significant dilation or constriction, while the absence or secondary position of the partner did result in significant pupil dilation. While this biological measure did find differences in the predicted directions and participants experienced pupil dilation as predicted, they did not experience pupil constriction as predicted. Following this trend, high anxiety or worry around the partner correlated with pupil dilation, but those with low anxiety and worry around their partner demonstrated no change from baseline. This relationship was mirrored for pupil area while thinking of the partner as an attachment figure and nervousness around the partner. Additionally, the pupil dilation was only significant to measures of anxiety, but not motivation, such as "craving" the partner. Finally, there was no relationship between pupil area to partner mental representation and relationship length, and this hypothesis was not supported.

In regards to factors that affected pupil area to thinking of the partner sexually, increased desire for the partner increased dilation, understandably, as did having an orgasmic relationship. Increasing comfort and familiarity resulted in significantly reduced sexual arousal based on pupil area constriction. Conversely, comfort with the partner as a safe haven lead to increased arousal.

Those who did not even list their partner as someone they would turn to for comfort did not experience pupil dilation, but even more so, they experienced pupil constriction during this condition (Figure 4). Comfort associated with familiarity appeared to reduce sexual arousal to the partner, while comfort associated with reducing stress appeared to increase it. This complicated relationship between sexuality and comfort is one that necessitates further study.

Pupil area while thinking of the partner as someone who will always have your back was correlated with many emotional closeness milestones, and, unlike the pupil area findings for the features of attachment, these relationships exhibited both pupil dilation and constriction. First, unlike thinking of the partner generally, thinking of the partner as an attachment figure correlated with significant constriction as the length of the relationship increased and, relatedly, with cohabitation. Similarly, the increasing frequency of emotionally close activities such as sleeping together without having sex, being around each other without talking, sleeping well together, and feeling comfortable expressing divergent thoughts all correlated with pupil constriction. Finally, thinking of the partner as "home", even superseding parents, correlated with significant constriction. While somewhat ironically lacking a relationship to the features of attachment, pupil area while thinking of the partner as an attachment was correlated with measures of closeness, comfort, and normative relationship progression.

These data suggest that pupil area reactions to partner mental representation may act as an unconscious biological marker of the secure base feature of attachment. These reactions do not appear to represent differences in all features of attachment, however. Alternatively, directing the partner mental representation to thinking about them as an attachment figure was consistently correlated with meaningful and ecologically valid experiences of relationship progression, including relationship length, where an undirected partner representation was not.

This difference in effect may be due to the wording used to prompt the attachment figure mindset, which was created from a description of the secure base feature of attachment. A future study could determine if these relationships replicate using directions based on the other features of attachment. Given the current data, pupil area differences to a global partner representation act as a biological marker of secure base, while pupil area differences to an attachment partner representation act as a biological marker of relationship progression.

The difference between pupil area for a global and attachment partner mental representation and the relative lack of constriction observed among the comparisons indicates there may be alternative interpretations of these data. Specifically, this paradigm, though successful in identifying biological differences unique to attachment and long term relationships, did not assess reward, but arousal. In addition to opiate and dopaminergic effects, pupil diameter is a measure of noradrenaline levels and emotional arousal (Bradley, Miccoli, Escrig & Lang, 2008; Einhäuser, Stout, Koch, & Carter, O, 2008; Partala & Surakka, 2003). In this sample, different types of reward, such as contentment or craving, had no clear relationship with pupil differences, but anxiety, worry, and nervousness around the partner did. While the memory of social isolation, which is both emotionally arousing and known to release opiates, did result in constriction, most other comparisons in this study failed to find the same level of miosis. It is possible that since attachment is accompanied by lower arousal and comfort with the partner than infatuation (Gonzaga et al., 2006), the biological paradigm was effective, but through measuring differences in arousal stemming from reduced uncertainty and anxiety in attachment.

Future studies should investigate the origin of the observed biological marker. There are a variety of ways to approach this. First would be to change the prompts to specifically focus on arousal and anxiety. Another option would be to administer human safe antagonists such as

clonidine or naloxone. If the same pupil reactions occur under the influence of clonidine, a noradrenaline antagonist, then this effect would not stem from arousal. If the paradigm does act as a measure of arousal, then a possible next step would be to explore pupil dilation as a measure of attachment anxiety. Additionally, the current study had a small pool of participants that were primarily young adult and primarily female. A replication with a larger and more diverse sample size is needed. Another future direction would be to use a similar paradigm to examine pupil area change among couples longitudinally and dyadically.

These results suggest there are perspicuous differences in physiological responses between individuals who are and are not attached to their relationship partner. Additionally, measures of pupil area may be an effective, biological, and unconscious measure of attachment and relationship progression that should be further investigated.

Chapter 3 References

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Chapter 3 Tables and Figures

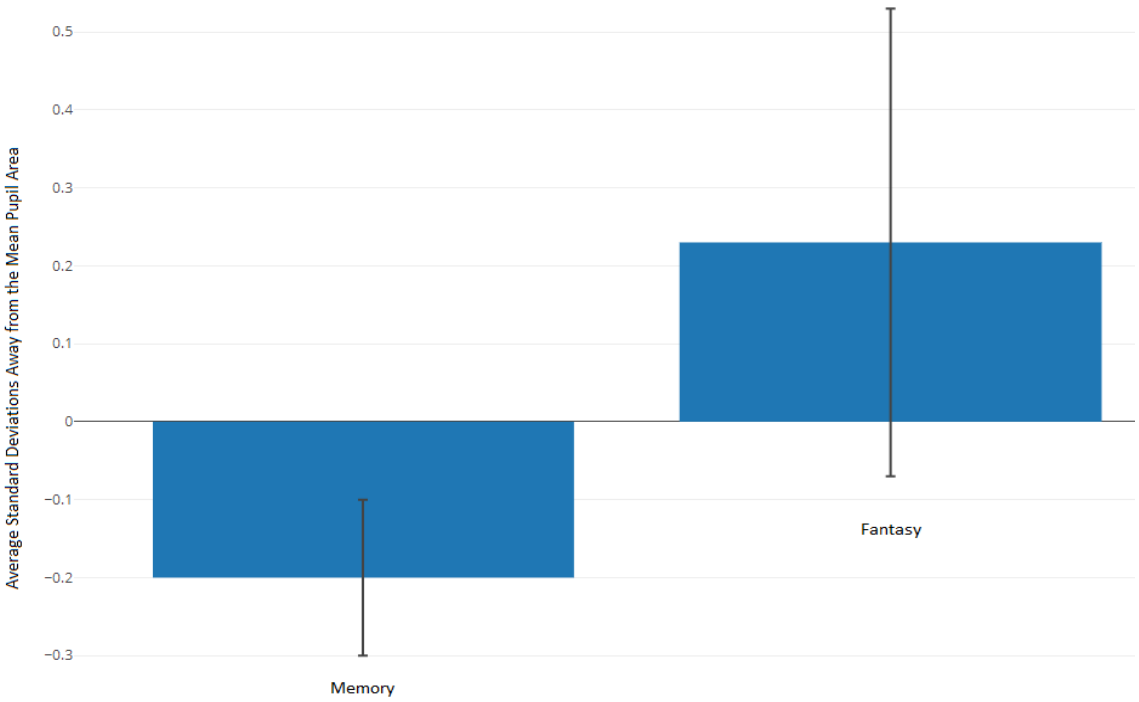


Figure 1. Average Standardized Pupil Area to a Memory of Social Isolation versus a Sexual Fantasy. Participants' pupil area was recorded while remembering a time they felt socially rejected and while fantasizing about a sexual scene. When remembering, participants experienced pupil constriction, while participants fantasizing experienced constriction. This condition in the study acted as a control condition to check if the paradigm worked as predicted. Because sexual fantasy is well documented to release dopamine, while social isolation and pain are release mu-opiates, memory should pupil constriction, while sexual fantasy should pupil dilation. There was a significant difference between the two conditions in the predicted direction. All values are z-score standardized.

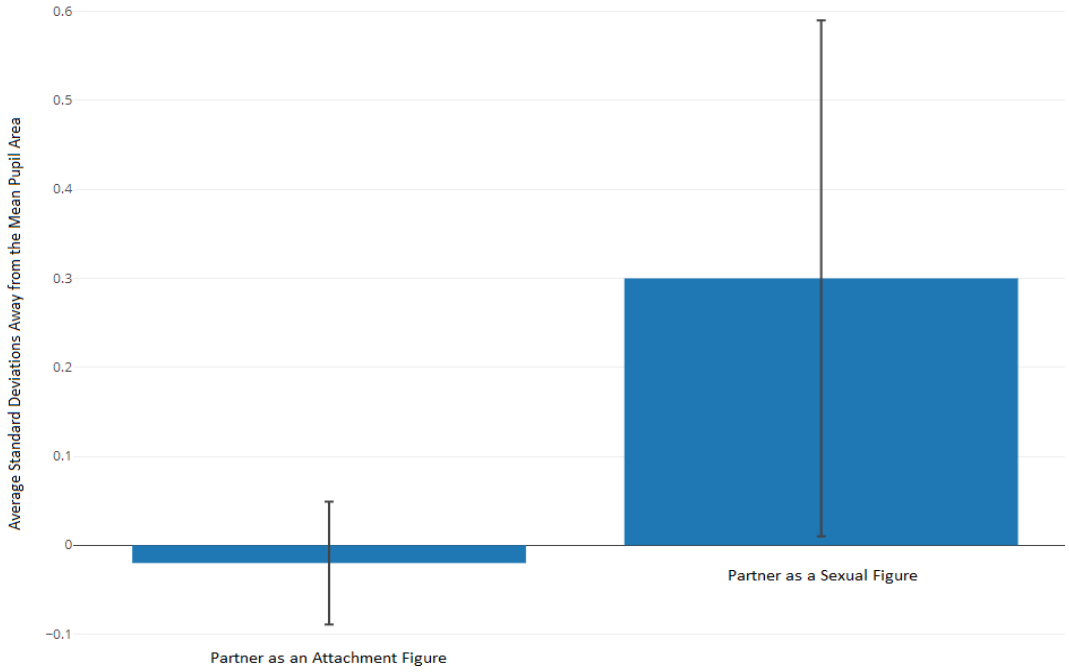


Figure 2. Average Standardized Pupil Area to Imagining a Partner as an Attachment Figure versus as a Sexual Figure. Participants' pupil area was recorded while thinking about their partner as a sexual figure and while thinking about their partner as an attachment figure. In this case, thinking about the partner as attachment figure should release opiates and cause pupil constriction, as they should be thinking of the satiety and safety elements of their relationships, whereas thinking of the partner sexually should lead to thoughts of sexual motivation and pupil dilation. There was no significant constriction to thinking of the partner as an attachment figure, but there was significant dilation to thinking of the partner sexually. There was a significant difference between the two conditions in the predicted direction. All values are z-score standardized.

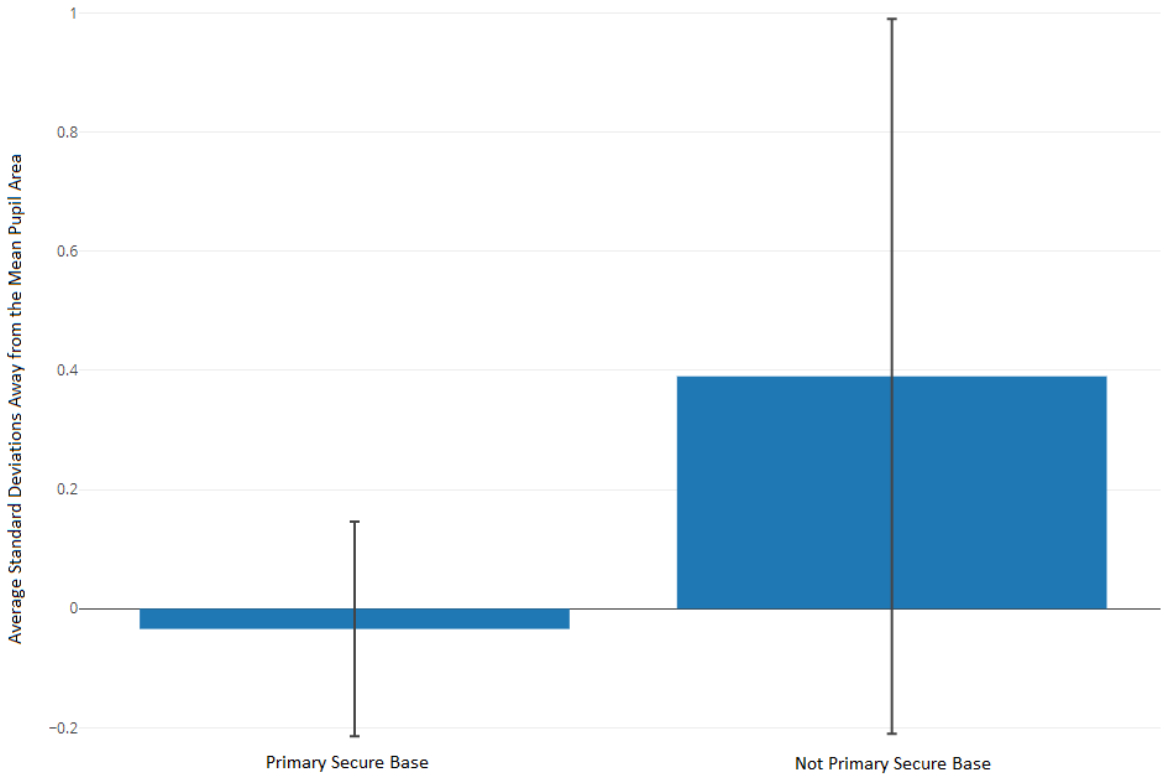


Figure 3. Average Standardized Pupil Area to Partner Mental Representation for Infatuated and Attached Individuals. Participants were asked to think about their partner for 2 minutes, during which time their average pupil dilation was recorded. Participants who ranked their partner as their primary (listed first) person for secure base ("person you know will always be there for you") had significantly greater pupil constriction (lower pupil area) than those who did not (greater pupil area). Attached individuals did not experience dilation or constriction, but unattached individuals experienced dilation. There was a significant difference between the two conditions in the predicted direction. All values are z-score standardized.

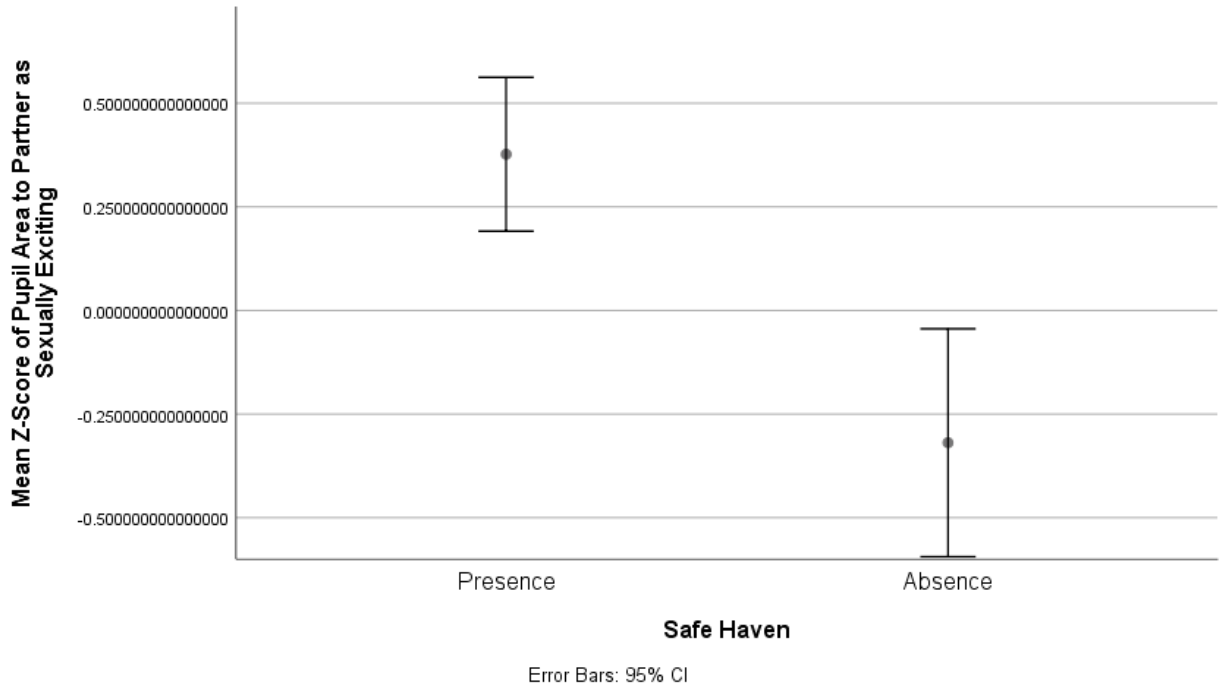


Figure 4. Average Standardized Pupil Area while Thinking of Partner Sexually to Safe Haven Presence and Absence. Participants' pupil area was recorded while thinking about their partner as someone who is sexually exciting. The participants exhibited significantly less pupil dilation (standard deviations above zero) to thinking about their partner sexually when they did not list their partner as someone they would immediately contact if something bad happened.

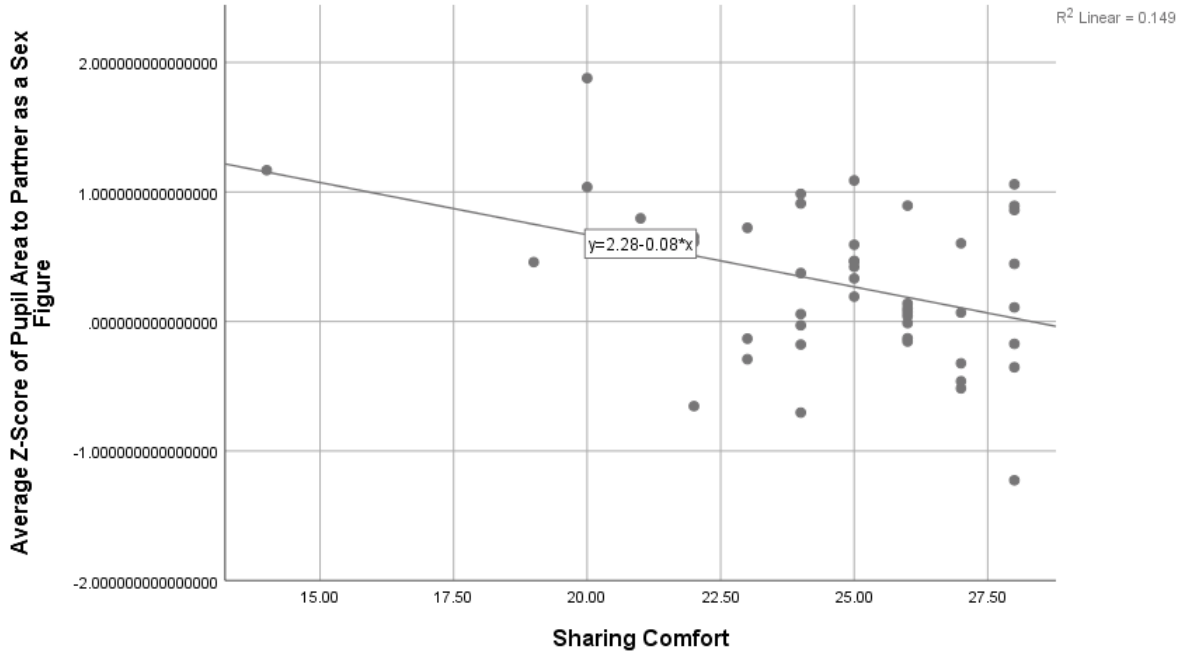


Figure 5. Correlation of Standardized Pupil Area while Thinking of Partner Sexually and Comfort in Sharing Personal Items. Participants' pupil area was recorded while thinking about

their partner as someone who is sexually exciting. The participants exhibited significantly less pupil dilation (standard deviations above zero) to thinking about their partner sexually as their comfort in sharing personal items such as food, soap, and the bathroom increased.

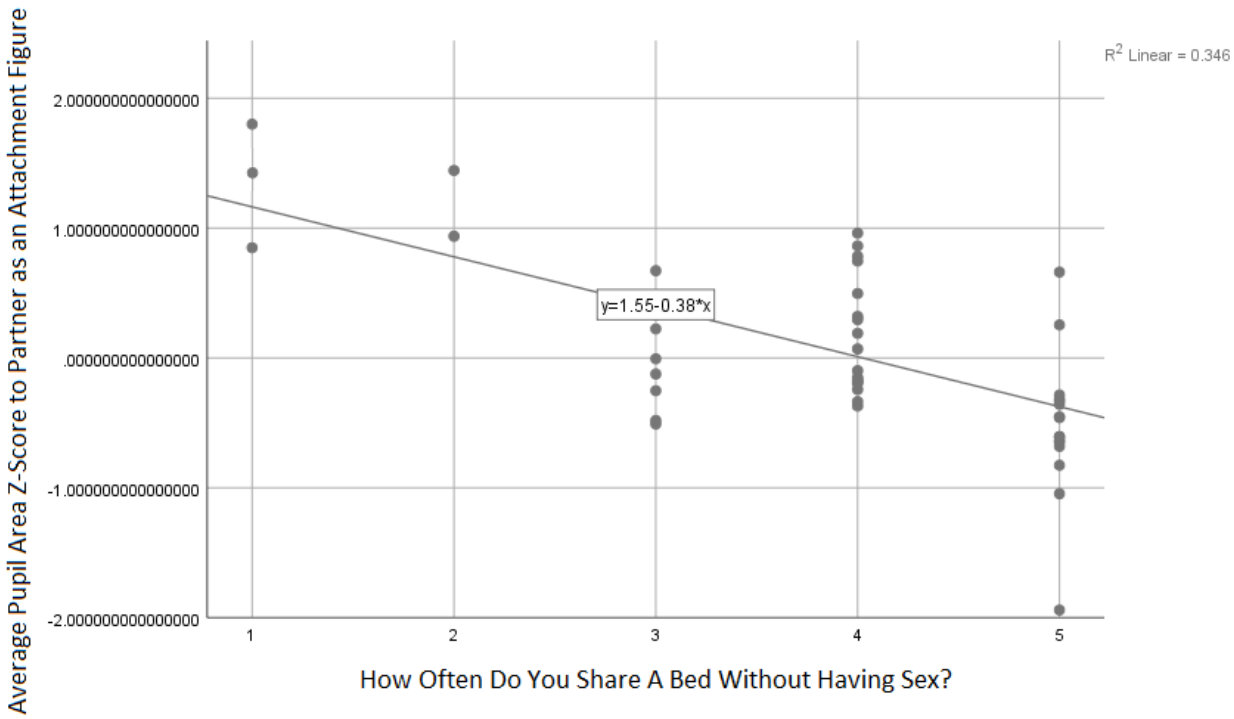


Figure 6. Standardized Pupil Area while Thinking of Partner as an Attachment Figure by Sleeping Together Without Sex. Participants' pupil area was recorded while thinking about their partner as an attachment figure. The participants who slept together with their partner without having sex exhibited significantly greater pupil constriction (standard deviations below zero) to thinking about their partner as an attachment figure than those who did so less often.

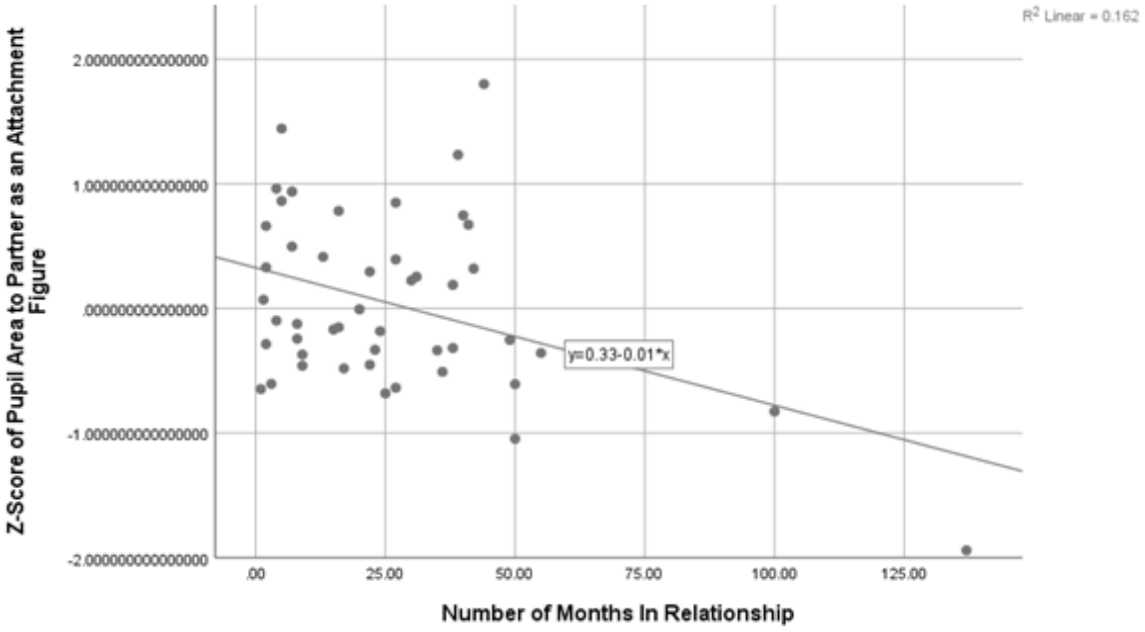


Figure 7. Standardized Pupil Area while Thinking of Partner as an Attachment Figure over Months in a Romantic Relationship. Participants' pupil area was recorded while thinking about their partner as an attachment figure. The participants exhibited significantly greater pupil constriction (standard deviations below zero) to thinking about their partner as an attachment figure with greater relationship length.

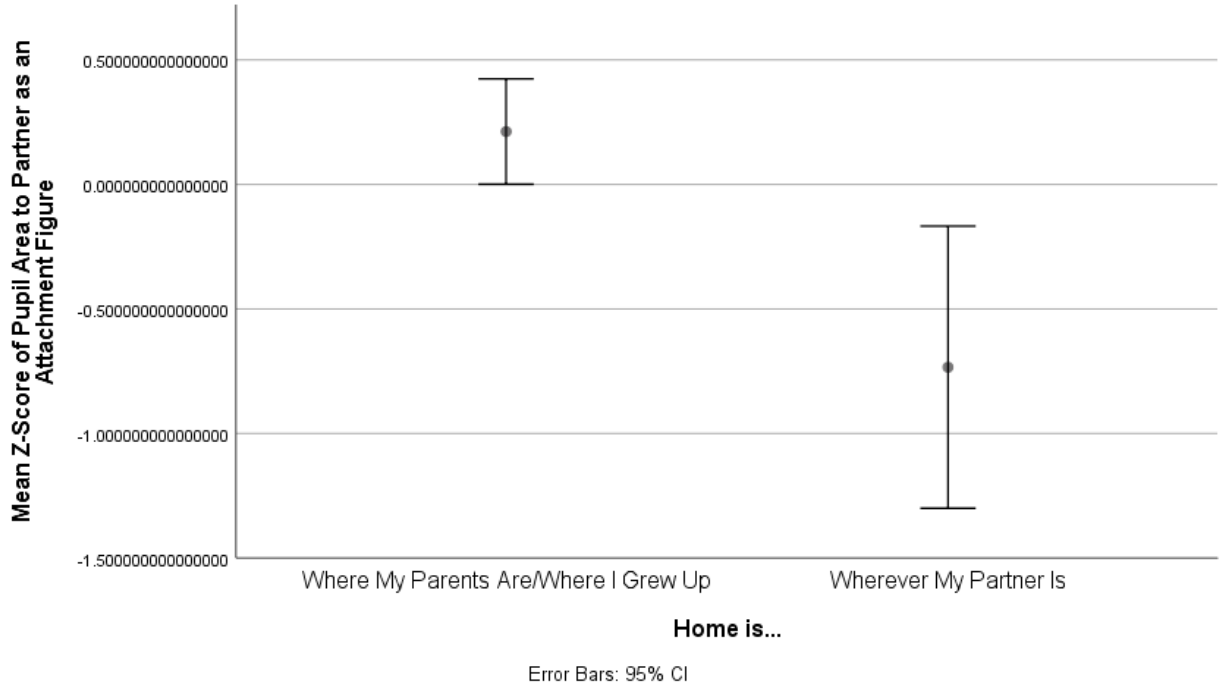


Figure 8. Plot of Standardized Pupil Area to Interpersonal Conceptualization of Home. Participants' pupil area was recorded while thinking about their partner as an attachment figure. The participants who endorsed the statement that their partner was "home" exhibited significantly greater pupil constriction (standard deviations below zero) than those who thought of their parents or birthplace.

Chapter 3 Appendices

Appendix A.

Relationship Closeness Questions.

How often...

	Never	Rarely	Sometimes	Often	All of the Time
Do you sleep well when you share a bed with your partner?	○	○	○	○	○
Do you feel comfortable hanging out with your partner without talking to each other?	○	○	○	○	○
Do you spend time thinking about your partner when you are not together?	○	○	○	○	○
Do you express your thoughts when you and your partner disagree?	○	○	○	○	○
Do you feel excited when you think about your partner?	○	○	○	○	○
Do you say loving things to your partner?	○	○	○	○	○
Do you share a bed with your partner without having sex?	○	○	○	○	○

In general, when you are in the company of your partner, how do you feel?

Comfortable	○ ○ ○ ○ ○ ○ ○	Self-conscious
Carefree	○ ○ ○ ○ ○ ○ ○	Worried
Relaxed	○ ○ ○ ○ ○ ○ ○	Anxious
Satisfied	○ ○ ○ ○ ○ ○ ○	Craving
Content	○ ○ ○ ○ ○ ○ ○	Nervous
Calm	○ ○ ○ ○ ○ ○ ○	Excited

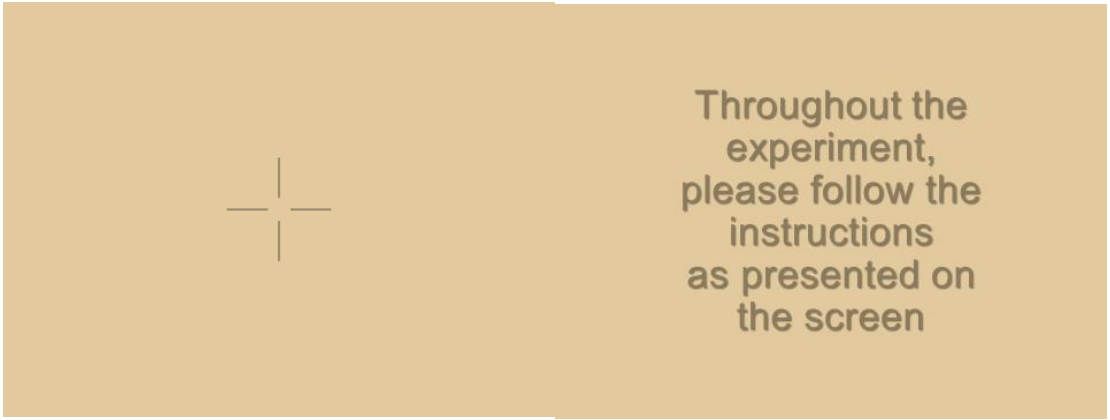
The degree to which we are comfortable sharing with others depends on the nature of our relationship with them. How comfortable would you be sharing the following with your partner?

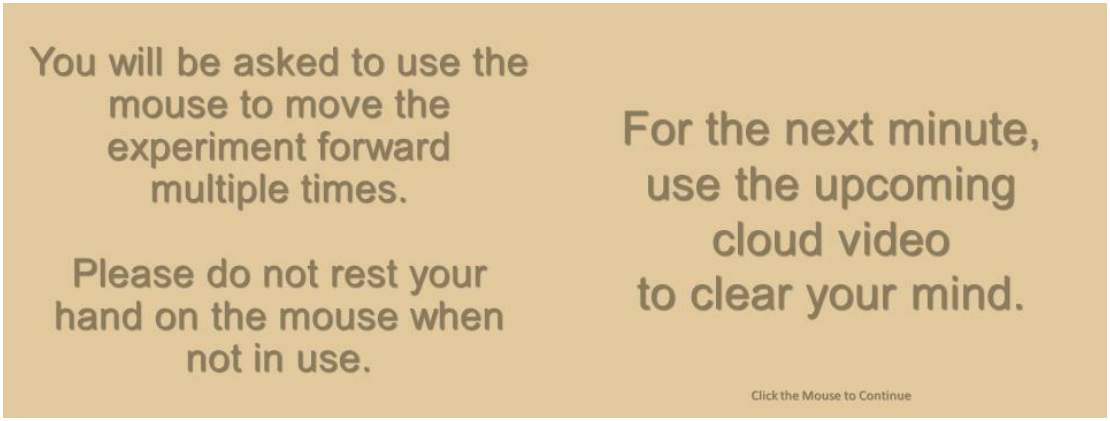
	Not at all	Somewhat	Mostly	Completely
A drink	○	○	○	○
A bath towel	○	○	○	○
A comb	○	○	○	○
A toothbrush	○	○	○	○
A plate of food	○	○	○	○
A bathroom	○	○	○	○
A bar of soap	○	○	○	○

"Home" is ...

- where my parents are/where I grew up.
- wherever my partner is
- Other (please specify):

Appendix B.





For the next two minutes
think about your partner as a
person you find sexually exciting

Click the Mouse to Continue

Memory

For the next two minutes
think about that time when you felt
socially rejected

Click the Mouse to Continue

Fantasy

For the next two minutes
think about that sexually exciting
fantasy

Click the Mouse to Continue

Chapter 4:

An Exploration of the Progression from Infatuation to Attachment in

Adult Romantic Relationships

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Abstract

Over time, romantic relationships evolve from the excitement and uncertainty of infatuation to the stability and comfort of attachment. Though significant work has been done, the transition from romantic infatuation to romantic attachment is still not well understood. This study endeavored to elucidate the likelihood and timing of this process, as well as individual differences that may affect it. 1,259 participants took a survey asking about the number of infatuations and attachments in their lifetime, as well as the length of the transition period between them. Participants also listed their current relationship length and noted whether this was an infatuation or an attachment. On average, people experienced approximately 6 infatuations, 3 of which became committed relationships, and 2 attachments in their lifetime, regardless of age. Taking these self-reported averages and assuming a progressive relationship trajectory, about 33% of infatuations and 67% of romantic relationships become attachments. Avoidantly attached men and anxiously attached women were less likely than average to move from infatuation to attachment. Additionally, these data supported the theory that the transition from infatuation to attachment occurs around 2 years ± 6 months, and, unlike other times in the relationship, this transition is characterized by concurrently feeling both attachment and infatuation. Additionally, high attachment avoidance, but not anxiety, significantly biases this transitionary period towards infatuation. This suggests the process of moving from infatuation to attachment is gradual. These data serve to better understand the process, timing, and likelihood of the transition from infatuation to adult attachment.

Keywords: Attachment, Infatuation, Relationship Length, Avoidance, Anxiety, Reward

Acknowledgements: Dr. Erika Mudrack

Introduction

Love takes many forms, from the ephemeral and fleeting to the everlasting. Similarly, experiences of romantic relationships shift and change throughout their progression. While every relationship is different and grows at its own pace, theories of relationship progression generally agree that the beginning of a relationship is more defined by excitement and passion, while later aspects of relationships are more akin to comfort and security (Tennov, 1979; Hatfield & Rapson, 1993; Fisher, 1998; Fisher et al., 2002; Marazziti and Canale, 2004; Wakin & Vo, 2008; Langeslag, Muris, & Franken, 2013; Fisher, Xu, Aron, & Brown, 2016). Nascent relationships are in a phase referred to as infatuation, limerence, or passionate love and exhibit a distinct symptomology of arousal, appetitive reward, emotional lability, and uncertainty (Hatfield & Rapson, 1993; Tennov, 1979; Fisher, 1998; Fisher et al., 2002; Wakin & Vo, 2008; Acevedo & Aron, 2009; Zayas, Merrill, & Hazan, 2015). As this relationship progresses, the intense feelings of infatuation decline (Tennov, 1979; Ahmetoglu, Swami & Chamorro-Premuzic, 2009). Not all romantic infatuations develop, but those that do evolve to a state of stability and trust. Long term adult romantic relationships possess the same defining features of attachment as infant-parent relationships: maintaining close contact, finding comfort, and growing the confidence to explore (Bowlby, 1979; Hazan & Shaver, 1994). This normative development in adult romantic relationships from excitement to comfort can be viewed as an attachment formation process (Hazan & Shaver, 1986; Hazan & Zeifman, 1999).

Though it varies greatly, the average duration of infatuation is theorized to be about two years, give or take six months—which corresponds to the average time it takes for an attachment bond to form (Tennov, 1979; Hazan & Zeifman, 1994; Fraley & Davis, 1997; Langeslag, Muris & Franken, 2013). Dorothy Tennov (1979) summarized the length of limerence, or infatuation,

to be between 18 and 36 months based on her many interviews with people in the early stages of love. An alternative hypothesis asserts that infatuation ends around 4 years (Fisher, 2016). This is based on the significance of 4 years as the point when most marriages end and the minimum amount of time a biparental strategy is preferable in human reproduction (Fisher, 2016). However, this 4 year divorce mark may actually be the end of limerence according to Tennov's (1979) timeline, plus the process of breaking up.

The shift from infatuation to attachment can also be affected by the individual's attachment style. Attachment styles were discovered by Mary Ainsworth (1973) and categorized as secure, avoidant, and anxious. Subsequently, Hazan and Shaver (1987) translated these attachment styles to adult romantic relationships. Attachment anxiety is characterized by worry and uncertainty about the partner and relationship, while attachment avoidance is characterized by a desire to avoid emotional closeness or reliance (Hazan & Shaver, 1987). Those with high attachment insecurity are more likely to seek out attachment relationships with romantic partners (Hazan & Zeifman, 1994). Additionally, those with high attachment anxiety are more likely to experience limerence (Feeney and Noller, 1990).

Though much work has been done on understanding both infatuation and attachment, the transition between them is less well understood (Zayas & Hazan, 2014; Zayas, Merrill & Hazan, 2015). The current study explored romantic relationship progression from an attachment process perspective. The main research questions of this exploration were: How many infatuations do people experience on average? How many infatuations become relationships? What is the average length of time before an infatuation becomes a relationship? What are the odds that an infatuation becomes an attachment? How many attachments do people experience on average? Does infatuation last approximately 2 years ± 6 months, 4 years, or a different amount of time

altogether? Is this process gradual or abrupt? Does attachment insecurity affect this timeline, the overall number of infatuations and attachments, or the likelihood of an infatuation becoming an attachment?

In order to best address these questions, the current study disseminated an exploratory survey to a wide cross-section of participants. The survey assessed the overall number of romantic infatuations and attachments, as well as the length of time each social bond took to move from infatuation to a romantic relationship and to move from infatuation to attachment, if it did so. This was investigated through both a retrospective approach inquiring about each participant's relationship history and a contemporary cross-sectional approach asking participants to classify their current romantic relationship. Both approaches were defined in terms of infatuation and attachment symptomology and experiences.

Method

Participants.

Participants in this study included 1,259 people above the age of 18, 959 participants recruited through snowball sampling via social media (Facebook and Twitter) and 300 male participants recruited through Amazon's Mechanical Turk system (MTurk). The study was advertised as a short relationship history survey. Participants who took the survey through social media were not compensated, but those males who participated on MTurk were compensated $2 for their time. The study lasted approximately 10 minutes. Participants who completed the entire questionnaire included 663 females and 442 males between the ages of 18 and 74 with a median age of 32. Approximately half (54%) of the sample identified as exclusively heterosexual and more than half (64%) identified as white/Caucasian. The majority of the sample (58%) was not at all or only a little bit religiously observant. More than half of the

participants lived in the United States (69%). Some of the other countries represented were India (9%), Canada (3%), the United Kingdom (2%), Australia (2%), Egypt (1%), and Belgium (1%). The study was only disseminated in English. More than half (69%) of participants were involved in a romantic relationship at the time of the study. Current relationship length ranged from 1 month to 672 months with an average length of 117 months and a median length of 72 months.

Materials.

Informed consent was obtained and all participants were knowledgeable about the benefits and risks of participating, voluntary participation, the purpose of the study, and contact information of the researchers before beginning. In the survey, participants were asked open-ended questions inquiring as to whether or not they had experienced infatuation, as it was described to them (see below), then the same was done for attachment. If participants endorsed having these experiences, they were asked approximately with how many different people they had experienced them. They were also asked how many infatuations became relationships, and how long this process took for each relationship listed. Likewise, they were asked, if any infatuations became attachments, how long this process took for each. Participants were also asked the length of their current relationship and asked to decide if this current relationship was an attachment, an infatuation, or an "other" option, which was open response, based on the provided descriptions.

Attachment and Infatuation Descriptions.

Participants were given descriptions of the "symptoms" associated with attachment and infatuation, referred to in the study as limerence.

"Here are a few of the most common "symptoms" of Romantic Limerence:

- *Being really excited when you are with this person*
- *Thinking about them all the time*

- *Constantly trying to figure out how they feel about you*
- *Experiencing strong mood shifts depending on whether they seem interested or not*
- *Feeling your heart race around them and an overall state of heightened arousal"*

This profile of infatuation was decided upon because it describes a combination of: excitement (a positive form of uncertainty), mental preoccupation and obsessive thinking, mood dependency, and physiological arousal. These facets of infatuation were decided upon based on the most common and overlapping symptoms presented in current scales attempting to measure infatuation, limerence, or passionate love (see for review Hatfield, Bensman & Rapson, 2012). The wording of the facets were adapted from a combination of items in the Passionate Love Scale (Hatfield & Sprecher, 1986), the Infatuation and Attachment Scales (Langeslag, Muris & Franken, 2013), the Wakin-Vo I.D.R. Model of Limerence (Wakin & Vo, 2008), and interviews conducted by Dorothy Tennov (1979). The aim of this list was to provide examples of the most characteristic experiences of infatuation, while still being understandable, relatable, and presented without jargon.

"Here are a few of the most common "symptoms" of Romantic Attachment:
- *Turning to them for comfort if you are upset*
- *Missing them during separations*
- *Knowing they are there for you if you need them*
- *Knowing they will always want the best for you*
- *Being relaxed when you are around the person and an overall state of calm and security"*

This profile of attachment was decided upon because it describes three of the defining features of attachment: separation distress, safe haven, and secure base (Bowlby, 1979). The fourth feature of attachment, proximity seeking, was not included due to its overlap with infatuation descriptions. The wording of these items was based on the WHOTO scale (Hazan & Zeifman, 1994; Fraley & Davis, 1997), a measure of attachment that is commonly used in attachment literature (see for review Mikulincer & Shaver, 2007). The last characteristic

focusing on calm and security is not taken from WHOTO terminology, but was chosen to convey facets of both safe haven and secure base while providing a direct opposite to the language used in the infatuation description.

Emotionally Close Relationships Scale – Short Revised (ECR).

Attachment avoidance and anxiety were determined using the partner-specific short, revised version of the Emotionally Close Relationships scale (Fraley, Heffernan, Vicary & Brumbaugh, 2011).

Reward Preferences.

Participants were given five forced-choice paradigms where they had to choose "In romantic relationships, which do you enjoy more?". Participants chose between two words where one related more strongly to consummatory reward (liking, gratification), while the other related more strongly to appetitive reward (wanting, desire). For example, "contentment or desire" and "calm or excitement". These questions were presented in a randomized order. The selections were then summed to create a scale where a high score indicated a relationship preference towards appetitive rewards.

Demographics.

Participants were asked to provide a number of demographics including sex, gender, age, sexual orientation, race, and country of current residence. Participants were also asked their lifetime number of romantic and sexual relationships.

Design and Procedure.

The research design of this study was exploratory and non-experimental aimed at better understanding the course of infatuation and attachment experiences throughout relationships. Components of the study asking about current relationships were cross-sectional, while

components of the study asking about past relationship experiences were both cross-sectional and retrospective. After obtaining informed consent, each participant filled out the survey using the Qualtrics web survey tool.

Data Cleaning.

Numbers of infatuations and attachments were input as numeric whole numbers and did not require data cleaning. However, the lengths provided for the time each infatuation took to become a relationship, the time each infatuation took to become an attachment, and the participant's current romantic relationship length were open-ended. These three questions were coded by research assistants into month intervals and then checked for agreement with a final research assistant. Answers that were deemed by the coders to be too vague, such as "a while", or uninterpretable, such as "I don't remember, maybe a few months?", were treated as missing data. People who answered the question about the time each infatuation took to become a relationship with simply "ongoing" or their current romantic relationship length were also treated as missing data. Answers that indicated multiple relationships for a specific length, such as "2 relationships took about 6 months and 1 took a year", were coded as multiple relationships of that length, which in this example case is: 6 months, 6 months, and 12 months.

Results

To understand the the likelihood of the transition from infatuation to attachment, we begin by examining the prevalence of infatuation and attachment in our sample. Every participant in the study had experienced romantic infatuation and romantic attachment at least once based on the provided descriptions. The mean number of infatuations was 6.03 (SD=10.8) with a median of 4 infatuations per person. There was no significant correlation between age $r(1054)$=-0.01, p=.62 or sex $t(1054)$=-1.07, p=.283, 95% CI [-2.62, 0.77] and the number of

infatuations. These data were highly skewed (8.22, *SD*=.07) with 1 infatuation as the lowest number and 155 infatuations as the highest number. The majority of the sample (92%) had 10 infatuations or fewer, with 3 being the most common answer (20%).

The mean number of infatuations that became relationships was 2.84 (*SD*=3.32) with a median of 2 infatuations becoming relationships. The minimum number was 0 and the maximum was 75 relationships. The majority of the sample (94%) had 6 infatuations become relationships or fewer, with the most common (26%) being 2 relationships. There was no significant correlation between age and the number of relationships stemming from infatuations $r(1054)=-0.01$, p=.64. However, women *(M*=3.07, *SD*=3.07) were significantly more likely to enter into a relationship from an infatuation than men (*M*=2.58, *SD*=4.46), $t(1054)=2.28$, $p=.023$, 95% CI [.07, .92]. This was a small effect Cohen's $d=.13$ (Cohen, 1988).

The mean number of attachments was 2.37 (*SD*=2.79) with a median of 2 attachments per individual. The minimum number of reported attachments was 0 and the maximum was 50. The majority of the sample (95%) had 5 attachments or fewer, with the most common (30%) being 2 attachments. There was no significant correlation between age and the number of attachments $r(976)=-0.03$, p=.41. However, men (*M*=2.96, *SD*=4.10) reported significantly more attachments than women *(M*=2.05, *SD*=1.54), $t(975)=-4.09$, $p<.0005$, 95% CI [-1.35, -.47]. This was also a small effect Cohen's $d=.29$.

To determine if there is any effect of attachment insecurity on the number of infatuations and attachments, a Poisson loglinear distribution generalized linear model was created with count data (number of infatuations) as the dependent variable, the average attachment avoidance and anxiety from the ECR as the covariates, and sex as a categorical factor. Sex was included as a factor due to the sex differences found in the number of attachments. There was no significant

main effect of sex or attachment avoidance on the number of infatuations. There was also no interaction between attachment insecurity and sex. However, there was a main effect of anxiety with more anxious people reporting slightly more infatuations $\beta = .06$, $\chi 2(1, N = 973) = 14.32$, $p < .0005$, 95% CI [-.06, .18].

Another model was created for the number of reported attachments. There was a significant effect of anxiety on the model $\beta = 1.47$, $\chi 2(1, N = 973) = 35.40$, $p < .0005$, 95% CI [.10, .19]. Participants with higher attachment anxiety reported a higher number of attachments. Those with higher attachment avoidance, however, reported fewer attachments $\beta = -.08$, $\chi 2(1, N = 973) = 5.02$, $p = .025$, 95% CI [-.14, -.01]. There was no interaction between sex and attachment avoidance, but there was an interaction between sex and attachment anxiety $\beta = 1.47$, $\chi 2(1, N = 973) = 20.44$, $p < .0005$, 95% CI [-.23, -.09]. Men, but not women, with higher anxiety reported more attachments (Figure 1).

Given the average number of infatuations reported was 6.03 and the average number of attachments reported was 2.37, the ratio of infatuations to attachments is approximately 39%. Assuming all infatuations have the potential to become an attachment and assuming the majority of romantic attachments begin with an infatuation phase, slightly more than 1/3 of the infatuations in this sample continued on to become attachments. However, it is possible that attachment insecurity or sex may bias this likelihood. To investigate this, a binary logistic generalized linear model for events/trials was created with the dependent variable being the number of attachments over the number of infatuations. Due to the mathematical capabilities of this test, participants who reported more attachments than infatuations (N=102, 8%) were removed for this analysis.

There was no main effect of sex on the attachment/infatuation ratio, but there was an interaction between sex and attachment anxiety $\beta = -.119$, $\chi 2(1, N = 866) = 12.40$, $p < .0005$, 95% CI [-.19, -.05] where higher anxiety is associated with a smaller ratio, and thus fewer attachments stemming from infatuations, than lower anxiety in women, but not in men. There is also an interaction between sex and attachment avoidance $\beta = -.131$, $\chi 2(1, N = 866) = 6.85$, $p < .009$, 95% CI [-.23, -.03] where higher avoidance is associated with fewer attachments stemming from infatuations in men, but not in women.

In addition to the number of infatuations, relationships from infatuations, and attachments, participants provided a timeline for each relationship listed. Participants listed the length of time from infatuation onset to the beginning of a relationship and the length of time from infatuation onset to attachment. This data was coded in months. For each participant an average relationship length was calculated for both: time from infatuation to relationship and time from infatuation to attachment. The mean of the average length of time for infatuation to become a relationship is 6.43 months (SD=11.94) with a median of 2.13 months. There was a minimum of 0 months for those who entered into a relationship immediately upon meeting their partner and a maximum of 120 months. The mean of the average length of time for infatuation to become an attachment is 9.40 months (SD=12.50) with a median of 6 months. There was a minimum of 0, for those who believed they became attached immediately or did not experience infatuation, and a maximum of 84 months.

Examining the correlates of these average lengths, age positively correlates with the length of time from infatuation to attachment r (839)=.069, $p<.05$, but negatively correlates with length of time from infatuation to a relationship $r(839)=-.064$, $p<.05$. Older participants reported a longer time from infatuation to attachment, but a shorter time for an infatuation to become a

relationship. The length to relationship $r(839)=.25$, $p<.0005$ and the length to attachment $r(840)=.12$, $p<.0005$ both positively correlated with religiosity, thus, more religiously observant participants recorded longer times before relationship or attachment formation than those who were less religiously observant. Attachment avoidance $r(941)=.119$, $p<.0005$ and attachment anxiety $r(941)=.173$, $p<.0005$ positively correlated with length from infatuation to beginning a relationship, meaning those with higher attachment insecurity reported waiting longer between the onset of infatuation and starting a relationship. There was no linear correlation between attachment insecurity and length of time from infatuation onset to attachment formation. However, there is a slight, significant, positive monotonic relationship between the length to attachment and avoidance $r(942)=.092$, $p=.007$ and anxiety $r(942)=.090$, $p=.009$. Using Spearman's rank-order correlation, a nonparametric correlation, allows the determination of a monotonic relationship, which indicates that as attachment insecurity increases, so does the time to attachment formation, though not necessarily in a linear fashion.

In addition to the average lengths, each relationship reported by each individual was also analyzed separately. With all of these taken into account, there are 2,495 reported relationships. Graphing the data by cumulative percent of the frequency allows for visual examination of the breaks in data (Figure 2). Next, Jenks Natural Breaks Optimization can split the large range of numbers into contiguous classes with minimized squared deviations. Based on the data visualization and best overall goodness of variance fit (GVF), the appropriate number of breaks appears to be 6 for both length types (Table 1).

In addition to retrospective data, participants also classified the attachment status and length of their current romantic relationships. Participants had the option to classify their relationship as an infatuation, an attachment, or something else that was open-ended. Those that

chose the other option primarily wrote either that they were no longer romantically interested in their partner or that they were experiencing both infatuation and attachment. For the purposes of exploring current relationship length, those who were experiencing romantic difficulties were treated as missing data and a third category, "Both", was included with infatuation and attachment classifications. These classifications were plotted against relationship length in Figure 3.

This data was then classified in a predictive decision tree model using a Chi-square Automatic Interaction Detector (CHAID) (Kass, 1980). This tool creates a multi-branching classification tree for non-normally distributed data, after which a merged Bonferroni adjusted p-value is calculated. The first CHAID tree was created with only participants who indicated their relationship was an infatuation or an attachment based on the provided description (Figure 4). A second CHAID tree was created including the third category of "Both" infatuation and attachment (Figure 5 and Figure 6). Covariates were introduced to the second tree to determine if they would lead to additional branching. All possible covariates were tested, but only two caused child branches in the CHAID tree: attachment avoidance and relationship reward preference. Attachment avoidance spit Node 3, from 13 to 36 months, into two child nodes of low and high avoidance $\chi^2(2, 173) = 23.53$, $p<.0005$ (Figure 5). In the high avoidance child node, these participants reported infatuation more and reported attachment and "both" less than in the low avoidance or parent nodes. Relationship reward preference, as determined through a sum of forced choice paradigms, split node 4, greater than 36 months, into two child nodes $\chi^2(2, 501) = 26.792$, $p<.0005$ (Figure 6). The child nodes represent a low score, or a more consummatory reward preference, and a high score, or a more appetitive reward preference. Those with an appetitive reward preference were less likely to classify their relationship of at

least more than 3 years as an attachment and more likely it as wholly or partly an infatuation than those who did not have this preference.

Discussion

This study sought to enhance our knowledge about romantic relationship progression from an attachment formation process perspective. While the average number of infatuations, 6, was substantial, participants in our sample had only one less attachment, 2, than they had infatuations that became romantic relationships, 3. Though this seems like a small difference, this still equates to romantic relationships only becoming attachments 2/3 of the time. These data indicate that, though people may have many infatuations, the majority of defined romantic relationships result in attachment formation based on self-reported experiences.

Age did not affect the number of infatuations, relationships, or attachments in this sample, and therefore available time with which to pursue romantic options was not a significant factor. This is most likely because attached partners are likely to stay together for a long period of time, and therefore, there would be no marked increase in the number of romantic attachments between 40 and 60 years of age, for example.

Though age did not affect the number of infatuations, sex and attachment insecurity did. While men and women experienced infatuation at the same rate, women were more likely to move from infatuation into a romantic relationship than men. However, men were more likely to classify past relationships as attachments. Participants with more attachment anxiety reported slightly more infatuations, supporting Feeney and Noller's (1990) earlier findings, and a higher number of attachments. Specifically, men with high attachment anxiety reported the most

attachments (Figure 1). Contrastingly, participants with higher attachment avoidance reported fewer overall attachments.

Both higher attachment anxiety in women and higher attachment avoidance in men significantly reduced the attachment to infatuation ratio. These two ratio reductions are coming from different sides, however. Higher anxiety women reduce the ratio by reporting more infatuations but also the average number of attachments, thus increasing the denominator without changing the numerator, while higher avoidance men reported fewer attachments and the average number of infatuations, thus decreasing the numerator without changing the denominator.

Attachment insecurity was also correlated with waiting longer to begin a relationship with an infatuation, similar to the more religiously observant participants in the sample. Interestingly, age did affect the relationship progress lengths, though not the overall number of instances. Older participants reported a longer time from infatuation to attachment, but a shorter time for an infatuation to relationship, which may be the result of relationship norms during different time periods, as there were 60 years separating the oldest and youngest participants in the sample. Additionally, the marriage rate has been declining for young adults in the United States (Gould & Paserman, 2003).

The breaks created by the Jenks Natural Breaks Optimization (Table 1) are heavily weighted towards nascent relationship experiences. The vast majority of evolving infatuations became a romantic relationship within 4.5 months and 91% of infatuations become relationships within the first year and a half. Notably, a break in both the time to relationship and time to infatuation optimizations is between 18 months and approximately 3 years, almost identical to the period in which limerence ends as presented by Dorothy Tennov (1979). However, the majority of participants reported a move to attachment within 4 months. Interestingly, many

participants who put zeroes or almost immediate transitions reported feeling that they did not experience infatuation at all. An area for future research could be to examine those who did not experience infatuation before attachment or why a person would be inclined to report that attachment occurred immediately.

The current relationship data also showed a bias towards early relationship experiences. This may be due to the self-report nature of the measure, however, whether this is more due to infatuation fading or attachment appearing is unclear and an area for future research. When splitting the sample into only those classified as infatuation or attachment (Figure 4), the splits are concentrated around whole numbers and are highly skewed towards the beginning of the relationship: 5 months, 1 year, and 5 years. This does not align with any current understanding of the infatuation to attachment trajectory, but does again indicate that many participants classified their relationship as an attachment over an infatuation even at fewer than 5 months. However, when adding in the third category of "both" infatuation and attachment the tree changes substantially (Figures 5&6). Again, many participants classified their relationship as an attachment early on, but with the inclusion of three classifications, the nodes changed to: 6 months, just over a year, and 3 years.

Node 3, from 13 months to 3 years, is the only node with a substantial population of people classifying their relationship as both infatuation and attachment. This was not an automatic option in the measure, but instead participants felt conflicted enough to write in this answer. These participants overwhelmingly fall into the node that is approximately the same as Dorothy Tennov's 18 to 36 month timeline, and Figure 3a illustrates that those who classified their relationship as both infatuation and attachment were almost exclusively between 1 and 3 years. This also roughly supports the 2 years ± 6 month timeline based on attachment theory

(Hazan & Ziefman, 1994). Therefore, these data support current theories that the transitionary period of infatuation waning and attachment increasing is focused loosely around 2 years. However, this transitionary period was skipped when looking only at romantic attachment and infatuation classifications. The importance of the "both" classification emphasizes that this transition is not rapid, but gradual, and that aspects of both infatuation and attachment are experienced concurrently during this period. Further research should investigate which aspects of infatuation and attachment overlap and focus on the microcosm of this period as being distinctive from other relationship phases.

This infatuation to attachment transitionary period was also affected by attachment avoidance (Figure 5). The node was split into high and low attachment avoidance, illustrating that those with low avoidance predominately classified their relationship as an attachment or in transition, while those with high avoidance were substantially more likely to classify their relationship as an infatuation. People with high avoidance were less likely to indicate attachment or transition. This is most likely related to a desire to avoid emotional closeness and vulnerability, as well as the reduced overall number of reported attachments.

Finally, the tree was also split in Node 4 (Figure 5), more than 3 years, by a measure indicating a preference for appetitive reward in relationships, such as desire, novelty, and excitement. In this last node, where 93% of participants classified their relationship as an attachment, participants who had a preference for appetitive rewards in their relationship (a high score), were much less likely to classify their relationship as an attachment, and more much likely to indicate that they were infatuated or felt both. In Figure 3b we can see there are a few outliers who, in decades long relationships, experienced infatuation symptoms in some form. It is possible that this classification has identified people who are experiencing long term

passionate love (Acevedo & Aron, 2009). Future studies should examine how this reward preference may affect long term relationship experiences, or conversely, how those experiences may affect reward preference.

Additional future studies should examine this transition period longitudinally to further break down the attachment formation process in adults. Using big data, such as social media or dating websites, to "diagnose" people's relationship stages would bypass issues with self-report and allow for a large sample size. Finally, future research should seek to examine the likelihood and timing of the transition from infatuation to attachment in other cultures. We know that there are significant differences in experiences of passionate love cross culturally, so it is possible likelihoods and timing would also differ (Hatfield & Rapson, 2005; Hatfield, Rapson, & Martel, 2007).

Understanding the progress of the evolution from infatuation to attachment, and the individual factors that affect it, further elucidates the process of adult attachment formation. These data serve both confirmatory purposes for the extant attachment literature and foundational purposes for the future study of infatuation and adult attachment formation.

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Chapter 4 Tables and Figures

Table 1. Jenks Natural Breaks Optimization of Infatuation to Relationship Length and Infatuation to Attachment Length. This statistical technique splits a range of numbers into classes that hang together. The model can be validated based on how close the Goodness of variance fit (GVF) is to 1. Six breaks were created for each length type. The lower and upper are the earliest and latest months in each class between breaks. The count displays how many participants are in each class.

Infatuation to Relationship Lengths

Jenks Natural Breaks Optimization			
class	lower	upper	count
1	0	4.5	1690
2	5	15	403
3	18	30	94
4	36	48	61
5	60	84	32
6	96	180	9
GVF	10949.64	375564.1	0.970845

Infatuation to Attachment Lengths

Jenks Natural Breaks Optimization			
class	lower	upper	count
1	0	3.5	653
2	4	8	360
3	9	15	197
4	18	30	112
5	33	60	65
6	72	120	10
GVF	8747.277	259076.4	0.966237

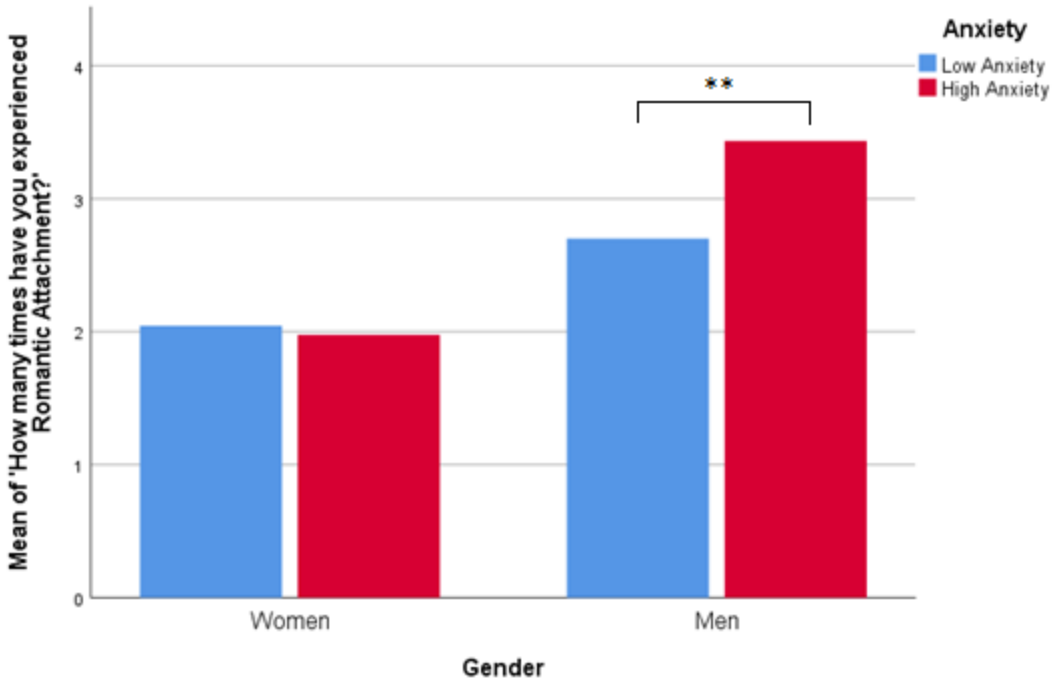

Figure 1. Interaction Effect of Sex and Attachment Anxiety on Total Number of Romantic Attachments. In this sample, men, on average, experienced more romantic attachments than women. However, men with high attachment anxiety, as determined by the ECR, report significantly more romantic attachments than either low anxiety men or women.

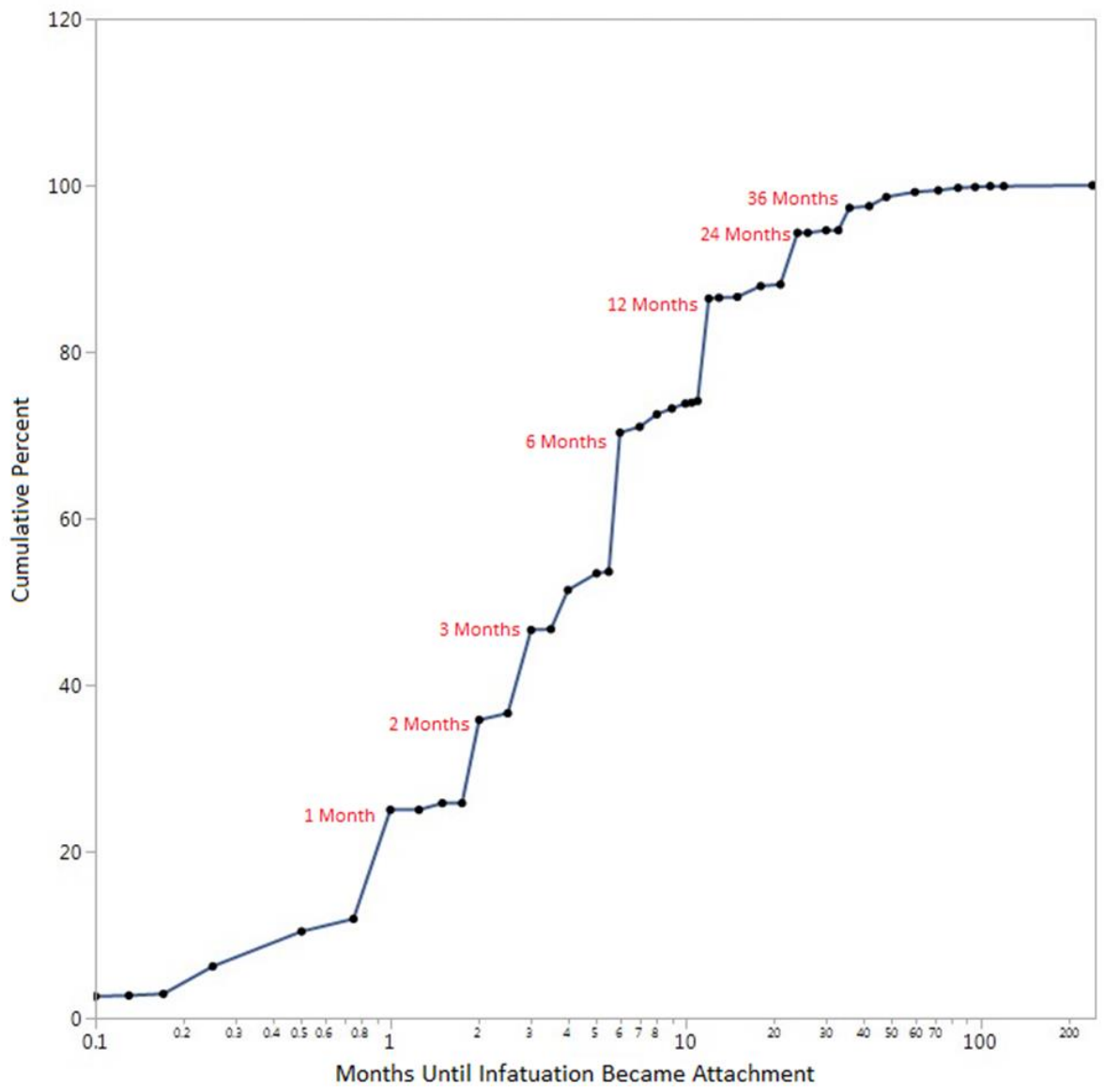

Figure 2. Plot of Cumulative Percent of Frequency By Months from Infatuation Onset to Attachment Formation. Graphing the amount of participants who reported each length from infatuation onset to attachment formation enables the visualization of large percentage jumps in the data. Many participants rounded, and as such, there are large jumps at round numbers. There are 6 large jumps and 1 smaller jump from 24 months to 36 months. The scale of months is not equally spaced. More than half of participants reported feeling attached within 6 months of infatuation onset.

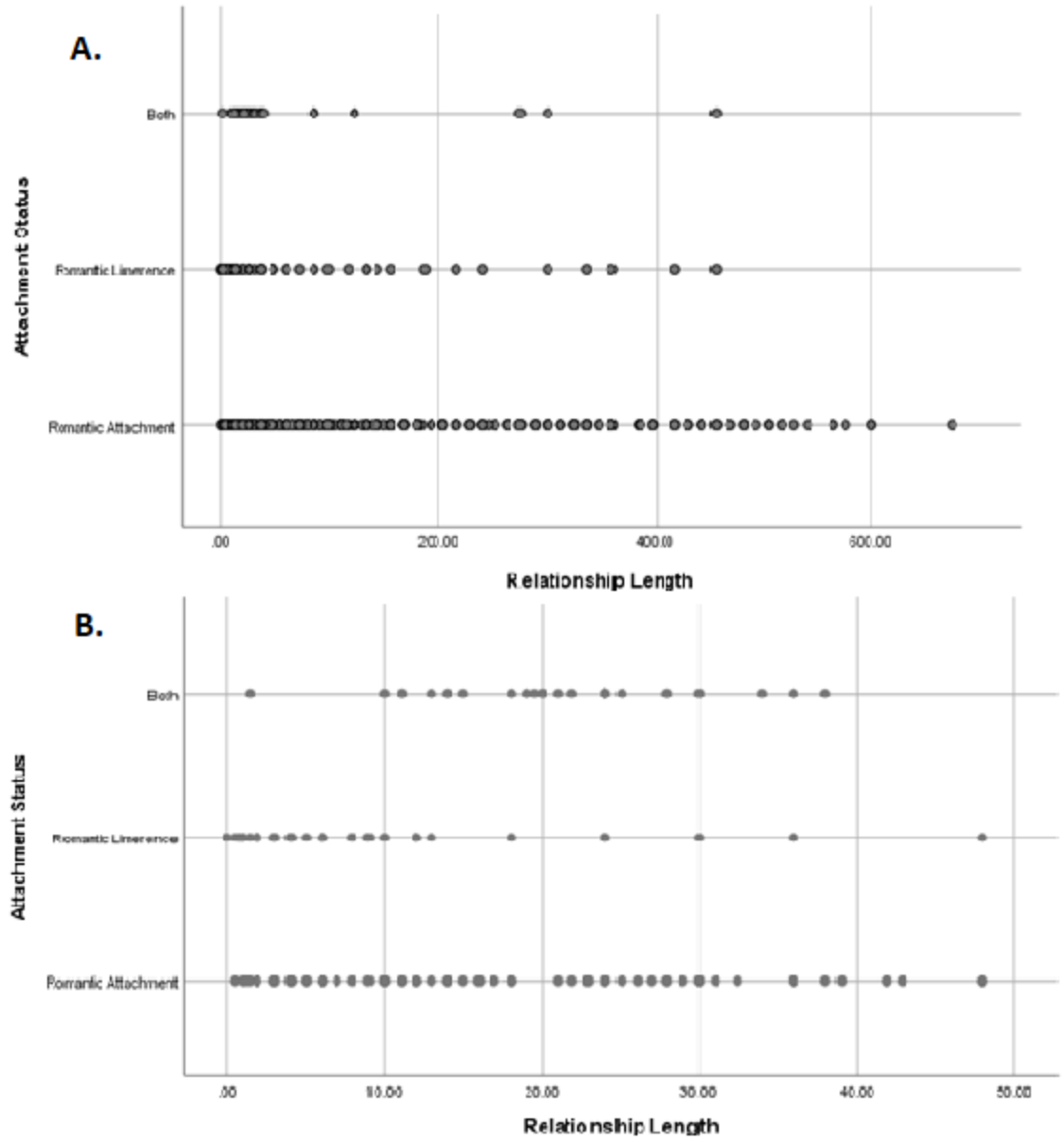

Figure 3. Self-Reported Attachment Status along Relationship Length. Plot A is the entire range of relationship length, but as there are some outliers in decades long relationships, Plot B is a closer look at the majority of the data between 0 and 50 months. Romantic attachment classifications are on the bottom row, romantic infatuation classifications are on the middle row, and concurrent infatuation and attachment classifications are on the top row. The romantic attachment is dispersed throughout the range of relationship lengths, but romantic infatuation (or limerence) is concentrated early in relationships. With the exception of a few outliers, people who endorse feeling both infatuation and attachment simultaneously are concentrated to between 10 months and 36 months.

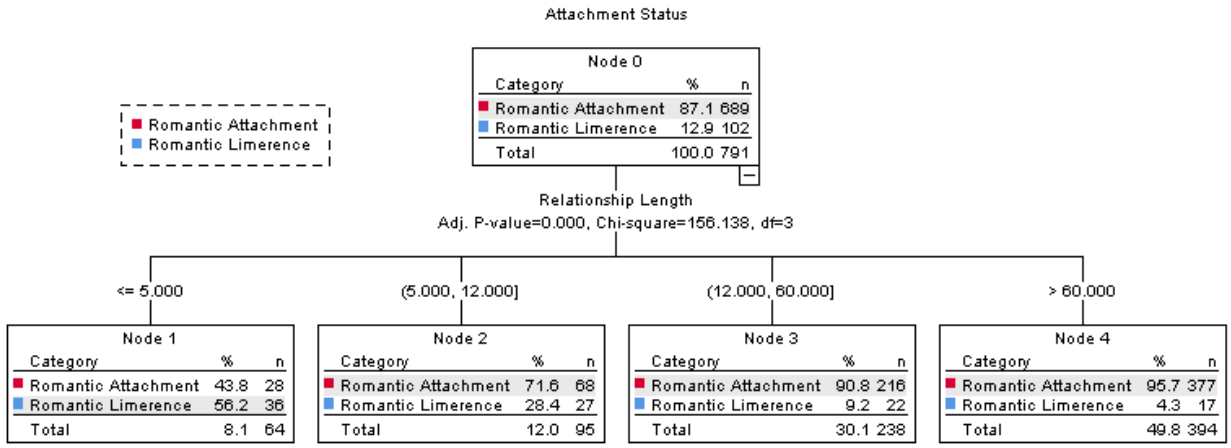

Figure 4. Self-Reported Attachment Status along Relationship Length. CHAID Classification tree branched into 4 nodes representing equal to or less than 5 months, between 5 months and 1 year, between 1 year and 5 years, and more than 5 years. This decision tree only includes romantic attachment and romantic infatuation (limerence). It does not include the classification of simultaneously endorsing both attachment and infatuation. Romantic infatuation only holds the majority in node 1, and by node 4, 95.7% of participants classify their relationship as romantic attachment.

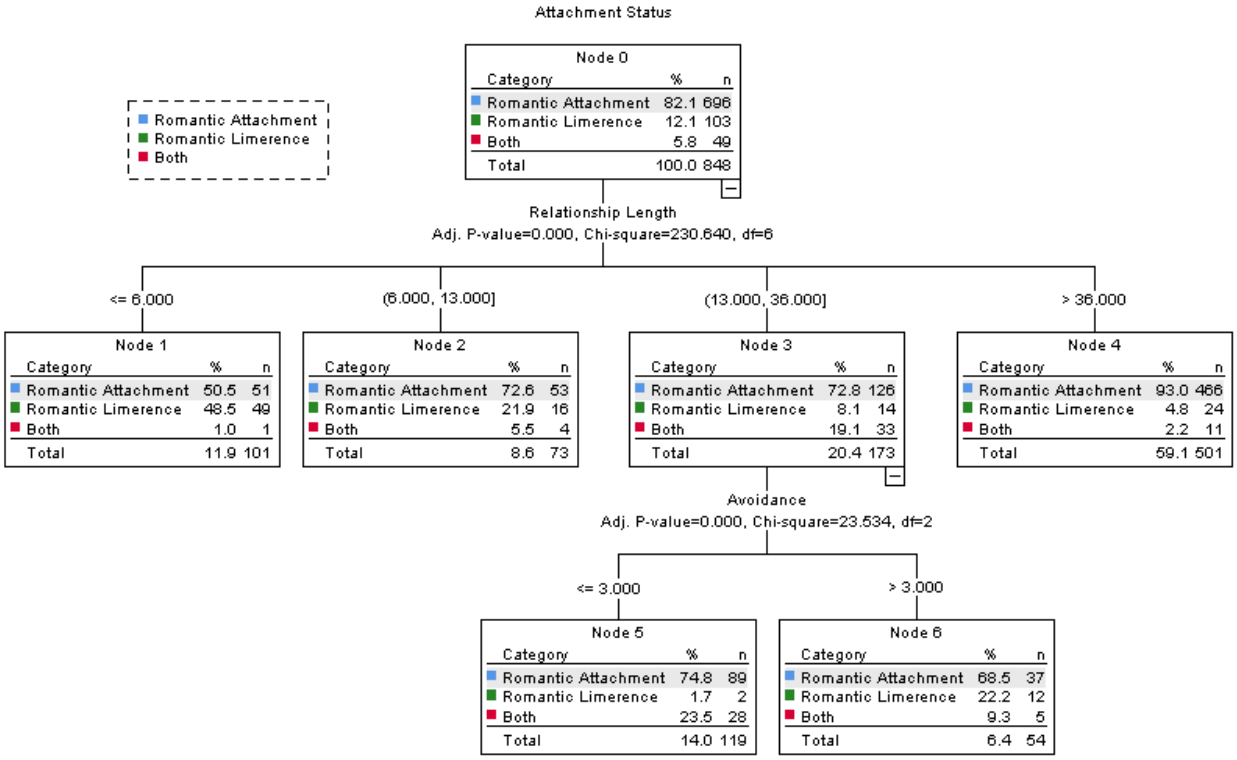

Figure 5. Self-Reported Attachment Status along Relationship Length with "Both" and Attachment Avoidance. CHAID Classification tree branched into 4 nodes representing equal to or less than 6 months, between 6 months and just over 1 year, between just over 1 year and 3 years years, and more than 3 years. This decision tree includes romantic attachment, romantic infatuation (limerence), and simultaneously endorsing both attachment and infatuation classifications. Node 3, from just over 1 year to 3 years, has 2 child nodes for high (>3) and low (<=3) attachment avoidance (based on ECR score). High attachment avoidance participants reported more romantic infatuation classifications in node 3 than low attachment anxiety participants.

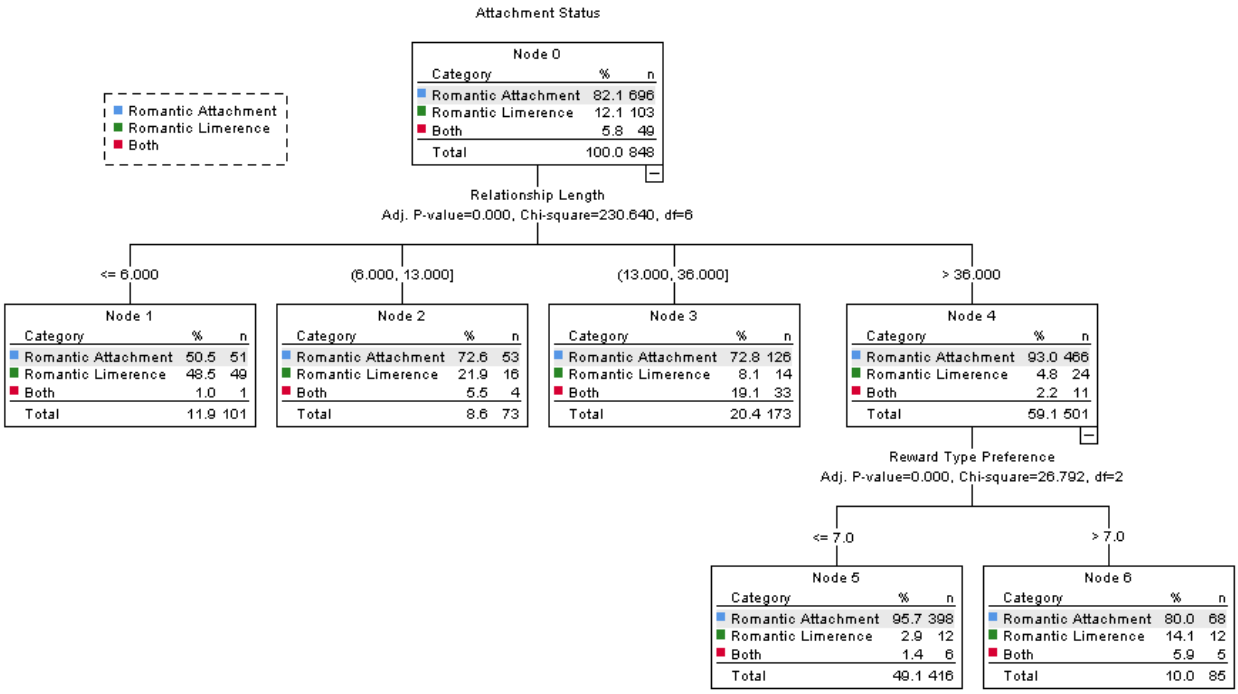

Figure 6. Self-Reported Attachment Status along Relationship Length with "Both" and Relationship Reward Preference. CHAID Classification tree branched into 4 nodes representing equal to or less than 6 months, between 6 months and just over 1 year, between just over 1 year and 3 years, and more than 3 years. This decision tree includes romantic attachment, romantic infatuation (limerence), and simultaneously endorsing both attachment and infatuation classifications. Node 4, over 3 years and beyond, has 2 child nodes for appetitive (>7) and consummatory (<=7) relationship reward preference (based on forced-choice scale sum). Participants with an appetitive relationship reward preference reported less romantic attachment classifications in node 4 than consummatory reward preference participants.

Chapter 5: Summary

This dissertation presented a neurochemical theory of the transition from infatuation to attachment in adult romantic relationships, an empirical study of pupil area as a marker for attachment and normative relationship progression, and an exploratory survey of the timing and circumstances of the transition from infatuation to attachment. Taken together, these works illuminate the period of attachment formation in adults. First, the large exploratory survey confirmed the previous findings that infatuation lasts about 2 years, plus or minus 6 months, as well as the findings that attachment takes about 2 years, plus or minus 6 months, to form. This period from about 18 to 30 months is unique among other periods of relationship progression in that it is a phase marked by the gradual transition from infatuation to attachment symptoms. This indicates that this change is quantitative, dimensional one, as opposed to a qualitative and categorical. There may be other, additional phases that should be looked to in adult attachment formation as well, specifically between 0-6 months and 6-13 months. Additionally, the likelihood of an attachment being formed from an infatuation is about 33%, and this likelihood is affected by attachment insecurity, which affects men and women differently.

Secondly, the neurobiological explains how the neurobiological shift from attachment may occur based on symptoms of each relationships phase and how this shift may affect the likelihood of an eventual full-fledged attachment from being formed. This theory proposes that infatuation and attachment are characterized by different rewards and neurochemical interactions that underlie their unique symptomologies. Specifically, infatuation is characterized by high dopaminergic activity and the appetitive reward system, while attachment is characterized by high opiate activity and the consummatory reward system. This is accomplished because of oxytocin's unique ability to bias the reward system away from novelty and towards familiarity

through interacts with endocannabinoid heterodimers. Oxytocin biases dopaminergic activity towards D2 receptors and the indirect pathway interaction with ventral pallidum, reducing D1 receptor in the nucleus accumbens shell and GABA disinhibition of the ventral pallidum. This allows for the prefrontal cortex to create connections with mu-opiate receptors instead of D1 receptors in the nucleus accumbens shell and encode an opiate-dependent social reward. This reward, unlike dopaminergic activity, does not habituate over time because oxytocin, through interaction with MOR-CB1 heterodimers in the ventral pallidum, ventral tegmental area, and caudate-putamen, is able to prevent opiate receptor internalization, and thus, opiate tolerance. Since oxytocin does not have this effect on dopamine, however, D2 receptors in the reward system, specifically the nucleus accumbens shell, will internalize and be downregulated due to continuous activation. Meanwhile, through homeostatic compensation, the under-used D1 receptors will propagate, and the dopamine from novelty and predictive error will cause kappa-opiate release and aversion. This may be a mechanism to maintain pair bonds by making other potential partner less attractive, and it may also be to prevent an attachment bond from being formed with an unpredictable and unreliable partner. This theory provides a foundation for an extensive program of research.

One of the potential studies built on this framework was conducted. Participants' pupil area was examined while thinking of their partner generally, as an attachment, and as someone sexually exciting. We found that pupil area change to mental representations did, in fact, act as a relationship marker. Specifically, a lack of pupil dilation acted as a marker for secure base and separation distress functions for the partner. Additionally, thinking of the partner as an attachment figure, specifically, illustrated relationship progression differences such as relationship length, thinking of the partner as home, and comfort disagreeing with them. This

may be an indication of the relationship partner's efficacy as an attachment figure, as well as normative relationship progression, which provides a basis for even further studies.

This work was not without limitations, however, and one future undertaking will be to replicate this work in larger and more diverse samples and possibly with linked partner dyads. To further validate the theoretical framework put forth would be the addition of another supporting variable, such as measuring prolactin levels. The hormone prolactin has been almost exclusively studied in infant attachment, yet could, in a uniquely effective way, provide insights into adult relationship formation. While more prevalent in biological females, prolactin is a universal hormone that can cross the blood brain barrier, making serum measurements reliable indicators of neural activity. Importantly, prolactin is gated by D2 dopamine receptor activity, and, in lab studies, more than 50% of D2 receptors must be occupied by antagonists for prolactin levels to increase. Therefore, prolactin can serve as a peripherally measurable index of central D2 dopamine receptor occupancy, which has already proven to be necessary in prairie vole pair bond formation. Additionally, prolactin has a direct negative effect on gonadotropin releasing hormone, and therefore a negative effect on sexual desire, which has been shown to increase initially and decrease as relationships develop. Finally, prolactin, as researched in breastfeeding, contributes to homeostatic co-regulation, an important component of attachment relationships that I believe is highly affected by sex. Therefore, two future possibilities would be to concurrently measure pupil dilation, as a marker of dopaminergic activity, and blood levels of prolactin in order to determine D2 receptor activity, specifically, while another would be to examine if the role that lactation plays for bonding between nursing mothers and their infants is the same as for the bonding between two sexual partners.

There are numerous studies that could come from this foundation of work in the future. For example, investigating sex hormones as a biological marker of attachment; how basal differences in oxytocin, vasopressin, prolactin, testosterone, and serotonin may lead to sex differences in relationship formation experiences; the effect of SSRIs on the attachment formation process; separations and changes in homeostatic coregulation; pupillometry measurement of asexual relationships that lack or have reduced appetitive sexual reward; the effect of intranasal oxytocin administration on memory formation for sexually relevant stimuli; comparing vagal tone in mothers who are and are not nursing; loudness dependence of auditory evoked potentials to measure serotonergic functioning during relationship formation; the biological validation of commonly agreed upon rules in sexually open relationships; possible effects of marijuana on cannabinoid-opiate and cannabinoid-dopamine heterodimers in relationship formations and dissolutions; using event-relate potentials to measure error negativity and error positivity to indicate changes in cognitive control and performance during different relationship phases; and cognitive and hormonal reactions to break-ups and rebound sex using an addiction model. All of these potential studies have clear theoretical bases in neurobiological, cognitive, evolutionary, and social findings and have direct application to healthily forming, maintaining, and ending relationships. This research provides an architecture for the empirical and interdisciplinary study of the relationship between love and sex.in, the frequency and quality of partners' sexual relationships. This work has formed an underpinning for a rich future program of research to better understand the transition from infatuation to attachment in adult pair bonds.