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Modeling dyadic processes using Hidden Markov Models: A time series approach to mother-infant interactions during infant immunization

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Abstract

The focus of the present longitudinal study, to examine mother-infant interaction during the administration of immunizations at two and six months of age, used hidden Markov modeling, a time series approach that produces latent states to describe how mothers and infants work together to bring the infant to a soothed state. Results revealed a 4-state model for the dyadic responses to a two-month inoculation whereas a 6-state model best described the dyadic process at six months. Two of the states at two months and three of the states at six months suggested a progression from high intensity crying to no crying with parents using vestibular and auditory soothing methods. The use of feeding and/or pacifying to soothe the infant characterized one two-month state and two six-month states. These data indicate that with maturation and experience, the mother-infant dyad is becoming more organized around the soothing interaction. Using hidden Markov modeling to describe individual differences, as well as normative processes, is also presented and discussed.

Keywords

infant distress; soothing; dyadic processes; time series analysis

From an evolutionary perspective, one of the primary roles of parents is to protect their children from harm. Secondly, when protection from harm is not possible or needed, as when a child is discomforted, then the parent functions to return the child to homeostasis by soothing the child's distress (Bowlby, 1969; Gunnar, 2005). Many studies have examined parental responses to infant distress but have not considered that infants also contribute to the success or failure of the interaction. In other words, the regulation of infant distress is a mutual, bidirectional (e.g. dyadic) process whereby both partners contribute (not always equally) to the return of the infant to a homeostatic state (Bronfenbrenner & Morris, 2006; Fogel, 1993; Tronick, 2006). Moreover, when these studies looked at parent regulation they combined these data across time ignoring the temporal patterning of the interaction. In the present study, we reanalyzed mother-infant interaction during an infant immunization procedure at two and six months of age using hidden Markov modeling, a time series method from the family of finite mixture models that produces latent states to describe the interactive process. Our goal is to describe this method and the latent states derived from the mother-infant interaction data. We also provide an example of how individual differences in

the dyadic process might be examined using the sequencing of the states for individual dyads as a preview to future analyses.

The successful regulation of infant distress is important to the child's physical health as prolonged distress and its accompanying physiological responses (e.g., stress hormones) may put the infant at risk for disease (McEwen, 1998; Sapolsky, 1994). Likewise, soothing the distress of one's child has implications for the development of the parent-child relationship, an essential ingredient of positive mental health. Attachment theory proposes that parental responsiveness is central to the development of attachment (Ainsworth, Blehar, Waters, & Wall, 1978; Bowlby, 1969), and several studies have confirmed that responsiveness to distress, in particular, predicts attachment security (DelCarmen, Pedersen, Huffman, & Bryan, 1993; McElwain & Booth-LaForce, 2006).

The ability to successfully console a distressed child also has implications for the parent. For example, being able to effectively soothe infant distress contributes to how a parent feels about his or her parenting competency, or self-efficacy (Coleman & Karraker, 1997). Indeed, in most measures of parenting self-efficacy items on how well parents feel they can soothe their child are included (e.g., Teti & Gelfand, 1991). Further, studies that show that parents of infants that are difficult to soothe rate themselves lower on parenting self-efficacy than parents of easily soothed infants (Stifter & Bono, 1998; Teti & Gelfand, 1991).

Central to the protective and socio-emotional function of parental responsiveness to infant distress is the infant's cry itself (Soltis, 2004). The cry functions to signal the infant's state and to motivate the caregiver to change the condition that threatens the infant's homeostasis (Barr, Hopkins, & Green, 2000). The cry is also conceived to be a graded signal; one that conveys degrees of distress and urgency of need (Gustafson, Wood, & Green, 2000). The evidence is particularly clear for infant cries due to pain. The acoustic characteristics of infant cries to an immunization shot, for example, have been shown to change as distress levels change (Green, Gustafson, & McGhie, 1998; Soltis, 2004) which, interestingly and importantly, are also perceived by adults (Gustafson & Harris, 1990). If parents are sensitive to changes in the degree of distress expressed by their infants then they may alter their soothing methods. For example, parents may pick up, hold, and rock an infant immediately after an immunization but as the crying decreases in intensity, parents may shift to methods that encourage the use of visual attention (Gustafson & Harris, 1990; Jahromi, Stifter, & Putnam, 2004).

Soothing infant distress, therefore, appears to be important to both members of the parent-infant dyad. The study of parent regulation of infant distress, however, has not approached this process dynamically. Rather, infant crying and soothing effectiveness have been predominantly examined within experimental contexts (Campos, 1994) or semi-structured conditions in the home (e.g., McElwain & Booth-LaForce, 2006) rather than within natural, unstructured mother-infant interactions. To further our understanding of parental regulation of infant distress research needs to examine the dyad in an ecologically-valid context that is common to all infants. In the present study we re-examined mother-infant interaction in response to immunization shots administered during a well-baby visit.

Several studies have examined parent-infant interaction during immunization, a procedure that typically evokes distress in all young infants (Axia & Bonichini, 1998; Blount, Devine, Cheng, Simons, & Hayutin, 2008; Braarud & Stormark, 2005; Lewis & Ramsay, 1999; Sweet, McGrath, & Symons, 1999). Although varying in the age of the infant, the majority of the results revealed maternal soothing to be associated with decreases in infant distress. Unfortunately, the correlational analyses conducted in these studies have left open the question of direction of effects (cf. Blount et al., 2008). In our initial examination of maternal responses to infant distress to immunization (Jahromi et al., 2004) (BLINDED for review) we aimed to address this gap by examining the effectiveness of the behaviors mothers used to soothe their two month and six month infants using contingency analyses. In brief, our findings revealed that holding/rocking and vocalization, in combination, were found to be effective at reducing all levels of infant distress at both ages. Either using food or a pacifier to soothe, on the other hand, was effective for only low and moderate levels of distress. Although our study was one of the first to demonstrate within the context of mother-infant interaction the effectiveness of a number of soothing behaviors, there were several limitations that we address in the present re-analysis.

In our attempt to assess effectiveness in the initial study (BLINDED) we used a contingency analysis to compare the dyads showing decreases in infant distress following the occurrence of a particular maternal soothing behavior to those dyads showing increases in infant distress. The contingency approach simply calculated the proportion of observations in which the soothing behavior was followed (within a 5-sec period) by a change in infant distress. This contingency approach, however, is not the best method for modeling what happens during this interactive process. For one, the approach is univariate and thus only allows the test of one behavior in relation to another, in this case, one soothing behavior in relation to one change in crying. In reality, however, soothing strategies are not generated and applied separately when responding to the distress of an infant. Although we previously examined holding/rocking and vocalizing together and found this combination to be most effective in reducing distress over each individual behavior (BLINDED for review) (Jahromi et al., 2004) we were only able to do this for each level of crying at a time, which brings us to the second limitation. The contingency approach also ignores the duration of the behavior. While one can examine lags in soothing behavior related to changes in crying each lag must be tested at one time. Some soothing behaviors may require, for example, three lags to assess their effectiveness while other behaviors take longer to affect cry level. Consequently, it is difficult to understand the process by which an infant, with the assistance of the parent, goes from crying intensely to quiescence. Finally, the contingency approach can miss rare events. For example, the use of a pacifier may only be needed once to produce a significant change but if only a few parents use that behavior it is not likely to be significantly related to changes in crying. In addition to the limitations of the analysis strategy we undertook, we were faced with the reality that although the parent is primarily responsible for how quickly and effectively the infant's distress is ameliorated, the soothing process is a dyadic one to which the infant can contribute toward its success. Infants may vary on the degree to which they react to the pain of the stimulus or to the ministrations of the parent.

To address these limitations as well as improve our understanding of the interactive process, we re-analyzed the immunization data using a time series method. A number of different

methods exist for modeling multivariate time series. But since we are modeling dichotomous variables that represent either the presence or absence of a mother's soothing behavior along with an ordered categorical variable representing the level of the infant's distress (no crying to high intensity crying), we selected a method appropriate for modeling a dynamic process for discrete variables, the latent or hidden Markov model (HMM: Rabiner, 1986; Visser, 2005). The HMM has the added advantage of being intuitively appealing. This method allows the dynamics of the process to be described through a set of latent (or hidden) states. For a set of behaviors (both infant and mother), each state is defined by giving the probability of each behavior for the interacting parent and infant in that state. The HMM then describes how dyads as a group move between states by giving the transition probabilities of moving from each state to any of the other states. Once these latent states are identified and the transition probabilities are determined, then individual differences can be investigated by examining each dyad's pattern of movement through these states (the posterior state trajectories).

Another distinct advantage of hidden Markov relates to its ability to successfully detect rare events (Chan, et al., 2004). Given its development as a method for pattern recognition, hidden Markov modeling has been shown to reliably detect infrequently occurring patterns.

Our first approach to our re-analysis of the immunization data presented here was to identify for the two-month data these latent states as a dyadic process and examine the probability of moving from one state to another across the interactive process for the entire sample. Once we established the model for the two-month data, we analyzed the six-month data to determine how the state definitions and transition probabilities differed between occasions. Our approach to estimating the number of latent states was basically exploratory with an initial expectation that the six-month data would show more complexity and variability in soothing behaviors than the two-month data. To preview the utility of HMM to examine individual differences, we also tested the relationship between infant irritability prior to immunization and the latency to reach a latent state as well as the duration of that state for each individual dyad.

Method

Participants

As part of a longitudinal study on the development of emotion regulation, 150 healthy full-term infants (67 first born) and their parents were recruited from a local community hospital. At two months of age, 141 subjects (75 girls, 66 boys) were available for the 2 month immunization (M age = 2.1 months, range 1.5 to 3.5 months) and 133 infants (66 girls, 67 boys) were available for the six month immunization (M age = 6.3 months, range 4.9 to 8.8 months). Families were predominantly white. Mothers averaged 29.7 years of age and were well-educated (15.6 years), with 84% married at the time of the infants' birth.

Missing observations (two months: $n = 9$; six months: $n = 17$) were due either to families moving out of town or to their refusal to have the procedure videotaped. For those who participated some instances were not codable (e.g., baby or parent obscured by nurse;

average of one 5-second interval per dyad). Missing observations were imputed using a one-step ahead prediction until a new data point appeared (Shumway & Stoffer, 2011).

Procedure

Infants and their parents were observed during a routine immunization which occurred either in their pediatrician's office or at a local health clinic. A research assistant met the families in the waiting room and described the procedures before entering the examination room. The research assistant also noted the degree of irritability the infant exhibited during this time. Injections (for hepatitis B, diphtheria, tetanus, pertussis (DTaP), pneumococcal, influenza, and polio) numbered between 1 and 4 per child and were administered by either a physician or nurse in the upper thigh. Immediately following the injection (s) the infant was given to the mother who was then free to soothe the infant in any manner she chose. From a corner in the examination room the research assistant videotaped the procedure from the start of the first injection until the infant exhibited 20 consecutive seconds of no crying. The number of injections and the site (pediatric office/health clinic) were unrelated to the cry and soothing measures. First born infants, however, were more likely to cry longer, $M = 155$ seconds, $SD = 63.5$, at two months than later born infants, $M = 126.0$ seconds, $SD = 59.8$, $t(139) = 2.88$, $p < .01$.

Measures

Infant distress—To capture the range of infant responses to the immunization procedure, infant distress was scored every 5 seconds from the time of the last needle extraction to 20 seconds of no crying. Infant distress was coded on a 4-point scale: 0 (no audible vocalization), 1 (fussing, whining or whimpering), 2 (low intensity crying, may occur with rapid frequency but no shrieking), and 3 (very intense, loud, piercing crying, usually with a red face, squinted eyes, and an open mouth). Coders were instructed to code the highest level of distress observed during the 5-s interval. Coders were trained to acceptable agreement (Cohen's kappa $> .75$) and 10% of cases were coded for drift reliability resulting in a kappa of .92. For purposes of the HMM analyses, we inspected the cry durations of the sample and found 4 minutes (48 intervals) of coding to be the maximum necessary to capture the wide range of crying durations. Two month olds averaged 28.03 minutes of crying ($SD = 12.63$) whereas six month olds averaged 21.98 minutes of crying ($SD = 12.32$). Only 9% of two month olds and 2% of the six month olds cried longer than 4 minutes.

Maternal soothing behaviors—Eight maternal soothing behaviors were coded during the same 5-s intervals as infant distress. For each 5-s interval the presence/absence of all observed soothing behaviors was coded allowing for the analysis of concurrent soothing behaviors. Behaviors were chosen based on review of the videotapes and previous research (Lewis & Ramsay, 1999). Mothers' use of affection (e.g., kissing, hugging, cheek-to-cheek), touching (e.g., patting, stroking), holding/rocking (e.g., holding infant with or without movement), vocalizing (e.g., talking, singing, shushing directed at infant), caretaking tasks (e.g., dresses infant, changes diaper, wipes nose/face, preparing to leave office), distracting (e.g., directing infant's attention away from discomfort of shot), presenting face (e.g., looks directly into infant's face, pulls the infant away from and held in front of mother), and feeding/pacifying (e.g., using bottle, pacifier or breastfeeding) during the period after the last

injection were coded independently by two coders. Coders were trained to reliability (Cohen's kappa > .75) and 10% of the videotapes were coded for drift reliability. Cohen's kappa ranged from .78 (touching) to .98 (feeding/pacifying).

Infant irritability—Prior to the immunization, the research assistant rated the infant's level of irritability while the parent and infant were in the waiting room using the Irritability ratings of the Neonatal Behavioral Assessment Scale (Brazelton, 1973). The infants' general irritability at two and six months of age was measured using a 9-point scale ranging from *no irritability* (1) to *irritable in response to all stimulation* (9) with the midpoint representing the norm.

Data Analysis

When describing any interaction, the questions that we are interested in can be generally described as follows: 1) what characteristics of the interaction are of interest; 2) what statistical model can best be used to describe this interaction; and 3) given this model, what are the dynamics of the system? The characteristics of the interaction of interest we focused on in the present study were the level of distress of the child, and the soothing strategies that the mother might employ. The hidden Markov model (Baum & Petrie, 1966) conceptualizes the interaction in the following way.

A set of latent states exist which are defined by the probability of both infant behaviors and parent behaviors co-occurring. In any state, each level of each behavior has a certain probability of occurring. If we consider infant distress, the level of distress with the highest probability is the most likely level of distress for the infant in that state. Typically, one level of distress will be most likely in that state; however, it is possible to have two levels with similar probabilities. At that level of infant distress the parent is likely to employ each possible soothing strategy with a particular probability. The higher the probability, the more likely the parent is responding with that behavior to that particular level of distress. The state thus represents a combination of the baby at a certain level of distress and the parent's soothing behaviors. At some point, the likely level of the child's distress changes. With that change come other likely changes in the probabilities of the parent using each of the possible soothing strategies. This new combination would represent a different latent state. In this state, she may continue with the same strategies or try some others.

One of the outcomes of the HMM is to derive a complete set of states that optimally describe the data. In a data reduction much like a factor analysis, the original set of variables is 'replaced' with a set of states. This reduction provides states that are different enough to describe the transitions across the interaction and parsimonious in the sense that a minimum number of states can be described that adequately accounts for the data. We will give a rough sketch of how this is done after first showing how a state is defined.

Each state is defined by the probability of each behavior (both mother and infant behaviors) occurring. The probabilities show how likely the infant is at a particular level of distress along with the likelihood that the mother is performing each of the possible behaviors. A possible state is shown in Figure 1. According to this figure, infants in this state are most likely to be at the highest level of distress, although there is some small probability that they

could be at some other level of distress. In this state mothers are employing both holding/rocking and vocalizing. There is just a small probability that mothers would employ any of the other strategies. So, although there is a small chance that dyads in this state could include a less distressed child and a mother who used distraction, for example, that combination is relatively unlikely.

Given a set of such states the model will also describe the probability of moving from each state to any of the other states as one goes from one observation to the next. These are the transition probabilities. The last piece of information used to define the HMM is the probability with which a dyad might be expected to start in each of the states, the initial probabilities. The set of state definitions, the transition matrix, and the set of initial probabilities represent the parameters that are estimated in the HMM. A state can be defined based on any number of co-occurring behaviors. Behaviors that are maintained, for example, in response to distress are indicated by the dyad remaining in the same state over a number of observations. A successful strategy would be indicated by a transition from that state to one in which the infant's distress level has decreased. Rare events would be indicated by a state which includes a behavior (e.g., using a pacifier) that is soon followed by a transition to another state which includes that behavior along with a change in the child's level of distress.

With the set of estimated parameters, the HMM can then be used to compute the state each dyad is in at each observation point; thus, the sequence of states each dyad passes through can also be determined. These are referred to as the posterior state trajectories. An example of the output of these trajectories can be found in Figure 2. The posteriors allow us to look at individual differences which are indicated by the patterns of states and the duration within each state through which each dyad passes. Since part of the focus of this study is to show differences in these interaction patterns across dyads and across ages, we expect substantial variability in these patterns. The next section presents the formal definition of the HMM.

The Hidden Markov Model

Hidden Markov modeling was developed by Baum (Baum & Petrie, 1966) in the late 1960's to provide probabilistic models used to uncover latent patterns in time series data, as in voice and letter recognition. HMM has been used in the medical, economic (Kim, 1994), and social sciences (Frühwirth-Schnatter, 2006; Wickens, 1982). Our implementation of this model, *depmix*, was developed by Visser (Visser, Raijmakers, & Molenaar, 2002) and is based on the method described by Rabiner (Rabiner, 1989). For more information see the R website at <http://cran.r-project.org/web/packages/depmix/index.html>

The model is one of a class of generalized mixture models. For categorical observed variables, it is an extension of latent class models to time series data. HMM can be computed based on a single dyad's time series (single group model) or as we do here on multiple dyads time series (multiple group model). The relationship between hidden Markov models and other latent variables approaches including latent class and latent transition models has been described by Bartholomew, et al., (2011). See Saul & Rahim (2000) for a comparison between hidden Markov models and common factor models. We note here that the latent classes in this HMM are not clusters of individuals as is typical in cross-sectional

latent class models, but instead are latent states that indicate co-occurring patterns of dyad behaviors.

The Parameters of the Hidden Markov Model—In the HMM, a system is presumed to have N distinct latent states: $S_1, S_2, \dots, S_N$. The state that an individual is in at time t is q_t . The probability of moving from one state, S_i to the next state S_j is the transition probability:

$$a_{ij} = P[q_t = S_j | q_{t-1} = S_i]$$

The defining characteristic of the process is the *Markov property* which states that the probability of currently being in a particular state only depends on knowledge of the previous state. If there are N states in the model, the transition probabilities will be collected in the *transition matrix*, A , which gives the probability of moving from any one state to any other state at any given observation.

Each state is described by a set of variables, often called *indicators*, which can take on any of a set of discrete (or continuous) values. Here we consider only a set of discrete variables. In our model there are $m_1=4$ possible values for variable 1 (infant's distress), $m_2=2$ possible values for variable 2 (feeding/pacifying) up to $m_p=2$ possible values for variable p (holding/rocking), the number of probabilities in a state is $M = m_1 + m_2 + \dots + m_p$. These state probabilities are often referred to as *loadings*. They are collected in the B , or *loading matrix*.¹

If $\pi_i = P[q_1 = S_i]$ is the probability of starting in a particular state S_i , then the complete set of parameters for the model are represented by the vector

$$\lambda = (A, B, \pi)$$

Estimating the model involves finding the set of parameter values λ that make the probability of observing the data most likely. In order to assess the fit of this model (whether the model accounts well for these data) we used the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) provided by the *depmix* program (Visser, Raijmakers, & Molenaar, 2007). The AIC and BIC can be used to select from a set of models². Typically, the model with both smallest AIC and BIC represents the best model for a set of data. When these two indices conflict, the AIC tends to accept the more complex model (more parameters) while the BIC tends to prefer the model with fewer parameters.

¹The model does not include measurement errors. Variables are assumed to be measured without error. The assignment to a state is based on the most probable value conditioned on the observed data.

²Given the high dimensionality (large number of parameters of the HMM), simple chi-square differences and chi-square derived measures would tend to look at any two models and say they are different. As a result penalized loglikelihood differences represented by the information criterion tests tend to be more conservative. In addition, chi-square difference tests can only be performed on nested models (models in which parameters are either added to or subtracted from the model, but not both). That is seldom the case with two hidden Markov models; so, in most cases, chi-square difference tests cannot be used. The literature on fitting hidden Markov models (Altman, 2004; Leroux, 1992; MacKay, 2002; Visser, et al., 2009) suggests that, considering the difficulty of comparing non-nested models, such comparisons are typically done using information criteria or graphical methods. We follow the suggestion of Visser, et al., (2009) which was implemented in the *depmix* software.

Once we have determined the λ we can apply the parameter values to the raw data to compute the *posterior state trajectories* for each dyad. These are the sequence of states that we use to describe individual differences.

In the more general HMM indicator variables are not limited to categorical variables. In addition, any of the parameters can be conditioned on covariates (e.g. a transition probability can be dependent on SES or education). Descriptions of these models appear in Visser (2005).

Results

Selecting a Model

As our data are longitudinal, we began our analyses by looking at the two-month immunization data. After selecting the best model for the two-month data, we attempted to fit that model to the six-month data. When that model fit poorly, we determined the best fitting model for the six-month data. The difference in these best fitting models for two- and six-month data describes the age-related change in the dyadic interaction.

For the two-month mother-infant data, we fit 2-, 3-, 4-, and 5-state models. The selection criteria can be seen in Table 1 which includes the *AIC* and *BIC* along with the $-2 \times \log \text{likelihood}$ fitting function and the number of total and free parameters. Based on our fit criteria, the 4-state model was clearly the best fitting model for the two-month data. When testing whether the identical 4-state (constrained) model fit the six month data the results indicated that this model did not fit the data well. A 6-state model emerged that best fit the six month data (see Table 1 for the fit of the constrained model along with the fit indices for the 2- through 6-state models for the six-month data). To conserve space, we only describe the best models: the 4-state model for the two-month data and the 6-state model for the six-month data.

The 4-State Hidden Markov Model for the Two Month Data

The results of this model appear in Table 2 and include a vector of initial probabilities, and the behavior probabilities related to each of the six states. The transition matrix can be seen in Table 3. The initial probabilities vector indicates that the dyads are most likely to start out in State 1 (.562), or State 2 (.405). There is very little chance that a dyad would begin in States 3 or 4. Figure 3 plots the number of dyads in each of the states across the 4 minutes of the procedure. It is important to note that the number of dyads in a particular state decreases or increases across the 4 minutes depending upon the state and when the infant ceased crying (i.e., 20 seconds of no crying).

State 1 is marked by a high probability of the child being highly distressed (.55) with a lesser chance of having a level of distress at lower intensities (.21). The most probable maternal soothing behaviors in this state are vocalizing (.54) and touching/affection (.41) with a lesser probability of distraction/face-to-face (.31). When taking into account the probabilities of caretaking tasks in the other states, however, the probability that mothers use caretaking tasks in State 1 is relatively high (.28). Because this state is defined by high levels of crying intensity accompanied by caretaking tasks such as dressing the child (among other

soothing methods) we interpret this as the time when the mother-infant dyad is transitioning from the administration of the shot to soothing. This is supported by the transition matrix for the two month data (see Table 3) in that over one-half (56%) of dyads start in this state (see Figure 3). Although it is more likely for all dyads to remain in one state (recall that the epochs are only 5 seconds long), the most likely transition is from State 1 is to State 2 (.113) which includes a high probability of the child being either highly (.53) or moderately distressed (.44). A look at Figure 3 indicates that the number of dyads in State 1 drops dramatically within the first 30 seconds while the number of dyads in State 2 increases within the same time period, further supporting the notion that the State 1 'caretaking tasks' state is short-lived and most likely transitions to State 2. Taken together, these indicators suggest that performing caretaking tasks when the infant is highly distressed may not effectively soothe the infant.

During State 2 for which the infant is crying intensely, the use of holding/rocking (1.0) to soothe predominates followed by vocalizing (.76) and touching/affection (.61), with a lesser probability of distraction/face-to-face (.35). Thus, it appears that mothers immediately pick up their infants and talk to them. Examination of the transition matrix (Table 3) suggests that State 2 dyads are most likely to move into State 3 (.076) which is characterized by low intensity or no crying (.61). As can be seen in Table 2 mothers in State 3 continue holding/rocking (1.0), and vocalizing (.68), increasing their touching/affection (.68). This state suggests that the continuation of vestibular and vocal soothing reduces infant crying. Examination of Figure 3 illustrates a steady increase in State 3 dyads across the first 75 seconds suggesting that many two month olds are soothed soon after receiving a shot.

State 4 is differentiated from the other states by the use of nutritive and nonnutritive soothing strategies. Although the probabilities for level of crying intensity is distributed across the three cry intensity levels, this state is marked by almost uniform feeding/pacifying (.99), holding/rocking (1.0), vocalizing (.62), and distraction/face-to-face (.59). Figure 3 illustrates that more dyads turned to pacifying/feeding over time, but that only a maximum of 25 dyads ever used this soothing method.

The 6-State Hidden Markov Model for the Six Month Data

The initial probabilities and state characteristics for the 6-state solution for the six month data can be found in Table 4, the transitional probabilities are in Table 5. Because of the number of states generated by the six-month data the number of dyads across the immunization period for the first three states can be found in Figure 4a while Figure 4b graphs the number of dyads in States 4, 5 & 6.

According to the initial probabilities, dyads are most likely to start out in State 1 (.841). Not surprisingly, this state is marked by almost uniform heavy crying (.99). The soothing behaviors employed are most typically holding/rocking (.77) and vocalizing (.77) with a lesser tendency to employ touching/affection (.50) and distraction/face-to-face (.43). According to the transition matrix seen in Table 5, dyads in State 1 are most likely to move to State 2 (.21). This state is very similar to State 1 with relation to soothing strategies but is characterized by moderate intensity crying (.85). This transition represents the maintenance of behaviors that seem to result in a decrease of distress. The most likely transition from

State 2 is to State 3 (.23) which is again similar with respect to soothing strategies but with the level of crying again decreasing to either low intensity crying (.55) or no crying (.44). Once in State 3, there is a high probability of remaining in that state (.92) and a small probability of shifting to the other states with the greatest shift probability of moving back to State 2 (.05).

As can be seen in Figure 4a the majority (73%) of mother-infants pairs at six months were more likely to be in State 1, the state in which the child was crying intensely. The sudden drop in the number of dyads within the first 30 seconds to only 31 dyads, the co-occurring increase and then decrease in dyads in State 2, and the gradual increase and then decrease to very few dyads in State 3, together suggest that mother-infant dyads are working effectively in reducing the infants' distress. Once dyads moved from State 2 to State 3 their interactions were likely successful and thus they were no longer included in the figure.

States 4 and 5 of the six-month model are characterized predominantly by feeding and/or pacifying, although other soothing techniques were also employed (see Table 4). Whereas the probabilities for infant crying intensity in State 4 are distributed across the four levels, infants in State 5 are more likely to be fussing (.35) or not crying at all (.60). What also differentiates these two states is that mothers are more likely to use distraction/face-to-face in State 4 (.61) but not at all in State 5. Inspection of the transition matrix suggests that dyads in State 4 are more likely to move to State 5 (.10) and then stay there (.99). In sum, it appears that a number of dyads use feeding and pacifying effectively. Figure 4b illustrates that as many as 18 mother-infant pairs used feeding/pacifying immediately to soothe (State 4). Interestingly, the number of dyads in this state increased steadily across the first 75 seconds to a high of 30 dyads suggesting that some mothers may have moved to using feeding/pacifying after using other methods to soothe their infants. This is further illustrated by the low number of mother-infant pairs in State 5 who were fussy or not crying at all. Finally, State 6 which is characterized by all levels of crying might be best described as the caretaking task state as it was the most likely method used (.73). When considering the low number of dyads across the immunization (see Figure 4b), this state likely represents those mothers who decided to pack up their things and leave the physician's office, particularly given that the code of "caretaking tasks" includes putting the child down and/or dressing the child.

The Effect of Infant Irritability on Soothing

Once the latent states are identified, the posterior state trajectories can be used to address any number of questions/hypotheses about individual differences. To illustrate this function we examined whether the infants' general level of irritability prior to immunization influenced their reactions, specifically the latency to reach each state as well as the amount of time spent in each state using simple regression. At two months, infants who were rated higher on irritability spent more time in State 2, $r = .20$, $p < .02$, and less time in State 3, $r = -.20$, $p < .02$. Infants who were high in irritability prior to receiving their shots spent more time in the high to moderate intensity crying state and less time in the soothed state. General irritability at two months did not predict the latency to reach any state.

At six months of age, infant irritability was negatively related to time spent in State 3, $r = -.22$, $p < .01$. In addition, irritability was positively related to the latency to reach State 3, $r = .23$, $p < .05$, and State 5, $r = .42$, $p < .07$, the two soothed states. Thus, six-month old infants who go into the immunization procedure with greater irritability are more likely to take longer to soothe than infants who were less irritable. Interestingly, irritability was modestly stable across this 4 month period, $r = .32$, $p < .01$, and two month irritability predicted more difficulty soothing at six months (latency to reach state 3 or 5), $r = .17$, $p < .05$.

Discussion

In this paper we present an alternative method to analyzing dyadic interactions around soothing infant distress. The hidden Markov model (HMM), a time series analytic strategy, produces latent states that take into account the distress of the infant and the soothing behaviors of the mother. Because both members of the dyad contribute to the success of this interaction, HMM provides a more complete description of the dyadic process. That is, not only does the HMM provide a test for the best model that fit the interaction data drawn from the immunization procedure, but it also provides the probabilities of each of the soothing behaviors occurring within the context of varying levels of infant distress. In addition, this method provides information regarding the probabilities of which state most likely follows another state. It is important to stress that the latent states derived by HMM describe the dyadic process at the group level and do not describe classes of individuals as might be expected from cross-sectional latent class models. Subsequent to the creation of these latent states, the sequence of each dyad's latent states, the state trajectory, can be examined to address questions about individual differences.

When the six month data was constrained to the 4-state model produced by the two month immunization data, the fit indices indicated a poor fit. Rather a 6-state model produced the best fit for the six-month immunization data. This finding suggests that age-related change likely occurred in the dyads. Whereas at both ages, the predominant state and sequence of states was one that went from high intensity crying accompanied by high levels of holding/rocking, and vocalizing, and moderate levels of affection/touch and distraction to one of low intensity or no crying and a continuation of the same soothing behaviors, several differences were evident which support developmental change not only within the infant, as might be expected, but within the dyad as well. We describe each difference and then consider them together in explaining this developmental change.

First, at two months the initial probabilities, the probability of starting in that state, are distributed between two states (State 1 and State 2) whereas at six months most dyads will start in one state (State 1) immediately after the shot. Secondly, the distribution of probabilities for levels of crying was different at each age. At two months the likelihood of crying at different levels is more diffuse, e.g., crying in State 1 & 2 was as likely to be of high intensity as it was to be either of moderate or low intensity, whereas at six months, high intensity crying was most probable in State 1 and moderate crying most probable in State 2. Finally, a comparison of the transitional probabilities shows that two month old infants were more likely to stay in a state of high intensity crying (State 1 - .86; State 2 - .89) than at six month olds (State 1 - .74). Taken together, these differences suggest that the six month

dyads are more organized in their soothing interactions than the two month dyads. That is, the majority of six month dyads began in the same state and moved neatly and swiftly from state to state using the same soothing behaviors. It may be that the child's maturation together with the experience of the dyad in soothing distress made it easier for the dyad to reach a calm state. The significant difference in the number of states between two months and six months also indicates that the six month dyads' responses to an aversive stimulus are more complex as it took 6 states to fully describe the data. Interestingly, the content of the states are more interpretable for the six month dyads as it is clear how, as a group, mothers and infants move from a state of high arousal to one of quiescence.

The interpretation of these developmental changes is supported by previous research on infant responses to pain. These studies (Gunnar, Brodersen, Krueger, & Rigatuso, 1996; Jahromi et al., 2004; Lewis & Ramsay, 1995) have shown that older infants cry less intensely, show fewer pain expressions, and soothe more quickly than younger infants. Interestingly, these age-related changes were accompanied by decreases in the stress hormone, cortisol (Gunnar et al., 1996; Lewis & Ramsay, 1995). Maternal soothing behaviors have also been examined and found to change with infant age (Jahromi et al., 2004; Lewis & Ramsay, 1999). Although informative, none of these studies examined infant reactions to inoculation as a dyadic process. Data from the present study indicate that these developmental changes are not located within one partner of the dyad but rather within the mother-infant interaction, consistent with dynamic system and mutual regulation theories of development (Fogel, 1993; Tronick, 2006).

What also distinguishes the present study from previous research is that HMM provides a more realistic picture of mother use of soothing strategies. That is, mothers were more likely to use soothing strategies in combination rather than individually. The results indicate that a mother is likely to rock, vocalize, and affectionately touch her child coincidentally for the purposes of soothing. Moreover, she will continue this combination of strategies until her infant has calmed. In our previous work we found that while holding/rocking was very effective in reducing infant crying, it was most effective when combined with vocalizing (BLINDED for review), however, these data were collapsed across dyads and time. While this previous work was able to indicate whether or not variables were associated, HMM estimates the probabilities and gives a stronger indication of the degree of association

One similarity among the two and six month dyads was the presence of a set of mothers who used feeding or pacifying to soothe their infants. Although the number of dyads at two months was low when this strategy was initiated, the probability of the infants' crying intensity was distributed across all levels. This suggests that a core of mothers may rely more heavily on feeding/pacifying regardless of infant distress level. Again, what differentiated the two month dyads from the six month dyads was the number of states in which feeding/pacifying was used. At two months only one latent state where feeding/pacifying predominated was identified whereas at six months two latent states were identified. The finding that 18 dyads at six months used feeding/pacifying (State 4) immediately after the administration of the inoculation in comparison to only 4 at two months suggests that by six months of age parents may have learned how effectively food or a pacifier soothes their infants and adopted this strategy as a sure-fire method to get their

infants to calm. There was also a difference in the number of dyads who used feeding/pacifying across time between two months and six months. The number of two month dyads peaked at 26 dyads one minute after the inoculation and then decreased in dyad numbers across the rest of the observation. At six months the number of available dyads using feeding/pacifying (State 4) increased over time, peaking at 30 dyads at 70 seconds after the immunization procedure and maintaining a relatively high level, fluctuating between 25 and 30 dyads for the next 60 seconds. This finding suggests that parents of six-month-olds may try other strategies before turning toward feeding/pacifying to relieve their infants' distress. Indeed, an inspection of the all 6 six-month states over time (Figures 4a & 4b) indicate that the remaining dyads in the last two minutes were more likely to be using feeding/pacifying than any other state. There is a paucity of research investigating the use of feeding and pacifying to soothe even though experimental research has demonstrated the effectiveness of these methods in calming the infant (Blass, 1999; Campos, 1994).

Although the latent states generated by HMM are informative, they reflect aggregated descriptions of the mother-infant interaction. Interpreting these aggregated results requires some caution, and also suggests some next steps in the consideration of these data. Most important is the underlying assumption of this model that the definition of states adequately describes each dyad. Since the posterior state trajectory for each dyad is dependent on these aggregated statistics, these results represent a tentative solution, conditioned on testing this assumption of *ergodicity* (Molenaar, 2004); namely, whether the aggregated model holds for each dyad. Under the aggregated model HMM provides a sequence of the most likely latent state each pair occupies at each observation point. From these posterior state trajectories we can consider individual differences in the pairs by looking at the sequence of states for each pair and describing the movement from state to state. In the present study we tested one individual difference to illustrate the utility of these data; whether irritability measured prior to the inoculation would be related to the latency to reach a state and the times spent in a state.

Infants who were rated higher on irritability prior to the administration of the shot spent a longer time in the high/moderate intensity cry state at two months (State2) and took longer to reach the soothed states (State 3 & 5) at six months than infants who showed little or no irritability. These results complement our previous finding and other studies that irritability was related to both the mean intensity and mean duration of crying (Jahromi et al., 2004) and suggest that keeping an infant calm prior to his/her inoculation will result in a quicker recovery. As irritability may reflect temperament – irritability was stable from two to six months of age, attention to this individual difference may not only reduce the infant's distress to immunization but it may also help parents to reduce their own stress reactions to their difficult-to-soothe child.

In this paper we introduce the utility of HMM to model dyadic data. We have shown how to create latent states from the data, generate trajectories of the states, and illustrated how one might examine individual differences using the individual trajectories of each dyad. There are, however, many options for analyzing the latent states generated by HMM. For example, in the present case we could cluster the trajectories to examine whether any naturally occurring groups emerged. Dyads who take a long time to recover from the inoculation

might show different trajectories than those who proceed quickly from dysregulation to regulation. Or, we might create groups based on a theoretically meaningful factor that could affect the dynamics of the interaction. In the current study we might consider the number of injections that the child received, the number of siblings, or the infant's temperament. Thirdly, we could test whether the 6-state model is the correct model for each dyad by estimating a separate HMM for each dyad. These individual models could be compared to the aggregated model to see which individuals are well-described by the overall model. For those dyads who do not conform to the group model, separate subgroups could be established by pooling in the manner described by Nesselroade and Molenaar (1999). These subgroups may represent qualitatively different processes that could then be the basis for additional research. This later example would be a direct test of the *ergodicity* assumption described above.

In summary, the present reanalysis illustrates the advantage of using HMM to understand how each member of the mother-infant dyad contributes to the soothing of the infant's distress. HMM, a time series method, was used to describe the dyadic process by identifying a set of latent states which provided the probabilities of both infant and mother behaviors co-occurring. The data suggest that dyads become more organized across time with six month dyads soothing more quickly and smoothly. As the generalizability of these data are limited to predominantly white dyads, and dyadic responses to infant pain, future research should examine these processes in more diverse samples and during less aversive situations to further understand how mother-infant dyads manage all levels of distress. HMM also generates posterior state trajectories that describe the sequence of states for each dyad. These data can be used to address a number of individual differences hypotheses. To illustrate this function we examined individual differences in irritability and found that higher irritability was related to the duration spent in a soothed state and the latency to reach that state. Future research might consider using HMM to address, for example, how variation in dyadic processes impacts socioemotional development, in furthering our understanding of the role of parent-infant interaction in child development.

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Figure 1.
Example of a Hidden Markov State

ID	Intervals																48
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	.	
1	3	3	3	2	2	1	1	1	1								
2	3	3	3	3	2	2	2	2	4	4	4	4					
3	3	3	3	4	4	4	4										
4	3	3	2	2	2	2	2	2	1	1	1	2	2	2	2	.	1
5	3	3	3	3	4	4	4	4	5	5	5	5					
6	3	3	2	2	1	1	1	1									
7	3	3	3	3	3	3	2	2	4	4	4	4	5	5	5		
8	3	2	2	2	3	3	3	2	2	1	1	1	1				
9	2	2	2	2	2	1	1	1	1								
10	3	3	4	4	4	5	5	5	5								
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.																	
.																	
50	3	3	4	4	4	1	1	1	2	2	4	4					

Figure 2.
Example of a table of the sequence of states for individual dyads (posteriors)

Figure 3.
Number of available pairs at each time point for the two-month 4-State Model

Figure 4.
Number of available pairs for each time point in States 1, 2, and 3 (a) and States 4, 5, and 6 (b) of the six-month 6-State Model

Table 1
Fit indices for hidden Markov Models for two-month and six-month infant inoculations

Two Month				
	2-state	3-state	4-state	5-state
AIC	32231.34	29885.77	27621.61	27595.25
BIC	32374.26	30123.97	27969.43	28065.82
loglike	-16094.7	-14907.9	-13759.8	-13728.6
# par	39	61	85	111
# free	21	35	51	69

Six Month				
	2-state	3-state	4-state	5-state
AIC	21264.64	21264.64	20201.56	19725.77
BIC	21505.51	21505.51	20552.53	20200.61
loglike	-10597.3	-10597.3	-10049.8	-9793.88
# par	39	61	85	111
# free	35	35	51	69
			6-state	4-state constrained
			19310.50	20977.90
			19922.98	21081.13
			-9566.25	-10473.95
			139	85
			89	15

Table 2

Initial probabilities and behavior probabilities for the two month 4-state model

	State 1	State 2	State 3	State 4
<i>Initial Probabilities</i>	.562	.405	.006	.027
Infant distress level				
<i>High Intensity</i>	.55	.53	.00	.12
<i>Moderate intensity</i>	.13	.44	.04	.14
<i>Low intensity</i>	.21	.03	.61	.36
<i>None</i>	.11	.01	.35	.38
Maternal soothing behaviors				
Touching/ Affection	.41	.61	.68	.30
Distraction/ Face-to-face	.31	.35	.31	.59
Holding/ Rocking	.01	1.00	1.00	1.00
Feeding/ Pacifying	.16	.00	.00	.99
Vocalizing	.54	.76	.68	.62
Caretaking Tasks	.28	.04	.02	.03

Table 3

Transition matrix for the two-month 4-state model

To this state:					
	State 1	State 2	State 3	State 4	
From this state:	State 1	.86	.11	.02	.01
	State 2	.011	.89	.08	.01
	State 3	.02	.04	.92	.02
	State 4	.01	.02	.00	.97

Note: Shaded cells reflect the probability of remaining in that state.

Table 4

Initial probabilities and behavior probabilities for the six-month 6-state model

	State 1	State 2	State 3	State 4	State 5	State 6
Initial Probabilities	.841	.069	.014	.045	.007	.025
Infant distress level						
High Intensity	.99	.04	.00	.31	.00	.31
Moderate intensity	.01	.85	.01	.11	.05	.23
Low intensity	.00	.10	.55	.24	.35	.24
None	.00	.01	.44	.34	.60	.22
Maternal soothing behaviors						
Touching/ Affection	.50	.57	.51	.30	.27	.01
Distraction/ Face-to-face	.43	.42	.54	.61	.00	.25
Holding/ Rocking	.77	.94	1.00	.72	1.00	.38
Feeding/ Pacifying	.01	.00	.00	.89	1.00	.00
Vocalizing	.77	.84	.74	.85	.54	.56
Caretaking Tasks	.04	.01	.02	.09	.00	.73

Table 5

Transition matrix for the six-month 6-state model

To this state:						
	State 1	State 2	State 3	State 4	State 5	State 6
From this state:						
State 1	.74	.21	.02	.00	.01	.02
State 2	.06	.67	.23	.01	.01	.01
State 3	.00	.05	.92	.00	.02	.01
State 4	.02	.00	.01	.87	.10	.01
State 5	.00	.00	.01	.00	.99	.01
State 6	.02	.02	.03	.01	.01	.91

Note: Shaded cells reflect the probability of remaining in that state.