A Dynamic Systems Model of Infant Attachment

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***Abstract*—Attachment, or the emotional tie between an infant and its primary caregiver, has been modeled as a homeostatic process by Bowlby's (*Attachment and Loss*, 1969; *Anxiety and Depression*, 1973; *Loss: Sadness and Depression*, 1980). Evidence from neurophysiology has grounded such mechanism of infant attachment to the dynamic interplay between an opioid-based proximity-seeking mechanism and an NE-based arousal system that are regulated by external stimuli (interaction with primary caregiver and the environment). Here, we model such attachment mechanism and its dynamic regulation by a coupled system of ordinary differential equations. We simulated the characteristic patterns of infant behaviors in the Strange Situation procedure, a common instrument for assessing the quality of attachment outcomes ("types") for infants at about one year of age. We also manipulated the parameters of our model to account for neurochemical adaptation, and to allow for caregiver style (such as responsiveness and other factors) and temperamental factor (such as reactivity and readiness in self-regulation) to be incorporated into the homeostatic regulation model of attachment dynamics. Principle component analysis revealed the characteristic regions in the parameter space that correspond to secure, anxious, and avoidant attachment typology. Implications from this kind of approach are discussed.**

***Index Terms*—Adaptive systems, behavioral science, developmental psychology, emotion, feedback systems, personality, temperament, self-regulation.**

I. Introduction

BOWLBY'S [7]–[9] theory of attachment is a complex and thorough synthesis of ethological and control systems perspectives that modernized the psychoanalytic view of the infant-caregiver bond [38]. The ethological perspective is used to explain the origins of the attachment mechanism in terms of evolutionary adaptation: attachment behavior offers infants a survival advantage, protecting them from danger and ensuring accessibility of the caregiver. Control systems theory provides a functional language with which to describe the mechanism of attachment: the attachment system is a homeostatic system regulating proximity with the caregiver (the "set goal") and operating through feedbacks in the form of "felt security." Because very little information about physiological processes was available when his theory was formulated, Bowlby focused only on ethological and functional explanations.

Since that time, there has been an explosion of inquiries into neurophysiological correlates of attachment variables. Especially suggestive from the control systems perspective are a number of studies relating fluctuations in opioid and arousal activity levels to changes in attachment and exploration behaviors over time (see, e.g., [52], [66], [94], and [77]), and . These studies suggest the possibility of homeostatic regulation models based on interactive neurochemical systems, where attachment dynamics (i.e., changes in attachment behaviors over time in response to characteristics of the environment and caregiving) emerge from innate mechanisms of neurophysiological regulation. Moving neurophysiological regulation to center stage allows data from neurophysiological studies of humans and primates to both constrain and inform, at least heuristically, theories and models of attachment dynamics.

According to this view, attachment can be seen simply as one of many diverse and interlocking mechanisms of physiological regulation (e.g., [60], [63], [78], and [79]). Moreover, neurophysiological responses to both social and nonsocial environmental stimuli are understood as key components of the mechanism underlying attachment dynamics. This is a key assumption in the study of infant temperament (see [70]), where neurochemical and neurophysiological responses to environmental and caregiving stimuli are examined in relation to attachment and its mechanisms. Two typical variables that are examined in temperament research are reactivity (the degree to which the infant's physiological systems respond to changes in the environment) and self-regulation (the degree to which the infant is able to reattain equilibrium after a disruptive event) ([40], [68], [69]). These variables are usually examined in terms of the influence that environmental stimuli have on measures such as heart rate or cortisol, and how individual differences correlate with differences in attachment dynamics (e.g., [21], [22], [32], [50], [55], [61], [72], and [82]). What is suggested by this line of research, but has not yet been attempted, however, is a synthesis in which an explicit homeostatic model of attachment dynamics is framed in a neurophysiologically plausible context.

In the sections that follow, we will present such a model, framing attachment dynamics as a product of joint regulation of opioid and arousal systems. The model is consistent with neurophysiological data in both humans and other mammals, and can account for certain human behavioral data, such as Braungart and Stifter [10], Connell [17], and van Ijzendoorn *et al.* [98]. By incorporating a very simple mechanism of neurochemical adaptation, the model is also able to account for the development of individual differences in temperament and attachment dynamics, in a way roughly consistent with existing views on the development of temperament over time (e.g., [68] and [69]). Moreover, we specify our model mathematically as a dynamic systems model [16], [49], [75], [87], [95]–[97]. By their nature, such models are simplified and exploratory, but can be useful in uncovering novel predictions that arise from dynamic mechanisms and their interactions, and that otherwise are not immediately obvious [96]. By identifying and isolating important features of a phenomenon rather than trying to model it in its natural

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Manuscript received March 02, 2009; revised October 22, 2009. First published December 8, 2009; current version published February 05, 2010.

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Digital Object Identifier 10.1109/TAMD.2009.2038190

complexity, one may examine the ways in which simplified theoretical mechanisms can give rise to complex and “emergent” [100] predictions not built into the model’s assumptions [92], [93], [97]. This is the motivation behind our mathematical modeling of the dynamics of infant attachment.

II. Background: A Neurophysiological Framework for Attachment Dynamics

Bowlby’s [7]–[9] control systems perspective led him to view infant behavior as governed by homeostatic regulation centered around a “set goal” of an optimal distance from the caregiver. Maintaining proximity with the caregiver, Bowlby argued, incurred a survival advantage for the infant. When the distance between the infant and the caregiver gets too large, this may trigger the “attachment behavioral subsystem” (including such behaviors as crying, grasping, clinging, and looking and moving toward the caregiver), designed to reduce the distance of the caregiver. On the other hand, when the distance between the infant and the caregiver is smaller than the set-goal, the “exploration behavioral subsystem” (including playing with toys, and looking, crawling or walking away from the caregiver), may be triggered, increasing the infant’s distance from the caregiver. Although the goal of the attachment mechanism is to regulate caregiver’s proximity, its operation manifests experientially for the infant as “feelings,” or “felt security” [81].

A. *Affect Regulation and the Opioid and Arousal Systems*

Negative affect and physical discomfort are often experiential signals of physiological withdrawal: signs that some chemical has dropped below the level to which the body has become habituated. For example, when the body’s naturally produced pain killers (the endorphins and enkephalins of the opioid system) drop below a certain level, this is felt as anxiety or fear, and a need for soothing [15]. This is usually associated with an increase in arousal system’s neurotransmitters (such as norepinephrine) and hormones (such as cortisol), producing complementary activity in the opioid and arousal systems [94]. The converse is also true, where high levels of opioids inhibit arousal and lead to arousal withdrawal, which is felt as boredom and a need for stimulation.

These physiological states of withdrawal not only correspond to departures from positive affect or “felt security,” but they also tend to trigger regulatory behaviors in infants. Specifically, it has been shown that artificial inhibition of opioid activity (by the injection of opioid receptor’s competitive antagonists such as naloxone) consistently triggers behaviors in Bowlby’s “attachment behavioral subsystem,” such as crying and clinging [18], [19], [51], [57], [58]. On the other hand, artificial increases in opioid activity (by the injection of small doses of morphine) not only eliminate signs of separation distress in animals [2], [34], [56] and humans [89] but also give rise to stimulation-seeking and exploration behavior [4], [41], [64]. Evidence suggests that it is specifically withdrawal that is triggering these behavioral systems, because artificial increases in both arousal and opioid system activity simultaneously result in a subjective state of euphoria [31, p. 247], but do not consistently trigger either attachment or exploration [66].

While departure from physiological equilibrium triggers attachment and exploration behaviors through feelings of negative affect, those behaviors in turn also provide the infant with opioid and arousal regulation. For example, when attachment behaviors on the part of the infant are successful in producing the presence of the caregiver and caregiving behaviors, this leads to increases in opioid activity in the infant (e.g., [66] and [94]), which acts to decrease arousal system activity [28], [42], [84], thus relieving opioid withdrawal and restoring equilibrium. Under normal conditions, endogenous opioids increase within minutes of the appearance of the caregiver, providing soothing for the infant [66]. However, if the opioid system is blocked, the presence of the mother has no soothing effect [4], [48]. Exploration behavior, on the other hand, quickly results in increased arousal [11], [14], [61], most likely because of an increased exposure to novelty and uncertainty [55], [74], relieving arousal withdrawal.

Understood this way, the caregiver can be seen as performing the function of a physiological regulator [35], [36]. Whenever the infant’s levels of physiological activity get too far from equilibrium (manifesting as withdrawal, or departures from “felt security”), the appropriate behavioral system (attachment or exploration) is activated to give a signal of its internal state, so that a proper response from the caregiver will then act to stabilize the infant. This casts Bowlby’s homeostatic system in a specific neurophysiological framework and puts the regulation of opioid and arousal activity at the center of the regulatory process. This is the first step in integrating temperament theory and data into a functional homeostatic model.

Of course, this model focuses only on the attachment and exploration behavioral systems, without addressing other complexities of infant behavior (see [73]). Likewise, the relevant internal state of the infant has been reduced to that of joint levels of activity in the opioid and arousal systems. These simplifications are very restrictive, thus preventing this model from addressing certain issues, such as the difference between anxiety and anger (both are characterized by low opioids and high arousal). However, they are necessary in order to make specific predictions, to a first approximation, about how attachment behaviors change over time. Moreover, this neurophysiological framework allows a natural integration with temperamental theories of individual differences in attachment.

B. *Individual Differences in Regulatory Physiology*

Both reactivity and self-regulation, two of the main variables studied by temperament researchers, can be understood in terms of opioid and arousal regulation: an infant’s degree of self-regulation corresponds to its ability to sooth its own withdrawal symptoms, whereas an infant’s reactivity corresponds to the degree to which opioid or arousal withdrawal actually translates into overt compensatory behaviors such as proximity seeking and exploration. In the temperament literature, regulation and reactivity of the arousal system have been more deeply investigated than those of the opioid system. It is well documented that changes in both cortisol [32], [50] and heart rate [61]–[63] are related to environmental stress, and are predictive of attachment dynamics. Moreover, infants that chronically appear depressed, and do not display attachment behaviors in response to stressful stimuli, show high levels of

TABLE I
EPISODES OF THE STRANGE SITUATION PROCEDURE

Episode	Persons Present	Entrances and Exits
1	Infant and Parent	
		(None: Introductory Episode)
2	Infant and Parent	
		Stranger Enters
3	Infant, Parent and Stranger	
		Parent Leaves
4	Infant and Stranger	
		Parent Returns, Stranger Leaves
5	Infant and Parent	
		Parent Leaves
6	Infant Alone	
		Stranger Returns
7	Infant and Stranger	
		Parent Returns, Stranger Leaves
8	Infant and Parent	

cortisol despite of below-baseline heart-rates [33], [67], [86]. This suggests that their arousal system is activated (as indicated by cortisol levels), but that this activity is not being translated into overt behavioral response of attachment or increased heart rate.

It is also important to note that individual differences in sensitivity to opioid or arousal systems can arise either from genetic predispositions, developmental influences, or both [68], [86]. Because an infant's sensitivity to its own opioid and arousal levels may change over time in response to its environment, hypotheses about how these changes occur could be integrated into the model of attachment dynamics in order to yield predictions about how such adaptation leads to changes in observed behavior (see Section IV).

C. Ainsworth's "Strange Situation" Procedure

Though not uncontroversial, a vast majority of the empirical research investigating individual differences in attachment is centered around Mary Ainsworth's Strange Situation procedure ([1], but for criticisms of limitations, see [44]). In the Strange Situation procedure, the infant is placed in an unfamiliar room with toys. After a thirty-second introduction to the room, novelty and maternal proximity are manipulated over the course of seven three-minute episodes (Table I).

Based on their behaviors during these episodes, infants can be grouped into one of three attachment categories: the secure infants (type B); the insecure resistant infants (type C); the insecure avoidant infants (type A). Secure (B) infants will show distress if separated from their caregiver, seeking proximity and contact with her following separation, but will be soothed by her presence upon reunion. Secure infants can vary in their distress, and range from B1 infants, that are not significantly distressed by separation, to B4 infants, that are highly distressed. Resistant (C) infants are generally extremely distressed upon separation, and will seek proximity and contact during reunion, however, they are not calmed significantly by the reappearance of the caregiver. Resistant infants will frequently continue crying throughout a reunion episode, and will mix attachment behaviors with pushing away, throwing toys, and even hitting the caregiver. Avoidant (A) infants generally show little or no distress during separation, and do not seek contact or proximity with the caregiver upon her return. Intermingled with exploration behaviors, avoidant infants will often actively turn or move away from the caregiver.

These characteristic patterns of exploration/proximity-seeking behaviors will be the subject of our current modeling effort. Also, since the attachment typology measures the outcome of interactions of an infant with its primary caregiver, our dynamic systems model will investigate the effect of temperamental factors (such as reactivity and self-regulation), perceptual factors (such as differential sensitivity to calming and arousing stimuli), and environmental factors in terms of caregiving style (such as responsiveness, bias, and recovery speed, see below for operational definitions) in determining an infant's attachment outcome.

III. MODELLING AND SIMULATING BASIC ATTACHMENT DYNAMICS

A. Formal Description of the Model

Let O and A represent levels of neural or hormonal activities in the opioid and in the arousal system, respectively. As discussed in Section II, neurophysiological evidence and previous theoretical work suggest three major influences upon these variables:

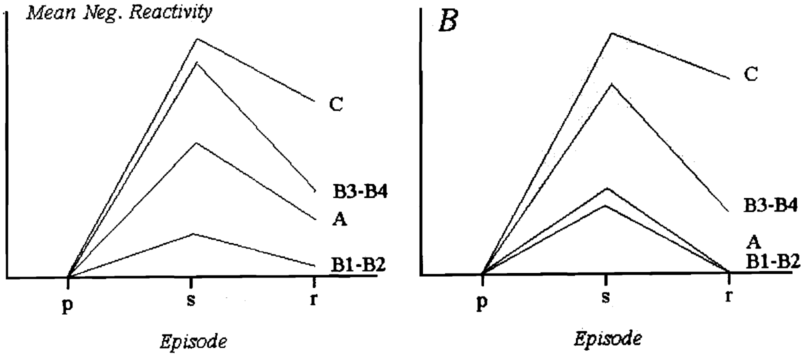
1) environmental inputs, where caregiver or otherwise soothing stimuli (denoted M) increase opioid activity, and novel or arousing stimuli (denoted N) increase arousal activity, both *as perceived by the infant*. Here we introduce multiplicative constants p_c and p_a to describe an infant's perceptual capacity to perceive and distinguish calming and arousing stimuli, respectively;
2) the infant's capacity for self-regulation (denoted μ);
3) the reciprocal inhibition between the two systems (denoted λ).

These factors combine to produce a pair of coupled differential equations, describing how O and A change through time

$$\frac{dO}{dt} = -\lambda A - \mu O + p_c M \tag{1}$$

$$\frac{dA}{dt} = -\lambda O - \mu A + p_a N. \tag{2}$$

The infant's opioid and arousal levels O and A are related to the infant's behavior through two individual difference parameters, s_c and s_a, that represent the infant's sensitivity to opioids and to arousal, respectively. When the infant's opioid and arousal levels are used in calculating the predicted behavior, they will be multiplied by this pair of sensitivity constants—we



(a) (b)

Fig. 1. Mean negative reactivity in each of the three kinds of episode of the Strange Situation for each attachment category. (a) Empirical data [10]. (b) Simulated data, where variable B corresponds to simulated negative reactivity (see text).

call $s_c O$ and $s_a A$ “expressed” opioid and arousal system activity levels, respectively. We postulate that the expressed activity level is the one that corresponds to behavioral manifestations of an infant. See below for details.

B. Simulating Braungart and Stifter’s [10] Study

Braungart and Stifter [10] used the Strange Situation procedure (see Sec. II.C) to measure individual differences in patterns of “negative reactivity” between different categories of infants. In order to compare relative levels of negative reactivity displayed by different categories of infants, Braungart and Stifter pooled the episodes into three categories of preseparation (episodes 2 and 3), separation (episodes 4, 6 and 7), and reunion (episodes 5 and 8) (following [27]). Their data are reproduced in Fig. 1(a).

These data have a number of characteristics that are typical of the secure, avoidant, and resistant attachment types. Secure infant are characterized by both high reactivity during separation (increased arousal and attachment behavior), and a high ability to be calmed by the caregiver’s return [10]. Their ability to be soothed, despite high arousal levels during separation, is part of what characterizes them as “securely attached” (e.g., [1]). Resistant infants, on the other hand, have overall higher levels of negative reactivity and arousal response [39]. Moreover, while their separation levels of distress are similar to secure infants, they do not show the same recovery upon reunion, indicating that they are “difficult to soothe” [30]. Finally, avoidant infants show little separation distress [27], [88] or arousal [40], suggesting that the attachment system might not be activated [13].

1) Model Simulation: Because negative reactivity is a behavioral manifestation of opioid withdrawal, i.e., the degree to which arousal system activity exists in excess of the calming influence of opioids, we may define

$$B = s_a A - s_c O \tag{3}$$

where the effect of each neurochemical system is scaled by the infant’s sensitivity, s_a or s_c, to that system. Positive values of B correspond to behavioral indicators of infant distress, or negative reactivity in the sense of [83], i.e., the infant withdrawals from the source of arousal when its level exceeds the amount of security the infant felt and hence becomes distressful to the infant. Negative values of B could be loosely understood as measuring arousal withdrawal with behavioral indicators of the infant’s lack of activation of the exploration behavioral system due to boredom or being prevented from exploration.

It should be noted that any given level of B may not correspond to a unique, subjective state. For example, high values for both arousal and opioid activity should indicate a subjective state of euphoria, while low values for both would likely correspond to depression [66], although these would map onto the same value of B (when $O = A$), we do not claim that behaviors in these two conditions are identical. What we do claim, however, is that in both cases behavior as described in terms of attachment or exploration is the same: what depressed and euphoric infants have in common is that neither approaches the caregiver, and neither explores.

In the simulation of the Strange Situation, opioid and arousal fluctuations were governed by (1) and (2) above, where the input to the model was determined by the people present in the room in the corresponding episode of the Strange Situation procedure (for example, the presence of caregiver corresponds to having a positive value of M, and the presence of the stranger a positive value N. The room itself is a source of novelty, therefore corresponds to an increased value for the N term.) The output of the model, i.e., O and A as a function of time, was combined into the B value, through (3). The time course was divided into seven segments of equal duration (Episodes 2–8; the introduction to the room was not simulated), averaged and pooled (as Braungart and Stiftler did) into: preseparation, separation, and reunion episodes.

To simulate the inverted U-shape of the preseparation/separation/reunion data pattern is direct and almost trivial, because they are sheer consequences of the assumptions of the model and the way inputs are specified. Novelty increases arousal-inducing input, while the presence of a soothing caregiver increases opioid-inducing input. What is nontrivial is to capture the individual differences in infants by systematic variation of model parameters—we were interested to see to what degree individual differences between attachment categories could be simulated by manipulation of the temperamental factors of reactivity (or sensitivity, s_c and s_a) and self-regulation (μ).

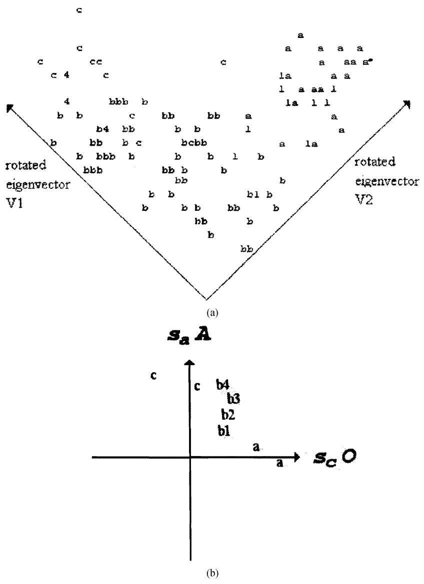


Fig. 2. Two-dimensional structure of infant behaviors, along with attachment category. Infants are labeled according to attachment category: a for avoidant infants, 1 for B1 infants, b for B2-B3 infants, 4 for B4 infants, and c for resistant infants. (a) empirical principal component analysis derived from 20 behavioral variables, taken from Connell [17], with a depiction of rotated principle component vectors (added here). (b). simulated structure based on average expressed arousal ($\mathrm{s_o A}$) and opioid ($\mathrm{s_c O}$) levels for infants in each attachment category.

From the previous discussions, it is hypothesized that avoidant infants would have higher sensitivity for opioid than for arousal ($s_c > s_a$), resistant infants would have higher sensitivity for arousal than for opioid ($s_a > s_c$), whereas secure infants have equal sensitivity levels to arousal and opioid ($s_a = s_c$). (In the actual simulation, $\mathrm{s}_c = \mathrm{s}_a = 0.5$ for secure infants, $\mathrm{s}_c = 0.4$ and $\mathrm{s}_a = 0.6$ for resistant infants, whereas $\mathrm{s}_c = 0.6$ and $\mathrm{s}_a = 0.4$ for avoidant infants). The range of secure responses from B1 to B4 was simulated by manipulating self-regulation (μ,) where self-regulation decreased from B1 to B4. The results are shown in Fig. 1(b). With the exception of the large difference measured by Braungart and Stifter between type A (avoidant) infants and type B1-B2 infants (which Braungart and Stifter, themselves, described as contradicting previous investigations), the empirical results they reported are closely simulated by our model.

C. Simulating Connell and van Ijzendoorn et al. Studies

The attachment categories devised by Ainsworth *et al.*, however, have not gone unquestioned (e.g., [29] and [71]). For example, many question the validity and reliability of dividing infants into these categories, while actual individual differences may be more appropriately represented as variation along continuous dimensions (also see discussions in Section III.D below). Connell [17] and van Ijzendoorn *et al.* [98] have both examined infant behavioral data from the Strange Situation in order to ascertain the clustering pattern of infant attachment categories. Both were able to identify an underlying two-dimensional structure of Strange Situation data. Connell, using data of 20 behavioral measures from Ainsworth's Baltimore sample (Ainsworth *et al.* [1]) and van Ijzendoom, using data of 15 behavioral measures from 136 Dutch children, extracted orthogonal principal components from their data sets, and found distinct patterns of clustering that distinguish secure (type B), resistant (type C), and avoidant (type A) infants (see Note 1).[1]

Fig. 2(a) shows the plot produced by Connell's analysis, along with a rotation of the components found by Connell, depicted by a set of rotated axes (see Note 2).[2] This rotation allows the infant attachment categories to be cleanly distinguished by their component values: secure (B) and resistant (C) infants can be distinguished by their value along the first rotated vector, V_1, where resistant infants have a higher value; secure (B) and avoidant (A) infants can be distinguished by their value along the second vector, V_2, where avoidant infants have a higher value. The principal components discovered by van Ijzendoorn *et al.* [98] have similar properties. They described one of their dimensions (corresponding to V_1) as the "dependency-exploration" dimension, and the other (corresponding to V_2) as the "avoidance-interaction" dimension. Thus, avoidant infants in their sample had high avoidance and low dependency, resistant infants had low avoidance and high dependency; and secure infants scored low on both dimensions.

These two components of attachment behavior can be predicted in the current model by levels of expressed arousal ($s_a A$) and expressed opioid activity ($s_c O$) produced by our simulations. We calculated the average levels of each of these values ($s_c O$ and $s_a A$) based on simulations with the same parameter manipulations described for the simulation of Braungart and Stifter's [10] data. These values are shown in Fig. 2(b). What is important to note about the distribution of attachment classifications in this figure is the fact that we can distinguish infant attachment categories in the same way that they are distinguished by the principal component analyses of empirical data. Resistant infants have low expressed opioid activity (corresponding to "avoidance" or V_2, above) and high expressed arousal ("dependency" or V_1, above), while avoidant infants show the reverse pattern, and secure infants have low or intermediate levels of each. In effect then, understanding the underlying dimensions of infant attachment categories in terms of opioid and arousal activity allows our model to predict the behavioral data of Connell

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[1] Connell extracted the two principal components of the measures based on their multidimensional factor analysis [18], while van Ijzendoorn performed a three mode principal component analysis [91], using children, behavioral measures, and episodes as the three modes. It should also be noted that Connell observed in his data that the clustering was most evident when the "borderline" secure infants, B1 and B4, were excluded from analysis. B1 and B4 infants are shown separately in the accompanying figure – they are only somewhat distinguishable from avoidant and resistant infants, respectively.

[2] The angle of rotation was -45 degree (45 degrees counterclockwise), so that the secure and avoidant infants are maximally differentiated along one axis (V_2), and secure and resistant infants are maximally differentiated along the other (V_1). A series of angles (between -60 and $+60$, at 5 degree intervals) were tested. At each angle, a distance along each vector, V_1 and V_2, could be measured for each avoidant-secure pair of infants, and each resistant-secure pair of infants. Summed together, the total distance of all avoidant-secure infant pairs along an axis can be construed as an index of their spread, or differentiation, along that axis. Because the direction in which secure infants are differentiated from avoidant infants is roughly orthogonal to the direction in which secure infants are differentiated from resistant infants, the two indices (one for resistant-secure pairs and one for avoidant-secure pairs) covary as the angle of rotation is increased. The chosen angle of -45 degrees represents an approximate maximization of these two values, i.e., V_1 maximally differentiates secure infants from resistant infants, while V_2 maximally differentiates secure from avoidant infants. The rotated eigenvector axes depicted in Fig. 2 are provided to illustrate their orientation only, so the origin of the axes as presented in the figure does not correspond to the origin of the original axes for Connell's data.

[17] and Van Ijzendoorn *et al.* [98] in terms of individual differences in the temperamental factors of reactivity and self-regulation. This is an important aspect of the structure of individual differences in infant attachment dynamics, as captured by our model, that is independent of the veracity of the strict categorization proposed by Ainsworth *et al.* [1].

D. Interim Discussion: Multiple Pathways of Development

The model that we present here is of theoretical interest because it provides a way of understanding multiple pathways to individual differences in attachment dynamics. Because it is a mathematical model, it must make explicit each of its assumptions about the steps underlying affective regulation. In doing so, this model allows the attachment mechanism to be decomposed into three component processes: first, environmental conditions, such as the presence of soothing or arousing stimuli, give rise to changes in the infant's opioid and arousal levels; second, these opioid and arousal levels may produce withdrawal, which are experienced as departures from "felt security" or adequate exploration; and third, these withdrawal states trigger regulatory behavioral mechanisms, such as attachment or exploration, that tend to give rise to subsequent changes in opioid and arousal levels.

Seen this way, individual differences in the attachment dynamic may emerge from differences in any of these processes. Consider, as an illustration, the conditions that may give rise to the insecure-avoidant (A) attachment pattern. First, the infant may have a low level of perceptual discrimination for novelty, so that perception of both the stranger and the mother have similar effects. If this were the case, both the stranger and the mother would increase opioid production, for example. This is especially consistent with the fact that avoidant infants show the most distress when left completely alone, and are soothed whenever anyone enters the room. Second, the infant could have low sensitivity to arousal, as discussed above, so that high arousal does not translate into withdrawal symptoms (corresponding to "low reactivity", see [39], [40], [69]). This is how avoidance was simulated in the two sections above, and is consistent with the fact that these infants show many signs of having high arousal, but that this arousal simply does not translate into attachment behavior. And finally, the infant may use some other regulatory behavior to soothe withdrawal symptoms. For example, Braungart and Stifter [10] found that avoidant infants are much more likely than any other class of infant to engage in self-comforting behavior, which may directly cause the stimulation of opioids for the infant (e.g., [59]). Indeed, different avoidant infants may show such avoidant attachment pattern for any of these reasons, or for different combinations of these reasons. There is no *a priori* reason to assume that all avoidant infants show the avoidant pattern for the same reason.

Note that the traditional categorical notion of attachment typology has recently been disputed by Fraley and Spieker [25], [26], who proposed instead a dimensionally based continuum account of attachment outcomes, based on a careful application of taxometric techniques for distinguishing latent classes versus latent continua. Our analysis here intrinsically treats the attachment dynamics along two latent dimensions, representing the activation of an opiate system and an arousal system. So our work is consistent with Fraley and Spieker in viewing attachment outcome as widely dispersed points in a two-dimensional continuous space rather than tight clusters of categories (types), though their labeling and hence conceptualization of those dimensions may differ from ours (see Fig. 1).

IV. MODELLING INDIVIDUAL DIFFERENCES IN TEMPERAMENT AND CAREGIVING

A. Adaptation to Caregiving Environment

Using neurochemical systems as the conceptual framework for this homeostatic model also allows us to include an important property of long-term neurochemical regulation: the development of "tolerance" or adaptation of sensitivity. On a neurochemical level, this simply means that having an ongoing high level of neurochemical activity in some system will lead to the down-regulation of sensitivity of that system. In this way, physiological systems adjust their "base-line" levels of activity to fit their environments.

The down-regulation of arousal sensitivity is well documented for animals and humans under continual stress, and moreover has strong implications for the mechanism of attachment dynamics that we have been discussing here. If an infant remains in a state of high arousal and agitation, and the caregiver does not provide soothing, decreases in arousal sensitivity will cause the infant to pass into what is often referred to as the phase of separation. This "despair phase" is marked by decreased motor activity, decreased attachment behaviors such as crying and clinging, and below-baseline heart rate and body temperature [37], [65]. That these changes are due to decreases in arousal sensitivity, rather than decreases in arousal system activity itself, is evidenced by the fact that neurochemical measures of arousal-system activity—such as serum cortisol levels—still continue to increase [14]. High arousal levels no longer lead to a high expression of arousal-related behaviors. Moreover, consistent with our aforementioned proposal that avoidant infants may have decreased arousal sensitivity, these symptoms have been found in monkeys raised by inanimate surrogate caregivers [33], [67], as well as in many avoidant human infants [86].

This down regulation can also occur for opioid sensitivity. Opiate activity during development influences opiate receptor density [6], and tolerance can develop even prenatally [51], decreasing subsequent sensitivity to both endogenous and exogenous opioids. Taken together, the general process of adaptation at work appears to be one where chronically high levels of either opioid or arousal system activity leads to decreased sensitivity to that system. This is a general property of the opioid and arousal systems, one that nevertheless has implications for models of attachment dynamics.

B. Formal Modeling of Long-Term Adaptation and Parenting Style

The long-term changes in the sensitivity parameters, Δs_a and Δs_c, can be formally modeled as

$$\Delta s_a = \kappa(s_c O - s_a A) = \kappa B \tag{4}$$

$$\Delta s_c = \kappa(s_a A - s_c O) = -\kappa B \tag{5}$$

where κ is the adaptation rate. So, when the expressed opioid activity $(s_c O)$ exceeds the expressed arousal $(s_a A)$, the sensitivity to opioid activity will decrease while the sensitivity to arousal activity increases, whereas when expressed arousal is chronically greater than the expressed opioid activity, the reverse happens. (As presented here, changes in one sensitivity parameter are accompanied by a corresponding change in the other parameter, reflecting a relative change between these two temperamental factors.)

To mathematically characterize caregiving style, we introduce an additional differential equation, dM/dt, that describes the dynamics of caregiving. Parenting style, abstractly represented, is some function that takes B (the infant's attachment or exploration behavior) as input, and converts it into some value, M, representing the caregiver's response. In general, we may write

$$\frac{dM}{dt} = \rho B - \alpha(M - \beta). \tag{6}$$

To explain the rationale behind this dynamic equation, recall that positive B values correspond to infant's proximity-seeking attachment behaviors and other signs of opioid withdrawal, whereas negative B values correspond to infant's exploration behaviors and other signs of arousal withdrawal. Ideally, a caregiver would respond to positive values (attachment behaviors) with an increase in caregiving and negative values (exploration behaviors) with a decrease in caregiving, or even an increase in stimulating behavior. However, the degree to which the caregiver is actually responsive to these behaviors on the part of the infant will depend on the caregiver's level of responsiveness or "psychobiological attunement" [20], captured by ρ here. A larger (and positive) value of ρ means that the caregiver is very sensitive to the infant's signaling and adjusts his/her caregiving behavior in proportional to the infant's attachment needs. Other factors characterizing the caregiver's behavior are the caregiver's response bias (β), i.e., the caregiver's overall presence or absence independent of signals from the infant, and the caregiver's recovery speed (α), i.e., how quickly the normal level of caring is re-reestablished when infant signaling is gone. Negative values of β, therefore, may indicate a caregiver who is chronically absent, while positive values of β would indicate a caregiver that is chronically present and that may require a great deal signaling before allowing exploration. The value of α is always positive—a larger value of α means that the caregiver resumes to the normal level of caring very quickly after a triggering event by the infant, whereas a smaller value of α implies that the caregiver allows his/her change in behavior to linger a while even after the triggering episode is over.

C. Analysis of the Influence of Parenting Style on Temperament

Equation (6) can be coupled to (1) and (2) in a single system, where opioid levels depend upon the amount of caregiving stimuli in the environment (because M increases O) and the amount of caregiving depends upon the behaviors of the infant (because B increases M). When this "caregiving function" is included in the dynamic systems model, the system of equations can be used to derive both short-term and long-term trends in the dynamics of infant-caregiver interaction. Although short-term trends that can appear are interesting—such as oscillations resembling behaviors observed during the infant's "practicing period" (e.g., [46]) as well as in other contexts [76], [80], [85]—what we are primarily interested in is the analysis of long-term trends in infant-caregiver interaction. These long-term trends produced by the model are the predictions about the chronic physiological state of the infant, which will lead to adaptation.

TABLE II
RELATIONSHIPS BETWEEN CAREGIVING AND INFANT ATTACHMENT: PREDICTION AND DATA

absent / unresponsive	N is large or $\beta < 0$, ρ is small	$B_{fp} > 0$ and large	avoidant	Tracy&Ainsworth,1981 Main & Stadtman, 1981 Ainsworth et al. 1978
Excessively Soothing	N is small or $\beta > 0$ ρ is small	$B_{fp} < 0$ and large	resistant	Belsky et al., 1984 Main & Stadtman, 1981
Highly Responsive	$\rho > 0$ and large	$B_{fp} \approx 0$	secure	Belsky et al., 1984 Ainsworth et al. 1978

The long-term behavior of a dynamic system is described by its "fixed points" (if they exist) or periodic orbits (otherwise). In the formal case, all of the fluctuations in infant-caregiver interaction will tend to center around these fixed points, so that over extended periods of time they represent the average levels of opioid and arousal activity experienced by the infant. These chronic levels of opioid and arousal activity, in turn, can be used to predict adaptations in the infant's sensitivity, based on (4) and (5). Because the fixed point values of opioid and arousal system activity depend on both the infant's sensitivity parameters (s_a and s_c) and the parameters that specify caregiving style (ρ, β and α) these equations can be used to show how the interaction between caregiving style and physiological predispositions in the infant gives rise to later infant security.

By setting the left-hand sides of (1), (2), and (6) equal to zero, we can derive the fixed-point (f.p.) values of the opioid and arousal systems, O_{fp} and A_{fp}, and therefore of B

$$B_{fp} = \frac{p_a N(\mu s_a + \lambda s_c) - p_c \beta(\lambda s_a + \mu s_c)}{(\mu^2 - \lambda^2) + \frac{\rho}{\alpha}(\lambda s_a + \mu s_c)p_c}. \tag{7}$$

Equation (7) shows how the infant's long-term withdrawal symptoms depend on parameters pertaining both to the caregiving style and the infant's temperament. When B_{fp} is positive, the infant is chronically aroused, and its sensitivity to comfort will increase while its sensitivity to arousal will decrease. Thus, those conditions that lead to $B_{fp} > 0$ will produce avoidance in infants. On the other hand, when B_{fp} is negative, the infant has chronically high opioid activity, producing the reverse effect. So, those conditions that lead $B_{fp} < 0$ will produce resistance in infants. Table II provides a summary of the influence of each parameter based on this equation.

Many of these model predictions can be directly compared with empirical findings in the attachment literature concerning the relationship between caregiving style and infant attachment category. For example, this model predicts that if the caregiver has a biased tendency towards being absent (highly negative β), despite the presence of arousing stimuli (large N), the infant will be chronically anxious $(B_{fp} > 0)$, leading to avoidance. If, on the other hand, the caregiver has a bias towards being chronically present (highly positive β), and the infant is shielded from novelty (small N), the infant will have chronically high opioid levels $(B_{fp} < 0)$, leading to resistance. Both of these predictions are consistent with the empirical evidence [1], [5], [47],[90]. However, from the perspective of this model, it is also important to distinguish between different kinds of caregiver behavior. The variable M specifically represents caregiving behaviors (at least with respect to positive values of M), that is, soothing behaviors that stimulate opioid activity. This is different from intrusive behaviors on the part of the caregiver that might in fact serve to increase arousal. For example, Belsky, Rovine, and Taylor [5] found that overstimulation (i.e., arousal-inducing intrusive behaviors) by the caregiver is associated with avoidant behavior—just as others have found that absent caregiving is associated with avoidance [47]. What both have in common is that the infant will be chronically aroused (positive B_{fp} values), leading to down-regulation of the arousal system.

Another prediction of our model is that whenever the caregiver is highly responsive (high ρ) to the infant's attachment and exploration behaviors, this reduces the magnitude of any withdrawal symptoms that might arise from changes in the environment. Thus, higher caregiver responsiveness keeps opioid and arousal levels close to optimal, reducing adaptations of the sensitivity to these systems, leading to secure attachment [5]. Low responsiveness, on the other hand, leads to magnifications of withdrawal symptoms, which may aggravate the effects of an unstable environment. It should be noted, however, that according to this model caregiver responsiveness is not strictly necessary, but only serves to buffer the infant against changes in an unpredictable environment. In a stable environment, if the caregiver simply has an overall bias (a level of presence) that matches against the level of stress and novelty in the environment, this can prevent withdrawal symptoms in the infant as well.

Another factor that may decrease the magnitude of withdrawal symptoms is the infant's level of self-regulation (high μ). Indeed, because self-regulation and caregiver responsiveness appear in additive terms in the denominator of (7), our model predicts that they play interchangeable, functionally equivalent roles in long-term regulation and adaptation. That is, the greater the infant's self-regulation, the less dependent it is on caregiver responsiveness, and the greater the caregiver's responsiveness, the less it must depend on self-regulation. By itself, this conclusion is intuitive, straightforward, and well documented [68], [69]. However, from the perspective of modeling, this conclusion is interesting because it was not "built into" any of the model's premises, but rather was derived as a mathematical consequence of the underlying dynamics of the system. This is a strong example of how formulating a model in mathematical terms can lead to new predictions that arise from the dynamics of the model, rather than being built into it.

Finally, in infants that are still deficient in self-regulation (low μ), our model suggests that increasing the ratio of ρ/α will help reduce the magnitude of withdraw symptoms that might arise with environmental change. In addition to increasing caregiver responsiveness (ρ) as discussed earlier, decreasing the value of α, i.e., allowing the psychobiologically attuned caregiver response to linger a little longer than requested by the infant, could also help lower B_{fp} and hence ease withdraw symptoms in either direction.

D. Interim Discussion: Regulating Infant Neurochemistry and Parenting Style

These are straightforward predictions about the influence of different aspects of caregiving style on opioid and arousal levels in infants, leading to different attachment dynamics. Importantly, however, this model also makes specific predictions about the interaction between caregiver's parenting style and infant's physiological predispositions in producing attachment outcome. According to (7), chronic levels of opioid and arousal withdrawal will be influenced not only by parameters pertaining to the caregiver's interaction style, but also by the infant's reactivity, or opioid and arousal sensitivity parameters, as well. Specific interactions between pre-existing biases in physiological or temperamental parameters, on the one hand, and the infant's history of interaction with a particular caregiver, on the other, are only beginning to be investigated (see, e.g., Mangelsdorf *et al.* [101]). NICHD Early Child Care Research Network [53] also published reports on the relation between early infant-caregiver attachment type and quality of continued maternal parenting in determining the social competence of the child in preschool and early school age. Specific predictions derived from (7) could be used to put our theory to test. For example, the influence of novel stimuli (N) and the influence of the caregiver's bias (β) each has a coefficient in (7). In weighing the influence of novel stimuli, self-regulation is multiplied by sensitivity to arousal; on the other hand, in weighing the influence of the caregiver's bias, self-regulation is multiplied by sensitivity to opioid activity. This means that there will be a bias in the degree to which the infant is influenced by arousal factors (N) or soothing factors (β) in the environment, and moreover, this bias will change depending on the infant's degree of self-regulation.

Consider an avoidant infant for whom sensitivity to arousal is lower than sensitivity to opioids. For this infant, arousing stimuli will have a greater influence relative to soothing stimuli when the infant has only a low level of self-regulation. However, as the degree of self-regulation increases, these coefficients first become equal (when $\mu = 0.5$), and then, for highly self-regulating infants with an avoidant predisposition, soothing stimuli will have a greater influence than arousing stimuli. For resistant infants, the opposite is true: soothing stimuli will have a greater influence for low self-regulating resistant infants, while arousing stimuli will have a greater influence for high self-regulating resistant infants. Further simulation work with this model could be used to make more precise, quantitative predictions about the differences in dynamics, and suggest further empirical inquiries into the interaction between reactivity and caregiver bias. Finally, it is important to note that this model differentiates between aspects of caregiver behavior that may not have been previously theoretically distinguished in the literature: the caregiver's responsiveness (ρ), caregiver's chronic level of proximity (β), and the caregiver's recovery speed (α). While responsiveness characterizes the magnitude of the caregiver's reaction to a given (triggering) behavior of an infant, chronic level of proximity characterizes the overall presence or availability of the caregiver, and recovery speed characterizes how fast the caregiver returns to such chronic level of caring after the infant's triggering is gone (i.e., to what extent soothing is continued even after the infant stops the distress call). Empirical measures of responsiveness may not have taken into account of the exact manner a caregiver can become "attuned" to the infant's needs (high ρ, low α, or both). For example, if responsiveness is measured over a short period of time, responsiveness may be underestimated if the caregiver's recovery speed of response is slow. Our model clearly argues that it is the high ρ/α ratio that would be beneficial to an infant with insufficient self-regulation (low μ). Thus, this model is not only consistent with existing data concerning the relationship between caregiver behavior and attachment type, but can also be used as a guide for new investigations.

V. CONCLUSIONS AND FUTURE DIRECTIONS

Casting a homeostatic model of Bowlby's [7]–[9] attachment mechanism in a physiological framework can lead to important and interesting theoretical conclusions. In Section I, we suggested that such an integration between a control systems approach and a neurophysiological framework can lead to greater theoretical insight, and new predictions and theoretical distinctions. In Section II, we provided some background of a specific homeostatic model of affective regulation involving opioid and arousal systems and incorporating relationships among environmental stimuli, and attachment and exploration behaviors. In Section III, we transformed the model from verbal descriptions into a mathematically well-founded dynamic systems model. We then show that this model, which is built upon neurophysiological data relating the opioid and arousal systems to attachment-relevant variables, is also able to predict behavioral attachment data that has been found by Braungart and Stifter [10], Connell [17], and van Ijzendoorn *et al.* [98]. Moreover, it is able to account for individual differences in a way that provides a synthesis of Bowlby's homeostatic attachment framework and research on factors such as infant reactivity and self-regulation in the literature on infant temperament [70]. Specific claims were advanced that relate individual attachment types to underlying imbalances of sensitivity to opioid and arousal systems. In Section IV, we described how a simple mechanism of neurochemical adaptation can be incorporated into the model to allow predictions about the relationship between infant attachment category and parenting style. A new theoretical distinction, between a caregiver's responsiveness and a caregiver's recovery speed, was advanced and could act as a heuristic to guide later research.

In addition to substantive claims, we hope to be successful at showing that mathematical modeling can be a useful tool in this domain of inquiry. Describing models of attachment mathematically not only allows them to make quantitative predictions that can then be compared with empirical data, but also allows us to discover new, emergent predictions that would not have been obvious from the verbal descriptions alone. Specifically, many of the predictions relating individual differences to parenting style (Sec. IV) were derived from the mathematical model and were not intuitively obvious from verbal description of the physiological mechanisms. As with all models, ours should not be taken veridically as the "true" process that underlies attachment, but merely a simplified implementation of Bowlby's homeostatic attachment mechanism framed in a neurophysiological context in order to aid theoretical underpinning.

Finally, this approach to modeling attachment mechanisms also has other implications. The explosion of cross-cultural comparisons of attachment research (e.g., [23], [43], [45], [54], and [73]) has shown a number of ways in which cultural variables can introduce systematic variations in attachment dynamics. Our model provides a quantitative framework of approaching this research and interpreting the results, examining how different caregiving practices in different cultures would lead to different chronic levels of opioid or arousal withdrawal, or to different behavioral regulation strategies. Moreover, individual patterns and processes of attachment later in life can have strong influences both in the structure of family and group dynamics (e.g., [76] and [77]) and in the influence of emotional regulation disorders [3], [12]. The kind of model presented here could be extended to adults, with some modifications, where mathematical analysis could also yield interesting emergent predictions. For instance, Fraley [24] advanced a much simplified dynamic systems model for describing the developmental pathway and stability of attachment over time

$$\frac{dS_t}{dt} = \eta(E_t - S_t) \tag{8}$$

where E_t represents the quality of caregiving environment at time t and S_t represents the security of an individual's working model at time t. [The model was extended in Fraley and Brumbaugh [102], to include the dynamic prototype process with multiple prototypes—the right-hand side of (8) was substituted by a polynomial $(p_1 - S)(p_2 - S)(p_3 - S)$, and hence simulating Waddington's epigenetic landscape with more than one attractors; it is quite remote from the current topic]. From our (1) and (2), it turns out that we can easily derive, by summing (1) and (2), the following equation:

$$\frac{dS}{dt} = (\lambda + \mu)\left(\frac{p_c M + p_a N}{\lambda + \mu} - S\right) \tag{9}$$

which is almost identical to Fraley's [24], (8) above, provided we identify S, the notion of "security of the working model" in Fraley's model, with $O + N$, the combined activations of both opioid and arousal systems according to our model. With this identification, it can be seen that Fraley's "quality of caregiving environment", denoted as E in (8), is nothing but (apart from a constant scaling) $p_c M + p_a N$, the presence of a soothing caregiver together with novel environmental stimulations. Furthermore, the proportional constant η in Fraley's [24] model can be interpreted as a variable related (in part) to the infant's self-regulation (μ parameter in our model). That our model can reproduce the dynamics of Fraley's conceptualization provides an encouraging direction to carry our investigation beyond the Strange Situation task and the attachment outcomes it measures. Such an effort is obviously relevant for research programs in autonomous mental development in robotics (see [99]). Taken all together, our effort can then be viewed simply as a starting point to bring about a new kind of research program in attachment (and developmental psychology by large) that integrates empirical/theoretical and mathematical modeling approaches.

ACKNOWLEDGMENT

The authors would like to thank B. L. Volling of the University of Michigan, Ann Arbor, and T. S. Smith of the University of Rochester, NY, for their insight and comments on a first draft of this paper circulated around 1997. Final revision of this manuscript (after intermittent unsuccessful attempts for its publication) was conducted solely by the second author, Dr. Zhang, when he was under research support from AFOSR and NSF grants. The lost of contact with the first author prompted the second author to preserve as much original writing and style as possible (apart from the last paragraph of Section V) in order to reflect joint work with equal contribution.

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