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Maternal Depressive Symptomatology and Child Behavior: Transactional Relationship With Simultaneous Bidirectional Coupling

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The present study investigated reciprocal relationships between adolescent mothers and their children's well-being through an analysis of the coupling relationship of mothers' depressive symptomatology and children's internalizing and externalizing behaviors. Unlike studies using discrete time analyses, the present study used dynamical systems to model time continuously, which allowed for the study of dynamic, transactional effects between members of each dyad. Findings provided evidence of coupling between maternal depressive symptoms and children's behaviors. The most robust finding was that as maternal depressive symptoms became more or less severe, children's behavior problems increased or decreased in a reciprocal manner. Results from this study extended upon theoretical contributions of such authors as Richters (1997) and Granic and Hollenstein (2003), providing empirical validation from a longitudinal study for understanding the ongoing, dynamic relationships between at-risk mothers and their children.

Keywords: dynamical systems, coupling, mother–child relations, maternal depressive symptoms, child behavior

The mother–child relationship involves a dynamic interplay between dyadic emotions and behaviors (Cummings, Davies, & Campbell, 2000; Whitman, Borkowski, Keogh, & Weed, 2001). Support for this transactional relationship has a long history in developmental theory (Belsky, 1984; Sameroff, 1975; Sameroff & Chandler, 1975). Specifically, when considering the dynamic interplay between maternal affect and children's behavior, it is likely that mothers with symptoms of depression may evidence higher rates of irritability and aggression, which in turn may induce distress, anger, and behavior problems in children (Cummings et al., 2000; Downey & Coyne, 1990). Children's resulting behavioral and/or emotional problems, such as disobedience and noncompliance, may lead some mothers to feel overwhelmed and frustrated, thereby exacerbating the severity of maternal depression (Feske et al., 2001; Forbes et al., 2008; Frye & Garber, 2005). In turn, the negative changes in maternal functioning may inadvertently reinforce children's behavior problems (Sheeber, Hops, Andrews, Alpert, & Davis, 1998). This potential downward spiral is a grave concern in at-risk dyads, such as adolescent mothers and their children. Young mothers are likely to experience multiple stressors outside the parenting realm that may contribute to depression (Borkowski, Whitman, & Farris, 2007), and as a group their children are at higher risk for psychopathology (Nicholson & Farris, 2007).

The present study modeled maternal depressive symptomatology and children's internalizing and externalizing behaviors, not with one as an outcome from the other, but rather as a dynamic, transactional relationship. Cross-lag panel models are one method that has been used to examine such relationships, but in the present study, we also sought to allow for feedback between mothers and children at an instantaneous timescale, for which cross-lagged panels do not allow. We accomplished this goal using a differential equation model of a dynamical system with coupling between changes in mothers' depressive symptoms and children's behaviors. The use of dynamical systems via structural equation modeling allowed for the modeling of a transactional relationship with

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constant feedback between members of the dyad; this was an appropriate analytic approach to match the theoretical underpinnings of the relationship being tested.

Dynamic Interplay of Maternal Depressive Symptoms and Child Outcomes

Maternal psychosocial well-being has direct and indirect effects on children's development (Ashman, Dawson, & Panagiotides, 2008; Herwig, Wirtz, & Bengel, 2004; Killeen & Forehand, 1998). For example, mothers who suffer from depression are often unable to separate their children's needs from their own, tend to express little positive affect toward their children, and respond more slowly, less contingently, and less consistently (Downey & Coyne, 1990; Goodman, 2007). Previous studies have demonstrated a variety of negative child outcomes associated with maternal depression. Behaviorally, children whose mothers are depressed have been shown to have affect regulation problems (Goodman & Gotlib, 1999; Gotlib & Goodman, 2002; Luoma et al., 2001) as well as externalizing behavior problems, decreased social competence, increased hyperactivity and attention problems (Ashman et al., 2008), and clinically significant child psychopathology (Beardslee, Versage, & Gladstone, 1998; Cummings et al., 2000; Downey & Coyne, 1990). A meta-analysis of 33 studies examining the magnitude of this relationship demonstrated a significant moderate correlation between maternal depression and child behavior problems (C. T. Beck, 1999). Taken as a whole, these findings illustrate the pervasive negative impact of maternal depression on children's development.

In contrast, less research has focused on the reverse pathway: the impact children may have on their parents (Forbes et al., 2008; Gross, Shaw, & Moilanen, 2008; Hammen, Burge, & Stansbury, 1990). As early as 1975, Sameroff criticized the mal-de-mere model, which implicated that bad mothering caused bad children (Chess, 1964), for possessing a unidirectional framework that failed to consider the impact of children's functioning on mothers' well-being. In recent years, he reemphasized this position and called for more appropriate models for understanding developmental psychopathology by using those that replicate the complexity of human behavior (Sameroff, 2000; Sameroff & MacKenzie, 2003).

In the absence of empirical evidence, even with theoretical support for a reciprocal relationship between maternal and child functioning, the transactional perspective has been called an "understudied topic" (Forbes et al., 2008). Few studies have employed analytic techniques that adequately address a bidirectional model in order to convey a transactional perspective between maternal functioning and child characteristics. Two decades ago, a negative mutual influence was identified through structural equation modeling to test the bidirectional relationship between maternal functioning and child characteristics (Hammen et al., 1990). Only recently, however, has empirical work tested the specific, direct relationship between children's behavior and maternal psychopathology (Forbes et al., 2008; Gross et al., 2008; Jaffee & Pouton, 2006). For example, Forbes et al. (2008) examined behavioral and physiological markers of child affect and the course of maternal depression over the span of a year. Longitudinal studies spanning across early to middle childhood (Gross et al., 2008) and middle childhood to early adolescence (Jaffee & Pouton, 2006) examined the relationship between maternal depressive symptoms and behavior problems.

This recent resurgence of studies (i.e., Forbes et al., 2008; Gross et al., 2008; Jaffee & Pouton, 2006) employed autoregressive analytic techniques to confirm the mutual influence of maternal depressive symptoms and children's emotional well-being through discrete time modeling. Gross et al. (2008) found consistent transactional relationships through autoregressive models for maternal depression and boys' externalizing behavior during childhood and early adolescence. The study conducted by Jaffee and Pouton (2006) provided evidence for a strong reciprocal relationship between maternal depression and child anxiety, depression, and antisocial behavior in middle childhood. Each contributed to a better understanding of the pathway between mothers and their children by addressing the transactional relationship through autoregressive models to test the mutual influence of maternal depressive symptomatology and children's negative affect and behavior.

Assessing Simultaneous Bidirectional Relationships

The need for more appropriate models is supported by prominent researchers in the field (e.g., Cicchetti, 1991; Cicchetti, Toth, & Maughan, 2000; Sroufe & Rutter, 1984). Specifically, there is a need to move beyond discrete time analysis (Delsing, Oud, & De Bruyn, 2005) and models of linear change (Granic & Hollenstein, 2003; Lewis, 2000; Sameroff & MacKenzie, 2003) in order to better explain the true nature of human behavior (Lewis, 2000; Richters, 1997). With recent technological and statistical advances, this can now be accomplished through the use of innovative analytic methods, such as dynamical systems approaches (cf. Granic & Hollenstein, 2003). Rather than consider only the effect of child or mother on each other, these models allow for continuous, bidirectional coupled relationships over time.

A *dynamical system* is a class of mathematical equations that describes time-based systems (Thelen & Smith, 2006). In these systems, which are made up of a set of variables, the current state of the system is dependent on previous states of the system. Dynamical systems models are especially interesting for the field of developmental psychology, as they (a) are consistent with most systems perspectives, (b) allow for the modeling of multiple reciprocal interactions (Granic & Hollenstein, 2003), and (c) provide a way in which to conceptualize, operationalize, and formalize complex patterns of interrelations between time, substance, and process (Thelen & Smith, 2006). Although a complete description of dynamical systems approaches is beyond the scope of this article, the interested reader is referred to Granic and Hollenstein (2003), Thelen and Smith (1994, 2006), Fogel (1993), and Lewis (2000).

One way to model a dynamical system is to use differential equation modeling. Differential equation modeling consists of any model that uses a derivative as a variable (Kaplan & Glass, 1995), in which a derivative expresses the change in some variable with respect to another variable. By using differential equation models, one can express the relationships between the current state of individuals on a measure and how individuals are changing on the same measure over time.

One differential equation model that may be particularly useful for the study of fluctuating psychological phenomena is a linear second-order differential equation, often called a damped linear

oscillator model. Psychological variables that would be well fit by this type of model are ones in which individuals tend to have some "typical" or equilibrium state around which fluctuation or intraindividual change occurs. The one physical example of a damped linear oscillator is a pendulum, which can be characterized by two parameters: its frequency of oscillation and the rate at which its amplitude changes over time. In psychology, the first parameter, which is related to frequency, can be interpreted as how rapidly someone tends to approach and move away from some typical or equilibrium state. The second parameter, referred to as the damping parameter, expresses the change in amplitude over time; much like a pendulum, a person may have a tendency to converge toward his or her equilibrium state or may tend to have more extreme states over time.

One application of damped linear oscillator models, the asymmetrically coupled damped linear oscillator, can examine the relationships between two simultaneously changing variables as if the variables were a pair of connected pendulums (Boker & Laurenceau, 2007; Boker, Neale, & Rausch, 2004). In this model, the pendulums are connected with a pair of unidirectional springs, such that the effect of each pendulum on the other can be asymmetric; for example, the effect of parents on children is not likely to be of equal magnitude as the effect of children on parents.

The type of damped linear oscillator model used in the present study was specifically chosen because it allowed for a range of trajectories that seemed theoretically plausible for the constructs being studied. For example, some mothers may have had consistent levels of depressive symptomatology over time, whereas others may have experienced worsening symptoms or recovery. Likewise, some children may have had consistent levels of internalizing or externalizing over time, whereas others may have experienced worsening symptoms or recovery that was or was not related to mothers' depressive symptoms. The coupled damped linear oscillator model allowed for all of these possibilities. This article is a first step toward recommending and testing more sophisticated, continuous coupled approaches to dyadic data analysis.

Present Study

The current study assessed relationships between maternal depressive symptomatology and children's behavior over time in a sample of adolescent mothers and their firstborn children. Due to circumstances surrounding teen pregnancies, adolescent mothers not only have more stressors in their lives than adult mothers, but also are generally less prepared for parenting and at greater risk for depression (Whitman et al., 2001). For example, teen mothers are more likely to have lower educational attainment, limited preparedness for parenting, and less social support, in addition to the stress associated with the nonnormative life event of having children during adolescence. Likewise, teen mothers in general, as well as those in our sample, tend to live in poverty (Whitman et al., 2001), which is a known risk impacting the relationships between maternal depressive symptomatology and children's development (Lovejoy, Graczyk, O'Hare, & Neuman, 2000). Moreover, the onset of internalizing and externalizing problems occurs earlier among children of adolescent parents as compared with the general population, and the rates and severity of these problems throughout childhood and early adolescence are often substantially elevated (Farris, Nicholson, Borkowski, & Whitman, 2010; Nicholson & Farris, 2007). However, research on the developmental progression of adolescent mothers and their children is particularly interesting: Although they generally represent a group at heightened risk for maladjustment, there is a significant amount of heterogeneity in the outcomes of both mothers and children. Consequently, substantial proportions achieve normative social, emotional, and cognitive outcomes despite the risks to which they are exposed (Borkowski et al., 2007; Furstenberg, Brooks-Gunn, & Morgan, 1987; Werner, 1993).

In this manner, children of adolescent mothers are an ideal population for the study of the relationship between levels of maternal depression and child maladjustment due to the increased risk for symptomatology as compared with the general population (Borkowski et al., 2007). Furthermore, our participants allowed us the opportunity to represent a typical community-based sample, as opposed to a clinically referred sample, in which the prevalence of clinical depression is relatively low (Whitman et al., 2001). Analytically, by not focusing on clinical diagnoses, we avoided splitting our sample into dichotomous diagnostic categories that would lead to unequal cell sizes and limit our statistical power; instead, the sample allowed for the continuous measurement of symptomatology (MacCallum, Zhang, Preacher, & Rucker, 2002). Theoretically, our investigation of symptomatology instead of clinical diagnoses is important, because prior research has evidenced that a dimensional approach with subclinical levels of depressive symptoms is as useful as a diagnostic one to fully understand how individual differences in maternal problems influence the mother–child relationship (Lovejoy et al., 2000).

Specifically, the present study assessed the transactional relationship between mothers' symptoms of depression and children's internalizing and externalizing behaviors. These constructs differ in many respects, yet both can be viewed as involving difficulties with the regulation of affect and behavior (Forbes et al., 2006). Internalizing problems reflect overregulation of affect and behavior and are most commonly displayed in the forms of depressed mood, anxiety, loneliness, shyness, and social withdrawal (Achenbach, Howell, Quay, & Conners, 1991). In contrast, externalizing problems are a result of underregulation of affect and behavior and are typically expressed in the forms of hyperactivity, aggression, and antisocial behaviors.

Similarly, studies of whether there are differential effects of depression for internalizing or externalizing behaviors seem to convey inconsistent findings. For example, Downey and Coyne (1990) presented that children of depressed mothers were 6 times as likely themselves to be depressed; however, null findings have also been presented for the impact of depression on children's internalizing behaviors (Ashman et al., 2008; Cicchetti, Rogosch, & Toth, 1998; Luoma et al., 2001). Therefore, in the current study, we recognized the importance of modeling the two behaviors separately to investigate differences in their relation with maternal depression.

It was hypothesized that there would be simultaneous bidirectional coupling between maternal depressive symptoms and children's internalizing and externalizing behaviors; in other words, depressive symptoms were expected to negatively affect maternal well-being to the degree that children would begin to act out (externalize) or show depressive or anxious symptoms (internalize) in response to a negative change in parents' affect. Moreover,

children's internalizing and externalizing behaviors were expected to affect the severity of maternal depressive symptoms because mothers may feel inadequate, sad, angry, and/or helpless when their children demonstrate maladaptive behavior (Cummings et al., 2000). Although recent articles have begun to illuminate this bidirectional relationship (Forbes et al., 2008; Gross et al., 2008; Jaffee & Poulton, 2006), previous research has not explicitly modeled this relationship using analytical tools in a continuous, bidirectional fashion to understand the transactional relationship between symptoms of maternal depression and children's behavior problems.

Method

Participants

Participants were 122 dyads of adolescent mothers and their firstborn children from a medium-sized midwestern city and a predominantly rural area of the South, who were part of a larger longitudinal study of the precursors, correlates, and outcomes of teen parenting (Borkowski et al., 2007; Whitman et al., 2001). Maternal age at childbirth ranged from 14.02 to 19.46 years (M = 17.06, SD = 1.25). The majority of the mothers were African American (64.75%), 27.87% were Euro-American, and 7.38% were Latina. Socioeconomic status was determined at the initial interview through the participants' reports of the education and employment status of the adults with whom they resided, as the teens generally were not self-supporting. In general, participants were from disadvantaged socioeconomic backgrounds on the Hollingshead Index (M = 55.90, SD = 13.2; Hollingshead & Redlich, 1958). Boys and girls were approximately equally represented in the sample (54.92% male). Hospital records indicated that the infants were typically born in good health in terms of birth weight and Apgar scores (Whitman et al., 2001).

Design and Procedures

Primiparous teenagers were recruited during the third trimester of pregnancy through local clinics, hospitals, and school-age-mothers programs. Informed consent was obtained from mothers, and assent was attained from their mothers or legal guardians when the participants were under age 18 at the initial assessment of the larger longitudinal project. Interviews were conducted on an individual basis and typically lasted 1–2 hr; mothers were provided with a monetary compensation for their time, and children at 8 and 10 years were given gifts for their participation in the project. Data for the present study were drawn from maternal and child assessments completed when the children were 3, 5, 8, and 10 years old. At all four time points, mothers provided self-reports of their own depression symptomatology through the Beck Depression Inventory and reported on their children's internalizing and externalizing behaviors using the Achenbach Child Behavior Checklist (CBCL).

The majority of attrition for the larger longitudinal study occurred during the initial prenatal interview and the first annual postnatal assessment when the children were 1 year old (36.46%) and was mainly attributed to loss of contact due to participants moving. However, retention of participants at the subsequent assessments included in this study (3, 5, 8, and 10 years) was relatively stable, and there were no significant differences when comparing those who discontinued participation based on demographic or dependent variables, except that African American mothers were more likely to remain in the study than Caucasian mothers. Of the original 288 dyads recruited for the study, 171 were available for interviews at the 3-year assessment, and by 10 years 150 were contacted. See Table 1 for the sample size collected for each time point.

Estimation of the second derivative required a minimum of three observations; this is similar to the need for three observations to estimate a quadratic trend. Dyads were required to have complete data at least at three of the four time points, leading to a sample size of 122. One participant had an incomplete externalizing score, reducing the sample size to 121. Participants included in the present study did not differ from those who were excluded in terms of maternal socioeconomic status, age at childbirth, years of education, IQ, or race.

Maternal depression symptomatology. The Beck Depression Inventory is a 21-item self-report measure (Groth-Marnat, 2003) of characteristic attitudes and symptoms of depression (A. T. Beck, Steer, & Garbin, 1988). Mothers were administered the inventory, specifically being asked about symptoms over the past week. The items are sum scored, with scores above 30 indicating clinically severe depression and scores below 9 being indicative of minimal or no depressive symptoms. Scores between 10 and 18 indicate mild depression, and scores between 19 and 29 specify moderate depression. Reliability and validity measures are well established (Richter, Werner, Heerlein, Kraus, & Sauer, 1998); specifically, internal consistency among items was good

Table 1
Internalizing and Externalizing T Scores and Sample Sizes at 3, 5, 8, and 10 Years

		Internalizing				Externalizing			
				%				%	
Year	N	M	SD	Borderline	Clinical	M	SD	Borderline	Clinical
3	171	56.13	8.60	18.4	4.3	53.77	8.80	7.8	4.3
5	161	50.47	8.98	6.5	4.3	53.99	9.11	13.7	7.9
8	151	51.40	9.09	8.9	3.6	52.75	8.61	8.1	1.8
10	150	51.64	9.61	10.0	5.0	52.06	10.36	13.4	0.0

Note. N = 122. Dyads were required to have complete data at least three of the four time points.

when administered to multiple clinical populations ($\alpha = .79–.90$; A. T. Beck & Steer, 1993).

Mothers' mean scores on the Beck Depression Inventory were consistently around 8 points, with a standard deviation of approximately 7 points (3 years: $M = 8.86$, $SD = 6.67$; 5 years: $M = 8.33$, $SD = 7.44$; 8 years: $M = 9.34$, $SD = 7.74$; 10 years: $M = 7.06$, $SD = 7.06$). In terms of severity, the percentage of mothers scoring in the minimum (<9) or mild (10–18) range suggested that the majority of mothers across all time points did not present clinical levels of symptomatology (3 years: 62.3% minimum, 24.7% mild; 5 years: 66.0% minimum, 20.6% mild; 8 years: 60.2% minimum, 22.2% mild; 10 years: 79.8% minimum, 10.5% mild), with about 10% of the sample reporting moderate depression at 3, 5, and 8 years. At these time points, severe depression was reported by 1.4% (3 years), 3.5% (5 years), and 6.5% (8 years) of the sample. A decrease in the prevalence of moderate and severe depression was found when the children were 10 years; only 5.3% of mothers reported scores classifying them in the moderate depression range, and 4.4% fell in the severe depression range. The correlation between time points was highly significant ($p < .01$) when examining the relationship between each time point (i.e., 3 and 5, 3 and 8, 3 and 10, 5 and 10, 8 and 10 years) except for the relationship between maternal depression at 5 and 8 years ($r = .18$, $p = .07$).

Internalizing and externalizing behaviors. The CBCL offers standardized problem scales that reflect behaviors consistent with internalizing and externalizing problems. When children were 3 years old, the 100 items of the CBCL/2–3 (Achenbach, 1992) were administered; at the 5-, 8-, and 10-year assessment, a different, developmentally appropriate version containing 113 items was given to the mothers (CBCL/4–18; Achenbach, 1991). Mothers rate their children over the past 6 months on a 3-point scale (0 = *not true*, 1 = *somewhat or sometimes true*, 2 = *very true or often true*) on their perception of their children's behavior. The mothers were asked to report how true statements were of their children. For behavior problems on both the internalizing and externalizing scales, standardized T scores between 60 and 63 are considered borderline, and those falling above this range are considered in the clinical range.

Although there is overlap between the CBCL/2–3 and the CBCL/4–18 on specific items (i.e., "Doesn't get along well with other kids"), different items asked between the two versions allow for appropriate changes across time in behaviors indicative of internalizing and externalizing in children during specific developmental periods. For example, the CBCL/2–3 asks mothers to rate "resists toilet training," whereas the CBCL/4–18 asks them to rate "acts too young for age." In fact, the CBCL/2–3 was created based on items from the CBCL/4–18 that were reworded to fit behaviors at a younger age. These items were created via child development literature and parent interviews about parental concerns during this time point.

Reliability and validity for both versions of the measure are well established: Test–retest reliability coefficients ranged from .79 to .92 for CBCL problem scales over a 7-day interval (Achenbach, Edelbrock, & Howell, 1987). An evaluation of criterion validity indicated that the measure differentiated between groups of children with and without psychiatric problems above and beyond the variance accounted for by child gender and maternal depression (Friedlander, Weiss, & Traylor, 1986). Acceptable construct validity for the subscales has been evidenced for both internalizing ($r = .56–.72$) and externalizing behaviors ($r = .52–.88$; Achenbach, 1991). Acceptable to high internal consistency was supported across all behavioral scales for a matched sample of referred and nonreferred girls and boys from 12 to 18 years ($\alpha = .68–.92$; Achenbach, 1991). Internal consistency for the current sample showed similar levels for the 3-, 5-, 8-, and 10-year assessment ($\alpha = .88–.93$).

Table 1 presents the mean scores for internalizing and externalizing behaviors and the percentage of children falling in the borderline and clinical range across the four time points examined. Standardized externalizing scores were fairly consistent across time points. Standardized internalizing scores were reported by mothers to be significantly higher at 3 years than at subsequent time points ($p = .001$). Standardized externalizing scores were highly correlated between all time points ($p < .01$); standardized internalizing scores were highly correlated at all time points, with the exception of the relationship between 3 and 8 years and 3 and 10 years ($p < .05$). Internalizing and externalizing scores were highly correlated with each other at all time points ($p < .01$).

Transforming data. The scores for each scale were centered with the mean of all observations (i.e., all individuals at all times). This step is necessary when using the damped linear oscillator model, as the equilibrium value is assumed to be equal to zero. The scores of each scale were also divided by the standard deviation of scores within each scale, across all individuals and time points, in order to improve the interpretability of the coupling parameter by making the variances of the scales equivalent (Boker, 2007; Boker & Laurenceau, 2007). The resulting transformed data consisted of z scores for each of the scales.

Results

Results are divided into two sections. First, the analytic plan is presented, with detailed descriptions of latent differential equation modeling and the interpretation of the parameters associated with damped linear oscillators. Next, a series of models are presented. The models tested were selected for two purposes: (a) to examine whether the coupled damped linear oscillator model seemed appropriate for these data and (b) to further examine the coupling relationship between mothers and children. Findings are provided on how well the data fit the models, including a discussion of parameter estimates.

Analysis

The coupling between mothers' depression symptoms and children's internalizing and externalizing behaviors was examined by fitting a coupled damped linear oscillator model (Boker et al., 2004) to time series data collected on each of these variables at 3, 5, 8, and 10 years of age. The relationships of depressive symptoms with internalizing and externalizing behaviors were examined in separate models, as differential coupling effects between these specific behaviors and depressive symptoms were anticipated. Optimization of each structural equation model was accomplished with the structural equation modeling and numerical optimizer OpenMx (Boker et al., 2011).

Latent differential equations assume that there is a continuous function underlying the data, and consequently, as long as the

spacing between observations is correctly specified, this modeling approach can be applied to data that are not equally spaced in time. For the present analyses, latent differential equation weights were adjusted to match the appropriate interval between occasions of measurement. Due to the presence of missing observations for some participants, estimation of models occurred via full information maximum likelihood.

The damped linear oscillator can be described with two parameters: one related to frequency (η) and the other to damping (ζ). The η parameter can be interpreted as how rapidly someone tends to approach and move away from some equilibrium state, whereas the ζ parameter expresses the change in amplitude over time. The latent differential equation model that was used describes mothers' depressive symptoms and children's behavior, each as a damped linear oscillation. For the damped linear oscillator model, the acceleration in scores is equal to the observed scores times η plus the change in observed scores times ζ.

The two oscillators were coupled with additional parameters labeled γ. These parameters connect the two models and express the effect of the acceleration in one construct on the other. As shown in Figure 1, the observed acceleration, estimated from the data, is equal to 1 times the estimate of the depression acceleration

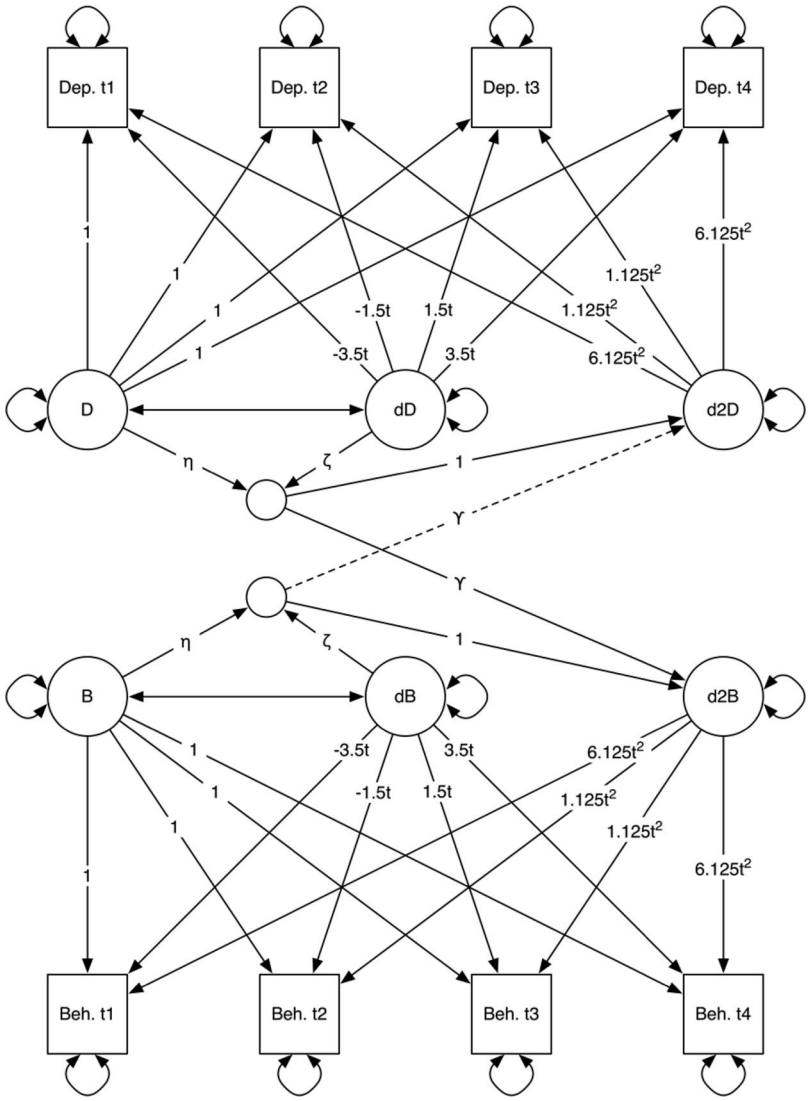

Figure 1. Dynamical systems model fit to observed data via structural equation modeling. Estimates of depressive symptomatology (D) and its first two derivatives (dD, d2D) as latent factors of Beck Depression Inventory scores across four time points (Dep. t1, Dep. t2, Dep. t3, Dep. t4) are modeled in the upper half of the diagram, and behavior (B) and its first two derivatives (dB, d2B) as latent factors of Child Behavior Checklist scores across four time points (Beh. t1, Beh. t2, Beh t3, Beh t4) are modeled in the lower half. The four time points of measurement are represented as t1, t2, t3, and t4; *t* determines the timescale of the parameters. In this case, $t = 1$ would produce estimates based on a timescale in which a one-unit change is equal to a change in time of 1 year. The models used are all variations of the full model depicted.

assuming a damped linear oscillator (the small circle) plus a coupling parameter (γ) times the estimate of the behavior acceleration. In other words, if maternal depressive symptoms were to follow the model of a damped linear oscillator, the expected acceleration, as represented by the small circle, would be subtracted from the observed acceleration in depression. The variance that remains is then regressed on the damped linear oscillator fit to the behavior data. When the slope of the regression is significantly different from zero, this would suggest that there is residual acceleration in depressive symptoms that is explained by accelerations in behavior.

Figure 1 shows the full model, that is, the model including all η, ζ, and γ parameters. In this figure the derivatives for the damped linear oscillators are defined by fixing the weights of the paths between the observed variables and the latent derivatives. This is similar to the way that latent intercept and slope estimates are achieved in latent growth curve modeling. The weights of the fixed paths between the latent variables and the observed variables are defined by Boker et al. (2004).

The first sequence begins with a null model that does not include the relationships between derivatives η and ζ, nor the coupling parameters γ. The subsequent four models—eta only, eta and zeta, eta and gamma, and full—add the parameters η; η and ζ; η and γ; and η, ζ, and γ, respectively. The models with η and ζ parameters consist of unconnected damp linear oscillators for mother and child; the addition of the γ parameter allows the damped linear oscillators to affect each other.

Finally, the coupling relationship between mothers and children was examined. The best fitting model from the previous series was altered to include either only coupling from mother to child or only coupling from child to mother. Except as noted in the final models, parameters were added symmetrically for both mothers and children.

Findings

Tables 2 and 3 present indicators of model fit: –2 log-likelihood, degrees of freedom, Akaike information criterion, and Bayesian information criterion. The tables reflect the relationships of mothers' levels of depressive symptomatology with children's internalizing and externalizing behaviors. The Akaike and Bayesian information criteria can be used to assess the relative fit of the models, with lower numbers indicating better fitting models (Akaike, 1974; Schwarz, 1978). Both information criteria penalize for additional parameters, to take into account the expected improvement in fit as the number of parameters increases. Table 4 provides the *p* values from likelihood ratio tests of specific pairs of models.

Table 2
Model Fit Indices for Externalizing Behaviors

Model	−2 LL	*df*	AIC	BIC
Null	2295.07	22	571.1	−919.5
Eta only	2284.29	24	564.3	−920.0
Eta and zeta	2282.93	26	566.9	−915.9
Eta and gamma	2272.97	26	557.0	−920.9
Full	2271.67	28	559.7	−916.8
Eta and one gamma (child to mother)	2282.50	25	564.5	−918.5
Eta and one gamma (mother to child)	2272.98	25	555.0	−923.3

Note. −2 LL = −2 log-likelihood; AIC = Akaike information criterion; BIC = Bayesian information criterion.

Table 3
Model Fit Indices for Internalizing Behaviors

Model	−2 LL	*df*	AIC	BIC
Null	2332.54	22	598.5	−916.3
Eta only	2323.39	24	593.4	−916.0
Eta and zeta	2323.08	26	597.1	−911.4
Eta and gamma	2310.86	26	584.9	−917.5
Full	2308.38	28	586.4	−913.9
Eta and one gamma (child to mother)	2318.43	25	590.4	−916.1
Eta and one gamma (mother to child)	2310.87	25	582.9	−919.9

Note. −2 LL = −2 log-likelihood; AIC = Akaike information criterion; BIC = Bayesian information criterion.

The pattern of results was similar for both internalizing and externalizing behaviors. The relative fit measures (Akaike information criterion, Bayesian information criterion) and likelihood ratio tests suggest that the η (frequency) and γ (coupling) parameters are necessary; however, the ζ (damping) parameters are not necessary. This suggests that a linear oscillator model is a reasonable model for these data. Furthermore, models that include coupling between mother and child fit these data better than models that do not include coupling.

Additional models examined whether both coupling parameters were necessary. The comparisons of the eta and gamma model to models that include only a single coupling parameter suggest that removing the coupling from child to mother does not result in a substantially worse fit to the data. However, the removal of the coupling from mother to child does result in a substantially worse fit to the data. These results suggest that although there is coupling between the mother's depressive symptomatology and the child's internalizing and externalizing behaviors, the coupling from child to mother appears to be less important to include in the model than the coupling from mother to child. Due to the potential for a Type II error, these results do not exclude the potential influence of child on mother; however, if there is such an effect, it is likely to be of much smaller magnitude than the effect of mother on child. The same patterns of results were observed for internalizing and externalizing behaviors.

Table 5 presents the frequency and coupling parameter estimates for the eta and gamma model. Regardless of the coupling,

Table 4
Comparison of Models Using the Likelihood Ratio Test

	p	
Model	Externalizing	Internalizing
Null–eta only	.005	.010
Eta only–eta and zeta	.507	.856
Eta only–eta and gamma	.003	.002
Eta and gamma–full	.522	.289
Eta and gamma–eta and one gamma (child to mother)	.002	.006
Eta and gamma–eta and one gamma (mother to child)	.920	.920

Table 5
Parameter Estimates (Based on Δt = 1 year), Eta and Gamma Model

	Externalizing				Internalizing			
			95% CI				95% CI	
Model	Estimate	*SD*	*LL*	*UL*	Estimate	*SD*	*LL*	*UL*
η_{mother}	.168	.063	.06	.45	.152	.006	.06	.54
η_{child}	−.039	.017	−.08	−.01	−.027	.017	−.07	.03
$\gamma_{mother–child}$	.604	.244	.20	1.0	.638	.152	.18	1.0
$\gamma_{child–mother}$	−.043	.375	−1.0	1.0	−.167	.758	−1.0	1.0

Note. CI = confidence interval; *LL* = lower limit; *UL* = upper limit.

the mother's frequency parameter does not suggest oscillation but rather approximate exponential divergence to or from equilibrium, such as a rapid increase or decrease in depressive symptomatology over the course of the study. The children's frequency parameter suggests the possibility of oscillation over the course of many years, but over the range of years examined suggests trajectories that are similar to an exponential or quadratic model; the range of years examined would cover about 20% of one cycle, so the trajectories could look like any 20% window of a single sine cycle. The exact trajectory will depend on the initial conditions of mother and child.

The coupling parameter (γ) represents the effect of the acceleration of one construct on the other. There is strong support for coupling from mother to child in these data. The parameter estimates were significantly larger than zero, as demonstrated with the likelihood ratio tests. For both internalizing and externalizing, the coupling parameter from depressive symptoms to behavior was positive (internalizing: $\gamma = 0.604$; externalizing: $\gamma = 0.638$). As the variables were standardized, one would expect coupling parameters to range between −1 and 1; a value of 0 suggests no coupling, an absolute value of 1 suggests the mother is having as much effect on the child as the child has on him- or herself, and an absolute value greater than 1 suggests the mother is having more effect on the child than the child has on him- or herself. The current γ values suggest that as depressive symptoms increased more rapidly (accelerated), so did internalizing and externalizing behaviors; the magnitude of the coupling parameter suggests that a large proportion of the child's acceleration is coupled to changes in the mother.

In contrast, the results do not clearly indicate coupling from child to mother. For both mother–child and child–mother coupling the standard errors are very wide, making it difficult to garner information about the true effect sizes. These results do suggest, however, that child-to-mother coupling may consist of a substantially smaller effect than for mother-to-child coupling. Figure 2 gives an impression as to whether the mother–child and child–mother coupling are likely to have a real impact on individuals. The coupling parameter is not easily translated into typical effect size terms (e.g., a standardized mean difference), as the effect on behavior will depend on the initial conditions of mother and child, such as whether their depression or behaviors were initially increasing, decreasing, or stable. Specifically, Figure 2 shows one possible trajectory that was generated with the model parameters and a set of initial conditions selected to represent a mother who transitioned from no clear signs of depression to the lower range for a moderate level of depression. The figure conveys that the

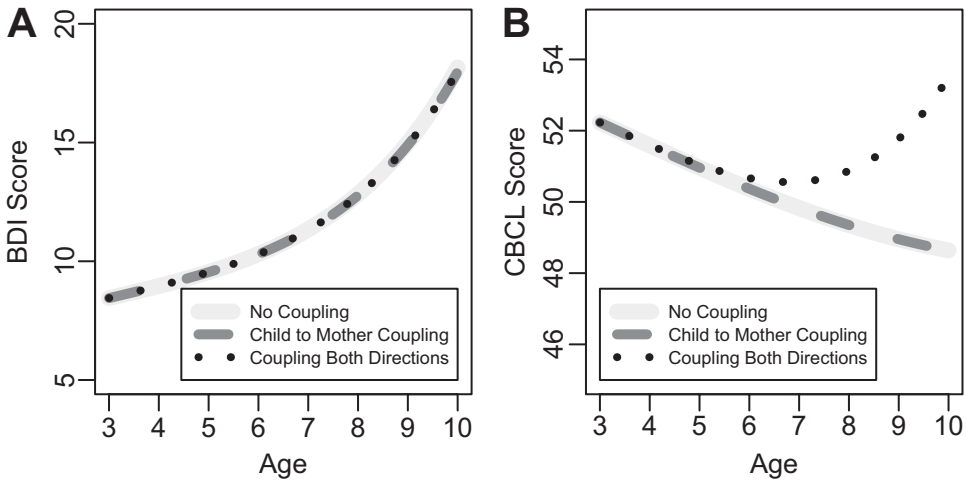

Figure 2. An example of the model-implied trajectories. The three lines correspond to the whether the Beck Depression Inventory (BDI) or Child Behavior Checklist (CBCL) scores are affected if there was (a) no coupling between mother and child, (b) coupling only from child to mother, and (c) coupling in both directions.

coupling of child to mother produces few observable changes in the mother's depression (Figure 2A: light gray vs. dark gray line). However, including the coupling from mother to child (Figure 2B: light gray line vs. dotted line) produces enough change that the child shows an increase of several points for behavior over the course of several years. The effect of mother on child may produce only a small change in terms of behavioral scores, even after 3 years. However, the ongoing, continued effect of the mother on child could lead the child to develop a different trajectory over time. In this example, a child with initially decreasing behavioral problems (negative slope) eventually developed behavioral problems with a positive slope due to the coupling with mother's depression. This example suggests that over the course of just a few years, the mother-to-child coupling is strong enough that even a transition to moderate depression can produce a large change in child behavior in terms of a behavioral score and the trajectory of a child's behavioral problems.

Discussion

Theoretical models in the field of developmental psychology have long suggested that reciprocal influences characterize parent–child dyads (Belsky, 1984; Cummings et al., 2000; Downey & Coyne, 1990; Sameroff & Chandler, 1975). Empirical work, however, has lagged behind theory in testing transactional models that can support or refute these theoretically proposed bidirectional relationships (Granic & Hollenstein, 2003; Richters, 1997) in which children are not passive recipients in the developmental process (Delsing et al., 2005). The models used in the present study enhance our understanding of simultaneous, continuous, bidirectional developmental phenomena such as the interwoven lives of at-risk mothers and their children. The dynamical systems analysis used a minimal amount of data in a way that addressed Richters's (1997) call for the abandonment of ritualized hypothesis testing in favor of more exploratory, creative approaches that emphasize the discovery process. Findings also addressed the call for more appropriate and realistic analytic models in the study of human development (Carothers, Farris, & Maxwell, 2007; Cicchetti et al., 2000; Granic & Hollenstein, 2003; Sameroff, 2000) and for research directly assessing the transactional relationship between maternal psychological well-being and children's behavior (Forbes et al., 2008; Gross et al., 2008; Hammen et al., 1990).

The unique data that were available for the present study have provided a glimpse into the complex relationships between maternal psychological well-being and children's socioemotional development. It has long been accepted that reciprocal influences between mothers and children constitute a mutual contingency in which each member of the dyad influences the other to some degree (Cummings et al., 2000). Specifically, findings have provided empirical support for theoretical work suggesting that parent–child interactions are sequential social exchanges (Pineda, Cole, & Bruce, 2007) and that development is continuous.

In the present study, we tested the bidirectional transactional coupling between mothers' depressive symptomatology and children's internalizing and externalizing behaviors using continuous time modeling. The effects of maternal depressive symptomatology on children's internalizing and externalizing behaviors were supported through both the model fit indices and the coupling parameters. The positive coupling parameters obtained from the models indicated that as maternal depressive symptoms became more or less severe, children's internalizing and externalizing behaviors changed in a similar fashion. Furthermore, the coupled rate of change of mothers to their children suggested that as depressive symptoms accelerated in change, children's behavioral problems mirrored this trend. Findings indicate that there is likely to be a mutual downward spiral if mothers' depression symptomatology increases and a mutual improvement in functioning if mothers experience healthier affect or behavior.

Model comparisons indicated an asymmetric bidirectional relationship between the dyads such that the coupling from child to mother was less integral to the model than the coupling from mother to child. In other words, changes in the severity of maternal depressive symptomatology had a greater impact on children's behaviors than the changes in children's behaviors had on their mothers' levels of depressive symptoms. Previous research has supported this type of give-and-take relationship between maternal affect and children's behaviors (cf. Lovejoy et al., 2000). For example, research has demonstrated a bidirectional relationship between maternal depression and boys' antisocial behavior, in which the influence of mothers on their sons was stronger than the influence of sons on their mothers (Gross et al., 2008). The current study, however, modeled the bidirectional relationship using a more realistic approach that allowed for continuous feedback between the mother and the child as if they were constantly interacting with each other. In contrast, cross-lag panel models allow for feedback only across a single fixed, relatively long period. The discrete time approaches previously employed to examine this relationship posit a strange coupling relationship that does not account for the constant back-and-forth interplay between mothers and children (Deboeck, in press).

The confidence intervals associated with the coupling parameters provided further insight into why the current study showed the effect of mother–child coupling was more influential than the child–mother coupling. The confidence intervals for mother–child coupling showed a clear departure from zero; in contrast, the child–mother coupling parameter showed a very wide range. The wide confidence intervals for child–mother coupling suggest two things: (a) The average coupling from child to mother is likely to be smaller than the effect of mother to child, and (b) the coupling from child to mother may differ dramatically for differing dyads. That is, the mother-to-child coupling may appear more consistent because the child may have more limited ways in which to react to a mother's depression. A mother, on the other hand, may have many options for coping with the child's misbehavior, from reacting with hopelessness or helplessness to seeking help from teachers, counselors, or community agents. The selection of differing strategies may lead the effect of children's behaviors on mothers' depression to result in different types of coupling for different dyads.

The current study found similar bidirectional relationships for the models examining internalizing versus externalizing behaviors, suggesting that children's internalizing and externalizing behaviors reacted in a similar manner to their mothers' depressive symptomatology and changes in these symptoms over time. This is an important finding given that these constructs represent two strikingly different manifestations of children's problems (Achenbach et al., 1991). It is likely this is not necessarily reflective on these behaviors being the same in their transactional relationship

with maternal depressive symptomatology, but suggests that nuanced differences may not have been detected in the present study for how depressive symptoms could differentially elicit or be affected by internalizing and externalizing behaviors.

Past research has presented inconsistent and contrasting evidence as to how children may react behaviorally to maternal depressive symptomatology. For example, some studies provide a link between maternal depression and internalizing behaviors (Downey & Coyne, 1990), whereas others indicate a null relationship (Ashman et al., 2008; Cummings et al., 2000; Goodman & Gotlib, 1999; Gotlib & Goodman, 2002; Jaffee & Poulton, 2006). Additionally, prior research has suggested that maternal depression may have a direct impact on children's internalizing symptoms (i.e., depression), but externalizing problems may be mediated through contextual factors, such as marital discord (Downey & Coyne, 1990). As such, the study's lack of differences between the two models of children's internalizing and externalizing behaviors could be explained by the true pathways of influence not being modeled.

Another unique aspect of the present study was the incorporation of a community sample with subthreshold maternal depressive symptoms as compared with extant studies that have focused on clinical depression (Ashman et al., 2008; Jaffee & Poulton, 2006). This may have impacted the assessment of any differential manifestation of children's behaviors as a result of maternal depressive symptoms. Adolescent mothers report higher rates of symptomatology than would be evident in a normative nonrisk sample, yet the prevalence of clinical depression in this sample was comparable to what would be seen in normative populations. Therefore, the similarity of findings between the bidirectional relationship supported by internalizing and externalizing models may have been influenced by the young mothers in our sample experiencing a range of depressive symptomatology instead of clinical levels of depression.

It is important to view the findings in light of the sample chosen: a community sample of adolescent mothers and their children. The highly interwoven level of development often seen between young mothers and their children (Whitman et al., 2001) makes it a meaningful population in which to assess the transactional give-and-take among dyads. Yet, although this population is generally considered to be at increased risk for the development of maternal depression or child behavior problems (Whitman et al., 2001), a significant degree of heterogeneity in outcomes is consistently found, suggesting that they are doing well despite the odds (Borkowski et al., 2007; Furstenberg et al., 1987; Werner, 1993).

Data collection for the present longitudinal study began before the formulation of the dynamical systems framework, yet it still offered a valuable attempt at understanding continuous, bidirectional coupling between high-risk mothers and their children and provided further empirical support for the direct relationship between maternal psychological well-being and child behavior. Future studies employing dynamical systems as an analytic tool may further explain the bidirectional relationship through multimodal assessment, an increased frequency of reporting across time, and increased sample size.

The data set used for the present study was limited to maternal reports about both members of the dyads; as such, it lacked potential perspective and convergent validity of change that would have been afforded by a multi-informant design. In addition, it is possible that maternal depressive symptomatology may have influenced perceptions of their children's behavior and contributed to shared method variance (Frye & Garber, 2005; Geiser, Eid, Nussbeck, Courvoisier, & Cole, 2010; Jaffee & Poulton, 2006). Maternal reports, however, are a valid portrayal of children's functioning, because many children display problem behaviors within the home that may not be viewed by others, such as teachers (Briggs-Gowan, Carter, & Schwab-Stone, 1996). Furthermore, the current sample was not a population of clinically depressed individuals. With the low rate of clinical levels of depression in our sample, the likelihood of mothers' symptoms impacting their perceptions of their children's behavior is much less likely (Ashman et al., 2008), especially as the tendency to overreport has been linked with increasing depression (Fergusson, Lynskey, & Horwood, 1993).

Ideally, data used for dynamical systems analyses would incorporate repeated measurements at closer increments and greater frequency in order to explain how developmental processes unfold over time and decrease potential bias in the data (Cummings et al., 2000; Granic & Hollenstein, 2003 Richters, 1997). With only four observations per individual, it was not possible to estimate individual model parameters but only a single group effect (Boker & Nesselroade, 2002). In reality, there may be significant individual differences in the relationships between constructs, such as age effects, which could likely further disentangle the association between the different forms of behavior problems and their relationship with maternal depressive symptoms (Ashman et al., 2008). Although this was a necessary limitation of the current approach, due to the limited length of the time series measured, collections of longer individual time series would allow for greater power for the estimation of intradyad parameters so as to explain interdyad differences and identify variables that may be predictive of healthier dyadic interactions. Additional research is also needed to further explore whether influences from child to mother would be stronger in larger samples with more data.

A future study that addresses these three limitations could expand upon findings by incorporating process-oriented variables, for example, including mediators and moderators of specific parenting behaviors, socioeconomic status, and age- or gender-related changes impacting the transactional relationship (Jaffee & Pouton, 2006; Lovejoy et al., 2000). For example, a dynamical systems approach is best suited to answer the question of whether children's internalizing versus externalizing behaviors are most influential on or influenced by maternal depressive symptoms. As prior studies on the relationship between internalizing and externalizing behaviors have shown inconsistent findings, this type of analysis could provide conclusive evidence not hindered by analytic capacity. In effect, these limitations point to the utility of the dynamical systems approach; a project designed with these limitations in mind would fully benefit from this approach in examining transactional relationships.

These findings have potential implications for intervention programming: The strong effect from mother to child suggests that if one were to design an intervention to address behavioral problems in children, it would be imperative to incorporate a family systems approach in which mothers' depressive symptoms and their effects on children's behavior problems were also addressed. In this manner, intervention programming may be more effective, as results from the present study suggested

that children mirror their mothers' changes and rates of change in symptomatology. Therefore, in accord with the results from the present study, a two-pronged family systems approach would be an ideal way to minimize children's behavior problems and would also have the benefit of helping mothers and the family as a whole.

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