Laying the Groundwork:

Dynamic Associations Between Physiological and Social Roots of Executive Function Development in a Latent Change Score Framework

by

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ABSTRACT

This study aimed to develop a measurement model for executive function (EF) in middle childhood for a low-income Mexican American sample and to elucidate dynamic change processes among measurable developmental correlates of EF during infancy and early toddlerhood as predictors of later higher-order EF abilities. Drawing from developmental theory and a model of neurovisceral integration, surges in neurocognitive regulatory abilities may be supported by both previous and concurrent changes in physiological functioning and engagement in reciprocal social relationships. Utilizing recent methodological innovations, the current study moved beyond traditional growth models to evaluate possible points of attenuation and acceleration in dyadic reciprocity and vagal functioning over time as well as dynamic associations between these unfolding developmental processes. Data were collected from 322 low-income Mexican American children in the home at 24 weeks and in a laboratory space at ages 1, 1.5, 2, 3, and 6 years. A parent-report measure of executive function also was collected over the phone between child age 7.5 and 9 years. Results suggested that, in this sample, EF was best modeled at child age 6 years as a unidimensional construct. Findings also supported the importance of earlier dyadic reciprocity for later EF, but there was a lack of evidence supporting the theorized link between EF and earlier vagal functioning and codevelopment of vagal functioning and dyadic reciprocity. This study highlights the importance of including dyadic measures of parent-child contingencies in studies of EF development and, from a clinical perspective, the potential use of relationship-based, dyadic intervention and prevention models to support crucial development of EF skills central to everyday adaptive functioning.

To my parents and siblings,
for being a source of constant love and support
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INTRODUCTION

Executive function is a universal cognitive process that emerges early and continues to mature as individuals progress throughout subsequent developmental stages. The processes subsumed under the umbrella term “executive function,” inhibitory control, working memory, and set-shifting, facilitate the coordination of goal-directed behavior (Miyake et al., 2000). Impairments in executive function, also referred to as executive *dys*function, have been related to a host of maladaptive physical and mental health outcomes during childhood such as substance abuse (Pentz & Riggs, 2013), internalizing and externalizing disorders (Rinsky & Hinshaw, 2011; Woltering et al., 2016), and obesity (Pentz, 2009).

The importance of supporting the development of executive function skills in early childhood has been highlighted as central to child health promotion programs (Pentz & Riggs, 2013), and significant resources have been devoted to expanding our understanding of developmental trajectories and neural substrates of executive function from infancy to an age of cognitive maturity in the mid -20s (Fiske & Holmboe, 2019). This work has uncovered periods of rapid developmental change in executive function during early childhood as the prefrontal cortex develops (Anderson & Reidy, 2012; Carlson, Davis, & Leach, 2005; Zelazo et al., 2003). Developmental theory and a model of neurovisceral integration (Thayer et al., 2009; Thayer & Lane, 2000) suggest that surges in neurocognitive regulatory abilities may be supported by both previous and concurrent changes in physiological functioning (e.g., cardiovascular regulation) and engagement in reciprocal social relationships (e.g., turn-taking), yet there is little empirical documentation to support the theorized interrelatedness of these processes during early development, especially among underrepresented minority groups. Within a sample of Mexican American children, this study utilized a dynamic approach to examine the interrelatedness of change in developmental correlates of early executive function skills (e.g., dyadic reciprocity and physiological functioning) as they relate to more complex EF abilities in middle childhood.

The Development of Executive Function

The amount of sensory information encountered daily by individuals as they navigate the world around them has the capacity to overload the sensory system if not for a “filter” that selects what information reaches cognitive awareness (Broadbent, 1958; Driver, 2001). Rooted in Donald Broadbent’s (1953) model of autonomic and controlled processes, this filter model provides a preliminary conceptualization of executive function as a construct. As humans, we have a limited ability to attend to stimuli in our environment and successful day-to-day functioning depends on an executive system within the brain that helps us select which stimuli should be favored and which should be considered irrelevant (Goldstein et al., 2014). Children, in particular, are continuously surrounded by and encounter novel stimuli in their environments, making the ability to pay attention to selected stimuli (e.g., the information presented by their teacher) over nonessential stimuli (e.g., the passing cars outside the window) foundational to learning. The functioning of this system, herein referred to as executive function (EF), is not a single phenomenon but rather a collection of supervisory neuro-cognitive processes (i.e., inhibitory control, working memory, and set-shifting) that are necessary for self-regulated and purposeful behavior. *Inhibitory control* is characterized by the flexible activation and inhibition of selected information and responses, *working memory* involves the maintenance and manipulation of information over a short period, and *set-shifting* (also referred to as cognitive flexibility) involves the ability to flexibly adapt to new and unexpected conditions by shifting the focus of attention.

The development of EF is posited to be hierarchical in nature, with simpler forms of skills (e.g., attending to a stimulus, delaying a response, holding information in mind) laying the foundation for the emergence of more complex forms of working memory, inhibition, and set-shifting (Garon et al., 2008; 2014). Rudimentary forms of working memory and inhibition are thought to exist in the first year of life (e.g., Diamond, 1990) but it is not until the second year of life that infants begin to actively coordinate these early skills in a useful fashion (e.g., using a simple rule held in mind to inhibit a motor response; Garon et al., 2008; 2014). Rapid developmental growth in more complex forms of EF occurs from 3 to 5 years of age (Carlson, Davis, & Leach, 2005; Zelazo et al., 2003). Johansson and colleagues (2016) provide some empirical support for the hierarchical model of EF development, with inhibition during infancy predicting working memory in toddlerhood. Further, sustained attention during a parent-infant free play session was positively associated with later EF abilities at 36 months of age but did not contribute above and beyond the predictiveness of concurrent simple EF. This finding suggests that, prior to 12 months of age, sustained attention underlies the development of simpler forms of EF and, after 12 months of age, sustained attention is an integrated part of simpler executive functions and no longer contributes independently. No stability in individual differences in EF skills was found from 24 to 36 months, possibly attributable, in part, to surges in prefrontal cortex development during this period (Johansson et al., 2016).

In recent decades, neuroimaging capabilities have afforded insight into associations between prefrontal cortex (PFC) development (e.g., connectivity within the PFC and between the PFC and other brain regions) and cognitive functioning, with evidence for periods of rapid developmental change emerging (Diamond, 2002; Fiske & Holmboe, 2019). Prefrontal cortex stimulation in the context of sensitive and stable caregiving (e.g., joint attention, supportive presence) during early childhood supports the development of EF (Raver & Blair, 2016). Family socioeconomic status is often associated with child brain structure and function, with evidence linking disadvantage to reduced gray matter and integrity of white matter tracts in EF regions and differences in the recruitment of the PFC during EF tasks (Merz, Wiltshire, & Noble, 2019). These early emerging SES-related differences in EF are shown to persist across early and middle childhood without accumulating or diminishing (Hackman et al., 2015). Neuroanatomically, different regions within the PFC are specialized to sub-serve different core components of EF, with specialization occurring to various degrees and at various points in development and different regions being recruited by children during certain tasks compared to adults (see Fiske & Holmboe, 2019 for a review). Attention and working memory, which overlap in developmental trajectories and share common neural underpinnings, are posited to provide an infantile foundation for the emergence of higher-order EF skills during the preschool years (Fiske & Holmboe, 2019).

Executive Function Assessment and Measurement

EF is a complex multi-dimensional construct, and its measurement has been a point of discourse in the field. Numerous conceptual models have been proposed in recent years (i.e., a unitary construct versus distinct components; Carlson, Faja, & Beck, 2016), resulting in an unsystematic approach to measuring and characterizing EF that compromises the extent to which accurate and meaningful conclusions can be drawn across studies. A common methodological approach to identifying the number of components and dimensionality of EF is to perform factor analytic work. This latent-variable approach is used to alleviate the problem of task-impurity which often arises in the measurement of EF through extracting shared variance across tasks (Miyake & Friedman, 2012; Snyder, Miyake, & Hankin, 2015). Miyake and colleagues (2000) created a tripartite model of EF in adults comprised of three correlated latent variables representing inhibition, working memory, and shifting, elements that are thought to be mediated by a fronto-parietal network (Fiske & Holmboe, 2019). Though other studies have also found support for the same three partially independent latent variables in adults, the findings with children have been less consistent. Studies involving preschool-aged children have found evidence for a unidimensional structure of EF (Wiebe, Espy, & Charack, 2008; Wiebe et al., 2011) whereas studies of EF in middle childhood offer support for a similar tripartite model to that found in adult samples (Lehto et al., 2003; McAuley & White, 2011). Results from studies comparing measurement models of EF across different age groups ranging from 7- to 21-year-olds suggest that the degree of unity and independence of the three components that make up Miyake's tripartite model may change across development (Best & Miller, 2010). Indeed, a recent systematic review and re-analysis of EF latent variable studies found the most commonly accepted models varied by age, with greater support for unidimensionality during childhood and adolescence compared to adulthood (Karr et al., 2018).

A newer framework, the *unity/diversity* framework, has been proposed by Miyake and Friedman (Friedman & Miyake, 2017; Miyake & Friedman, 2012) to examine individual differences in EF. This framework includes updating-specific (i.e., working memory) and shifting-specific factors in addition to a common EF factor which, when included, leaves no inhibition-specific variance (Friedman et al., 2008, 2011; see Figure 3b). The *unity/diversity* framework represents the most up to date conceptualization of EF measurement in the field of clinical psychology (Snyder et al., 2015). Miyake & Friedman's concept of "unity" is supported by results of a meta-analytic study of fMRI data demonstrating the existence of common neural activation across EF tasks in children (McKenna, Rushe, & Woodcock, 2017), though this globalized neural activation is thought to refine and become more localized as children develop (Fiske & Holmboe, 2019). Among 6- to 12-year-olds, there was no evidence of separable areas of neural activation for shifting and updating components (McKenna et al., 2017). Given that EF abilities are thought to develop in a hierarchical fashion, with inhibitory control emerging early and forming the basis for later EF abilities (Johansson et al., 2016), inhibitory control may be a stronger indicator when examining individual differences in EF among children younger than six-year-olds and may not be fully accounted for by a common, general EF factor at earlier developmental stages.

Whereas more complex EF tasks are needed in studies with adults in order to avoid ceiling effects (Miyake et al., 2000), there is a greater reliance on parent and teacher reports of everyday behavioral manifestations of executive function or dysfunction with younger children who are perhaps less capable of completing complex EF tasks (Roth, Isquith, & Gioia, 2016). Though parent and teacher report measures are thought to have high ecological validity, they can often lack the high internal validity achieved with laboratory tests of EF. Indeed, parent-report EF measures (e.g., BRIEF-2) are purported to index different underlying processes compared to performance-based measures (Pino Muñoz & Filippetti, 2019). These two ways of measurement, though examined independently, are part and parcel, both providing important and often different pieces of information contributing to the larger puzzle of EF characterization and assessment during childhood.

Social Origins of Executive Function

From birth to early adulthood, the development of EF is, to some degree, shaped by our experiences. The motivation to *want* to exert control over one's own behavior is thought to be socially based, with origins tracing back to the parent-child relationship (Carlson, 2009; Mead, 1934; Sroufe, 1996). During interactions with caregivers, children learn to navigate the give and take of social interactions and develop an understanding of how their actions elicit a reaction from their caregiver. Over time through repeated patterns of events, children learn that, by controlling their impulses and actions, they can attempt to elicit, with intentionality, specific reactions that are in line with their goals by modifying their behavior accordingly. Parental scaffolding behaviors, with consideration given to their timing and contingency (Bibok, Carpendale, & Müller, 2009), support the child as they practice integrating their attention, working memory, and self-control to support engagement and sustained attention. During infancy and early childhood, children are more heavily reliant on parental scaffolding to help them navigate their environment, with parents essentially serving as an "external frontal lobe." This early guidance is positively associated with EF development (e.g., guided learning; Suor et al., 2019). As abilities emerge across development, children begin to play an increasingly active role in reciprocal social interactions with their caregiver. As children transition to school-age, they should be able to draw on self-regulatory skills at increasingly demanding levels (e.g., planning and flexible problem-solving). Individual differences in parental ability to flexibly modify the level of support provided based on their child's success or difficulty on a task (e.g., parental scaffolding) are predictive of later child EF abilities (Hammond et al., 2012; Hughes & Devine, 2019).

The dynamic back-and-forth exchange described above is often referred to as dyadic reciprocity. When mothers and children attend and respond to each other's cues, the dyadic interaction is considered reciprocal. Turn taking, peek-a-boo, imitation games, imaginary play, and storytelling are all examples of reciprocal activities that support EF development in children of various ages (Center on the Developing Child at Harvard University, 2014). Dyadic reciprocity within the caregiver-child interaction is an exceptionally important component of the caregiving environment, with long term effects for child socioemotional, cognitive, and linguistic outcomes (Feldman, 2007; Feldman, Bamberger, & Kanat-Maymom, 2013). Given what is known about differences in dyadic reciprocity based on developmental timing, relatively few studies have investigated the stability of this construct as children mature. During the second 6 months of life, dyadic reciprocity has been shown to increase as the capacity to regulate affect and joint attention emerges (Ferber, Feldman, & Makhoul, 2008). Stability in mother-child and father-child reciprocity has been documented from infancy to adolescence and was found to be significantly associated with long-term child outcomes (Feldman et al., 2013). However, only correlations and linear trends, examined using ANOVAs, were studied;

meaning, investigations employing non-linear growth models or incorporating later change as a function of prior level may yield different results. Little work has investigated the rate of growth in dyadic reciprocity over time to determine possible points of attenuation and acceleration. For example, when children are old enough to engage in coherent verbal communication with their caregivers in addition to nonverbal communication, one would expect significantly more opportunities for reciprocal exchanges. The development of EF may be sensitive to surges in reciprocal exchanges within caregiver-child interactions that occur with the sophistication of verbal ability around 2 – 3 years of age.

Aspects of the caregiving environment can also influence children's functioning at a biological level (Calkins & Hill, 2007; Calkins et al., 2008; Perry et al., 2020). More specifically, the early social and caregiving environment plays an important role in shaping the dynamics of a child's physiological regulatory system (McLaughlin et al., 2015). Poor maternal-child relationship quality during toddlerhood, indexed using global codes of positive maternal behavior and hostility and counts of maternal statements that encouraged child-oriented goals, predicted poorer cardiac vagal regulation (e.g., the influence of afferent and efferent pathways of the vagus nerve on cardiac functioning) when children were 5 years old, even after controlling for vagal functioning during toddlerhood (Calkins et al., 2008). Conversely, physiological flexibility (e.g., vagal functioning and the regulation of cortisol) has also been found to predict prosociality in childhood (Miller, 2018), suggesting that children with adaptive physiological regulation that matches the environmental demands (e.g., not hyper- or hypo-aroused) are better suited to cope with social challenges due to their ability to notice and attend to the cues of others. These findings suggest that dyadic reciprocity within caregiver-child interactions may serve to support emerging physiological regulatory abilities and that physiological regulatory abilities may also serve to support a child’s ability to successfully engage in a reciprocal manner during interactions with their caregiver. Empirical tests of the codevelopment of dyadic reciprocity and physiological functioning are needed to determine the extent to which development is correlated versus coupled and whether the coupling is unidirectional or bidirectional. This can be evaluated by testing whether subsequent changes in physiological regulation are accounted for, in part, by the prior level of dyadic reciprocity and vice versa.

Parasympathetic Activity and Executive Function

The same brain systems involved in the regulation of cognitive and emotional function are also implicated in the regulation of autonomic function. The *neurovisceral integration hypothesis* links individual differences in vagal functioning to cognitive performance and emotional regulation (Thayer et al., 2009; Thayer & Lane, 2000). A significant body of literature has spotlighted the underlying connectivity between emotional and autonomic regulation, with relatively less attention paid to links between cognitive and autonomic regulatory functions. Yet, efficient and effective performance on tasks that require EF is thought to be supported by a set of neural structures involved in cognitive, affective, and autonomic regulation, and heart rate variability (HRV) has been posited to index the functional capacity of these structures (Thayer et al., 2009). Consequently, higher HRV has been associated with greater performance on cognitive tasks tapping into attention, working memory, and inhibitory control processes (e.g., Hansen, Johnsen, & Thayer, 2003; 2009; Thayer & Brosschot, 2005).

Within the central nervous system (CNS) there is thought to be a common central functional network comprised of the central autonomic network (CAN), the rostral limbic system (RLS) network, Damasio's "emotion circuit," and related systems that share structural overlap and function to afford the brain control of visceromotor, neuroendocrine, and behavioral responses known to support goal-directed behavior and adaptability (Thayer et al., 2009). The autonomic nervous system, and the peripheral nervous system more broadly, connect the CNS to the rest of the body because they function to convey information from the brain to visceral organs which allows for flexible adaptation to changing environmental contexts. The parasympathetic branch of the autonomic nervous system is responsible for reducing heart rate and returning the body to homeostasis during times of rest, when active stressors are absent (Appelhans & Luecken, 2006). Afferent and efferent pathways of the vagus nerve, the 10th and main cranial nerve of the parasympathetic nervous system, facilitate a bidirectional influence between the brain and other bodily organs (Muhtadie et al., 2015). This efferent vagus nerve pathway originates in the nucleus ambiguus of the brain stem and terminates in the sinoatrial node of the heart, which is commonly referred to as the "heart's pacemaker" (Rottenberg et al., 2007). The integration across these complex systems and the bidirectional influences that result facilitate cortical control of cardiac activity and allow internal resources to be allocated in a way that supports goal-directed behavior.

Parasympathetic influences on heart rate are often estimated by a noninvasive measure called respiratory sinus arrhythmia (RSA). RSA measures the systematic variability in heart rate during inhalation (when the vagal control is obstructed), compared to exhalation (when vagal control is admitted; Muhtadie et al., 2015). The vagus nerve functions to inhibit sympathetic influences on the heart to return the body to a state of calm. That is, higher RSA implies greater vagal control of the heart which entails a greater influence of the parasympathetic nervous system. When an environmental stressor is present, the vagus nerve often withdraws its inhibitory influence; this withdrawal allows heart rate increase to meet the demand of the stressor and is manifested as a decrease in RSA (Muhtadie et al., 2015). The PNS supports social interaction and is implicated in the modification of behavior by allowing for the reallocation of internal resources to support engagement and sustained attention (Porges, 2001). Even infants are able to reduce PNS influence on the heart when controlling attentional engagement, reflected in decreased RSA due to vagal withdrawal, so that neural resources can be reallocated to the prefrontal cortex (e.g., Richards & Casey, 1991; Suess, Porges, & Plude, 1994). Controlled attentional engagement is a requisite for higher-order cognitive processes and, as such, positive associations are often found between RSA and performance on EF tasks when measured concurrently (e.g., Hansen et al., 2003).

Within-person changes in RSA reactivity are influenced by task-specific demands and provide insight into the dynamic engagement of regulatory processes (Sulik et al., 2015) whereas differences in resting RSA, measured at baseline without a stressor present, are thought to reflect somewhat stable, trait-like differences in regulatory style (Beauchaine, 2001). Children with higher resting RSA were rated higher by their parents on an effortful control scale of temperament questionnaires (Chapman et al., 2010; Sulik et al., 2013). At 3.5 years of age, higher resting RSA was positively predictive of EF task performance within the same experimental session (Marcovitch et al., 2010).

Though stability in resting RSA may be supported in later adolescence and adulthood, initial forays into characterizing RSA development during infancy and early childhood suggest individual growth in physiological capacity is evident. Instability in RSA during infancy may be reflective of developing self-regulatory systems and a greater reliance on external coregulation provided by caregivers (Calkins, 2007). By the toddler years, resting RSA is more consistently associated with appropriate levels of reactivity (Calkins, 1997), suggesting physical and neural maturation has occurred that allows toddlers to better, and with more consistency, regulate their internal bodily processes. Among Latino infants from under-resourced environments, resting RSA has been found to increase across time from 6 weeks to 24 months (Jewell, Suk, & Luecken, 2017) and from 6 to 60 months (Alkon et al., 2011). The significant variance in both intercept and slope found by Jewell and colleagues (2017) suggests the developmental process of change in resting RSA was different across infants, with change accelerating overtime. The differences in rate and timing of acceleration in physiological regulatory capacity may be meaningfully related to other developmental processes, such as EF and social engagement; those these associations remain to be tested.

Despite indications of developmental interwovenness, much of the supportive evidence for the neurovisceral integration model comes from concurrent associations during EF tasks and, in doing so, effectively neglects important insights that can be gleamed from longitudinal investigations across infancy and early childhood. Adopting a neurodevelopmental perspective, the continuous maturation of the brain structures implicated in the neurovisceral integration hypothesis across early childhood should serve to support the rapid development of cognitive and autonomic functions concurrently and prospectively during this period. If periods of rapid acceleration (e.g., change) in vagal functioning can be identified and found to be more strongly linked to later EF performance than periods characterized by less accelerated growth, this would suggest that EF development is more “sensitive” to certain periods of physiological development than others. Due to overlap in structure and central functional networks, measuring vagal regulation during early childhood may prove to be a useful, more developmentally appropriate, and more easily attainable proxy for a child’s emerging simple EF (e.g., attentional control) or, at the very least, prove to be a supportive process underlying EF development and other important co-occurring processes (e.g., prosocial development).

Cultural Influences on Executive Function Development

The social origins of a child’s motivation to want to exert control over their own behavior is closely tied with familial cultural history, traditions, and ideals that serve to govern what constitutes desirable and undesirable behavior within that family. Culture has been conceptualized as the “developmental niche in which beliefs about communicating emotions are cultivated (Cole, Bruschi, & Tamang, 2002, p. 983)” and defines what constitutes “appropriate” and “adaptive” responses. Culturally informed display rules and behaviors are often shaped and internalized by means of the family social system, specifically the parent-child relationship, making it an important context in which to study the learning of control. More specifically, impulse and expression control are learned through reinforcement (i.e., acceptance or inclusion) for what different cultures consider socially desirable behavior and punishment (i.e., social rejection or isolation) for what is considered undesirable behavior (Mesquita & Frijda, 1992). Qualitative data suggests that Mexican mothers place high value on the process of ethnic-racial socialization (Umaña-Taylor & Yazedijan, 2006), defined as the transmission of cultural values, beliefs, traditions, and behavioral norms (Hughes et al., 2006). Indeed, socialization practices have been found to be influential in developing ethnic identity and shaping ethnic behaviors for Mexican American children (Knight et al.,1993). European American mothers and fathers, comparatively, were found to report lower social desirability responding, or acting in a way that casts someone in a positive light, than Latin American parents (Bornstein et al., 2015) and are generally considered to be more accepting of displays of negative emotions than other cultures (i.e., Nelson et al., 2012). That being said, it is problematic to consider European American and Mexican American as separate and exerting two distinct influences given how commonplace it is across the United States (and world) for children to be raised in multicultural environments. According to the U.S. Census Bureau (2010), 1 out of 4 children have at least one foreign-born parent, and 29% of the foreign-born population were born in Mexico. Longitudinal, multi-method investigations of EF development among ethnic and culturally diverse populations often focus on between-group comparisons (e.g., compared to non-Hispanic, White children from middle class families) rather than within-group differences (e.g., White & Greenfield, 2017). This study examined EF development and developmental correlates among a sample of Mexican American children with the goal of producing results that can be used to strengthen theories and inform specific, tailored recommendations for intervention and prevention.

The Current Study

The theories and supporting empirical literature reviewed above provide pieces of support for a larger, developmentally dynamic, and complex puzzle. There is clear overlap in autonomic, social, and EF development during infancy and childhood. What remains unclear is *how* and *to what extent* they support one another in a dynamic fashion across these foundational periods of rapid development. Cross-sectional data often falls short in addressing these questions of temporal dynamics and causality. Akin to all developmental studies, our understanding of the interrelatedness of these processes is complicated by their continued maturation across the period of interest. Further, the reviewed literature supports the supposition that individual growth in these processes across time is not constant and provides evidence for periods of time with more rapid growth than others (e.g., rates of acceleration).

Latent change score models (LCSMs; McArdle & Hamagami, 2001) and latent growth curve models (LGM) often have equivalent counterparts, though they differ in how change over time is conceptualized (Serang, Grimm, & Zhang, 2018). Whereas LGMs view change as a static process and view the outcome as a function of time, LCSMs are dynamic in that change is a function of scores at previous occasions (Serang et al., 2018). The use of a latent change framework allows for examinations of between-person differences in rate of change and acceleration in nonlinear models (Grimm et al., 2013). In the LCSM, latent change is a function of both constant (e.g., slope, fixed across time) and proportional change parameters, with difference scores corrected for measurement error. Proportional change is dependent on the preceding score such that it captures the effect of prior level of the variable on later change in the same variable (Kievit, de Mooji, & Van Harmelen, 2017).

A bivariate extension of the LCSM allows for the simultaneous modeling of two developmental processes over time. The previous widely adopted use of cross-lag panel models (CLPMs) was thought to address issues of directionality in causal processes though, more recently, it has come to light that the lagged parameters often lead to "erroneous conclusions regarding the presence, predominance, and sign of causal influences" (Hamaker, Kuiper, & Grasman, 2015, p. 102). Bivariate LCSMs have been proposed as an improved model to answer similar questions to CLPMs because they include cross-lagged paths from prior level of one variable to later latent change in another, such that change becomes a function of constant change, proportional change, *and* the preceding level of the other variable (Hamaker et al., 2015). These paths are referred to as coupling parameters in the latent change score framework (as opposed to autoregressive parameters) and can be used to examine a specific type of lead-lag dynamic relations. Both the proportional change and coupling parameters are typically invariant across time and capture nonlinearity in change over time. For example, a nonzero coupling parameter indicates a deflection (either positive or negative) from the usual exponential trends (Grimm et al., 2012), but the magnitude of the deflection is not widely interpreted.

Through the use of bivariate LCMs, this study aimed to examine dynamic associations within and between baseline vagal functioning and dyadic reciprocity during mother-child interactions from child age 24 weeks through 3 years as well as how latent change related to later EF (see Figure 1). By placing an emphasis on time-sequential within-person change, we can model rapid maturation in one domain (e.g., vagal functioning) and determine the extent to which that rapid development is dependent upon its prior status as well as the status of another variable (e.g., dyadic reciprocity). In this manner, the question of whether individual differences in vagal functioning may precede changes in dyadic reciprocity, or vice versa, could be addressed.

Specific Aims

The primary specific aims were as follows:

Aim 1. Identify a developmentally appropriate factor structure of performance-based EF during middle childhood (approximately 6 years of age) for the current sample. Though the combination of the measures available and the lack of ethnic and cultural diversity in prior investigations of the EF factor structure make specific hypotheses difficult, I predicted support for the unity/diversity model of EF in that both general and specific dimensions would be evident. I expected a nested factor model (see Figure 3b) would fit the data best.

Aim 2. Estimate a series of univariate LCSMs for both dyadic reciprocity and vagal functioning, independently, from 24 weeks through 3 years including no change, linear change, and proportional change models (e.g., exponential) within the latent change score framework (McArdle, 2001; McArdle & Hamagami, 2001). I expected significant proportional change parameters for both dyadic reciprocity and vagal functioning, such that later change in each variable was dependent upon its prior level.

Aim 3. Examine dynamic associations between child vagal functioning and dyadic reciprocity in 6-month time intervals from child age 24 weeks through 3 years using a bivariate LCSM (McArdle & Hamagami, 2001). The resulting flow was predicted to show bidirectional coupling influences, with prior level of vagal functioning tending to positively impact later change in dyadic reciprocity and, conversely, prior level of dyadic reciprocity signaling subsequent change in vagal functioning.

Aim 4. Determine the extent to which individual differences in executive functioning in middle childhood, using the factor structure for performance-based measures identified in the first aim, are dependent upon changes in dyadic reciprocity and vagal functioning during infancy and early childhood. I hypothesized that greater latent change in vagal functioning between 1.5 and 2 years and in dyadic reciprocity from 2.5 to 3 years would be most predictive of later EF.

METHODS

Participants

Participants include 322 Mexican American mothers and their children (54% female) recruited through clinics in the Phoenix metro area during routine prenatal care visits. Pregnant women were identified during the third trimester and recruited for the study if they self-identified as Mexican or Mexican-American, had a self-reported household annual income below $25,000 or were eligible for Medicaid funding, spoke English or Spanish fluently, were 18 years of age or older, and were expected to deliver a singleton baby. At time of recruitment for the study, expecting mothers were, on average, 28 years old (range 18 – 42) and 30% were married. Twenty-two percent were first time mothers, 83% of mothers were unemployed, 59% had an annual household income of $5,000 - $15,000, and 82% of mothers spoke Spanish as their first language. Additional sample characteristics are presented in Table 1. Informed consent was obtained in the women's homes between 26-39 weeks' gestation. The Arizona State University IRB and the Maricopa Integrated Health System IRB approved all study procedures.

Procedures

Time points for the current study include the prenatal home visit, a home visit at infant age 24 weeks, laboratory visits when the children were 1, 1.5, 2, 3, and 6-years-old, and a phone call between child age 7.5 and 9 years. A "planned missing" design was employed for the home visits to reduce participant burden while maintaining sufficient power (Graham, Taylor, Olchowski, & Cumsille, 2006). Each participant was randomly assigned to miss one of the 12-, 18- or 24-week postpartum visits. Of the 322 participating dyads, 209 completed the 24-week visit (93% of those randomly assigned). For the laboratory visits, 82.2% (265 dyads) completed the 1-year visit, 73.6% (237 dyads) completed the 1.5-year visit, 75.4% (243 dyads) completed the 2-year visit, 66.7% (215 dyads) completed the 3-year visit, 71.4% (230 dyads), 65.6% (212 dyads) completed the 6-year visit, and 78% (251 mothers) completed the phone call between child ages 7.5 and 9 years. The postpartum home and laboratory visits included structured interviews, questionnaires, physiological data collection, child cognitive and socioemotional assessment measures, regulatory tasks, and mother-child interaction tasks.

Interaction tasks. At the 24-week home visit, mothers and their infants engaged in 5 interaction tasks: free play (5 minutes), arm restraint (2 minutes), soothing (3 minutes), teaching (5 minutes), and pee-a-boo (3 minutes). At the 1, 1.5, and 2-year visits, mother and child completed the following tasks: free play (5 minutes), clean up (2-5 minutes), bubbles (3 minutes), and 4 teaching tasks (5 minutes each). At the 3-year visit mother and child again engaged in the free play, clean up, and bubble tasks followed by 2 teaching tasks. Mothers were asked to "teach" their child four tasks that involved a skill slightly beyond the child's developmental capabilities; meaning, teaching tasks were designed to elicit mild frustration and modified at each visit to provide a context for the assessment of dyadic functioning. Only free-play and the teaching task/s were consistently completed across time points. The teaching task was selected for inclusion in the current study because a specific uniform task was presented across dyads within each time point that facilitated dyadic interaction. In contrast, mothers and children could have chosen to play independently during the free play task which may have been more reflective of other processes aside from dyadic reciprocity (e.g., attachment). More detailed teaching task information at each time point is provided in Table 2.

Measures

Executive function. *Kiddie Computerized Performance Task (K-CPT):* The NIH Toolbox K-CPT (Conners, 2006) is a 7.5-minute computerized measure of executive control in children 4 to 7 years of age. Children viewed a series of pictures in the center of a computer screen and were instructed to press the spacebar after the target stimuli (e.g., a fish). The presentation sequence lasted approximately 7 minutes and consisted of the target stimuli interspersed with a large number of nontarget stimuli (e.g., distractors). The K-CPT is a useful indicator of early onset executive control difficulties in preschool-aged children (Barnard et al., 2018). The following indices derived from this task were examined: commission errors, omission errors, reaction time for commission errors, and reaction time for correct hits. This measure was collected at the 6-year time point. Results for 7 participants indicated poor performance validity (greater than 60% commission or omission errors) and data were removed from analyses.

Head-Toes-Knees-Shoulders Task (HTKS): The HTKS task represents a complex measure of EF and is purported to integrate measurement of attention, working memory, and response inhibition (McClelland & Cameron, 2012). This measure has been translated and validated with Spanish-speaking children (Ponitz et al., 2009). The HTKS task is comprised of multiple parts (10 trials each) that increase in difficulty as you progress from one part to the next. Prior to beginning each part, children first completed a practice to ensure adequate understanding of the instructions. In Part I of the task, children were instructed to do the opposite of what the interviewer says (e.g., when they hear “Touch your head,” they should touch their toes instead). In Part II, the cognitive load is increased and the task is expanded from touching head and toes to touching shoulders and knees as well, continuing to do the opposite of what was said by the interviewer (e.g., when they hear “Touch your shoulders,” they should touch their knees). In Part III, the rules of the game are changed (e.g., “Touch your head” means touch your knees; “Touch your knees” means touch your head; “Touch your shoulders” means touch your toes; “Touch your toes” means touch your shoulders). Children received a score of 0 (incorrect), 1 (self-correction) or 2 (correct) for each trial for a maximum of 60 points total. HTKS tasks were double coded from video recordings for reliability. This measure was collected at the 6-year time point.

Digit Span Backwards. The Digit Span Backwards subtest from the Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Wechsler, 2003) captures working memory. Children are required to repeat a string of increasingly longer digits in backwards order, meaning they had to hold the information in mind and mentally reverse the order to answer correctly. This measure was collected at the 6-year time point.

Behavioral Rating Inventory of Executive Functioning, 2nd Ed. (BRIEF-2): The BRIEF-2 (Gioia et al., 2015) is considered the gold-standard rating form for executive function testing. Mothers completed the BRIEF-2 parent version, a 63-item standardized rating form that assess multiple interrelated domains of youth executive functioning commonly discussed in the neuropsychology literature. T scores are used to interpret the level of executive functioning based on both age and gender, with scores above 70 considered clinically elevated. Domains of executive function assessed/scale names include the following: inhibit, self-monitor, shift, emotional control, initiate, working memory, plan/organize, task-monitor, and organization of materials. These scales load onto three indices Behavioral Regulation Index (BRI), Emotional Regulation Index (EMI), and the Cognitive Regulation Index (CRI), which then combine to form the overall score, the Global Executive Composite (GEC).

The parental report indices on the BRIEF-2 were not included in the factor structure of EF at 6 years due to findings of selective and low correlations between BRIEF-2 ratings and performance-based measures of EF (Pino Muñoz & Filippetti, 2019). Completion of the BRIEF-2 takes approximately 10-15 minutes, and three internal reliability scales are included: Negativity, Inconsistency, and Infrequency. This measure was collected via a single phone call in the mother's preferred language between the 7.5- and 9-year time points.

Respiratory sinus arrhythmia. Child heart rate was recorded at 256 Hz using electrocardiography (ECG) equipment from Forest Medical, LLC (Trillium 5000; East Syracuse, NY, USA) across a 7-minute resting period. Children were seated upright in a car seat during the 24-week home visit, on their mother's lap for the 1-, 1.5-, and 2-year visits. Approximately 2-3 minutes prior to baseline data collection, trained research assistant placed electrodes on the child's left shoulder and right and left waist in a standard three-lead configuration. Heart rate was measured at infant age 24 weeks and child ages 1, 1.5, 2, and 3 years. However, data for the 3-year visit was considered unusable and dropped from the current study, resulting in 4 time points of heart rate data.

Resting respiratory sinus arrhythmia (RSA; ln[ms^2]) calculations were consistent with the Porges method (Porges, 1986). Data was first processed using QRSTool software 1.2.2 (Allen, Chambers, & Towers, 2007), which automatically identified R-spikes in the ECG data. Misidentified or unidentified R-spikes were manually corrected by trained research assistants using the QRSTool and CardioEdit software (Brain-Body Center, 2007). R-R time interval data was obtained and CardioBatch software (Brain-Body Center, 2007) was used to apply a moving polynomial filter to extract heart rate variability in the frequency band of RSA (for infants, 0.3-1.3 Hz). Resting RSA estimates were log-transformed and a mean resting RSA value averaged from 30-second epochs across the first 5 minutes of the resting period was obtained (e.g., the last 2 minutes of data were not included).

Dyadic reciprocity. At the 24-week, 1, 1.5, 2, and 3-year visits, mothers and children were observed during 5-minute structured teaching tasks (see Table 2 for task descriptions). Video-recorded interactions were retrospectively coded by pairs undergraduate students who were trained and supervised by a graduate student. Reliability was completed on 15-20% of all videos and two-way mixed, consistency, single-measure interclass correlations were computed on the single item global score of dyadic reciprocity: 24-week ICC = .57; 1-year ICC = .74; 1.5-year ICC = *in progress*; 2-year ICC = .86; 3-year ICC = .71. Dyadic reciprocity was assessed via the Coding Interactive Behaviors system (CIB; Feldman, 1998), a global coding system designed to capture the quality of mother and child behavior and emotions across a number of critical dimensions. Dyadic reciprocity refers to the level of “give-and-take” between mother and child and was rated from 1 (low) to 5 (high). High ratings of dyadic reciprocity suggest a well-coordinated exchange defined by joint participation in the interaction, appropriate back-and-forth responses, and a feeling of synchrony between partners. For time points with multiple teaching task interactions, an average score was computed for each dyad ($\alpha_{1\text{ yr}}$ = .61; $\alpha_{1.5\text{ yrs}}$ = .81; $\alpha_{2\text{ yrs}}$ = .74; $\alpha_{3\text{ yrs}}$ = .75).

Potential covariates. A number of potential covariates considered for inclusion were collected via maternal report at the prenatal visit: maternal age, maternal level of education, maternal country of birth, number of years mother has lived in the United States, family economic hardship, and the biological sex of her child. Maternal report of infant temperament at 6 weeks postpartum was considered as a covariate, given the conceptual and empirical overlap between EF, effortful control, and orienting/regulatory capacity (e.g., Putman, Rothbart, & Gartstein, 2008; Tiego et al., 2020).

Analytic Strategy

Preliminary Analyses

Descriptive statistics and correlations were examined for all study variables using SPSS version 26. Missingness on primary study variables was examined in relation to participant demographics.

Primary Analyses

Aim 1: Measurement model of child executive function at 6 years. Using objective data from the 6-year lab visit, a series of confirmatory factor analyses (CFA) of components related to EF were performed to determine which theorized model (see

Figure 3) was most appropriate for the data in the current sample. Eight variables derived from objective, performance-based laboratory tasks were evaluated for inclusion in identification of the factor structure of EF: 1) digit span backwards, 2) proportion of commission errors, 3) proportion of omission errors, 4-5) and two reaction time measures (for commission errors and correct hits) derived from the CPT, and 6-8) the score for each of the three trials on the HTKS task entered independently. The variables derived from the CPT were given negative loadings in all models, since scores on these variables are interpreted such that higher scores indicate worse task performance (e.g., a high number of commission errors is reflective of poor EF) whereas higher scores on the other variables indicate better task performance. The CFAs were performed in M*plus* 8.4 using maximum likelihood estimation with robust standard errors (MLR) and were evaluated with oblique geomin rotation to allow for correlation among factors. The CFAs were evaluated using chi-square (χ^2), comparative fit index (CFI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). A nonsignificant chi-square statistic, CFI greater than .95, RMSEA less than .05, and SRMR less than .08 suggest good model fit (Hu & Bentler, 1999).

Associations between the identified factors and the indices on the BRIEF-2 and Block Design and Vocabulary subtests from the Weschler Intelligence Scale for Children, Fourth Edition (Wechsler, 2003), administered at the 6-year visit, were examined to provide initial validation of the model. Further, research investigating gender differences in EF has yielded mixed results, with some work suggesting gender differences on specific measures of EF (e.g., measures of inhibitory control; Berlin & Bohlin, 2002; Carlson & Moses, 2001) and others finding no main effects (e.g., measures of inhibition and working memory; Brocki & Bohlin, 2004; Welsh, Pennington, & Groisser, 1991). Recent work suggests that the influence of gender may be more complex than traditionally thought, positing gender may interact with developmental processes to influence specific deficits in executive function in specific disorders (Grissom & Reyes, 2019). Considering the multifariousness of these results, multi-group invariance by gender was examined using the "Model = Configural Metric Scalar;" command in *M*plus v 8.4. Measurement invariance was evaluated using absolute (significance of the change in χ^2), comparative (ΔCFI), and alternative fit indices (e.g., ΔRMSEA, ΔSRMR; Putnick & Bornstein, 2016). In addition to a nonsignificant change in χ^2, a -.01 change in CFI, .015 change in RMSEA, and .030 (metric) or .015 (scalar) change in SRMR were used as cutoffs for determining significant improvement (Chen, 2007).

Aim 2. Univariate LCSMs (McArdle, 2001; McArdle & Hamagami, 2001) were run independently in M*plus* 8.4 using maximum likelihood estimation to examine time-sequential change for both dyadic reciprocity and RSA at baseline from 24 weeks through 36 months (see figure 2 for RSA model). These univariate LCSMs were specified using measurement occasion as the time metric (*t*1 = 24 weeks; *t*2 = 1 year; *t*3 = 1.5 years; *t*4 = 2 years; *t*5 = 2.5 years; *t*6 = 3 years). Data were not collected at 2.5 years of age so, in order to meet the model assumption that time intervals between measures (e.g., 6-month intervals) are constant, a phantom variable was included as the 2.5-year and 3-year (RSA only due to unusable data) time points to keep the time lag constant (Oud & Voelkle, 2014).

Aim 3. The two univariate LCSMs were combined into a bivariate LCSM, with bidirectional coupling parameters specified to evaluate prior level on later change (See

Figure 4).

Aim 4. The best fitting model from the third aim was extended to include paths from the latent change score parameters to the 6-year EF factor score from the first aim. In traditional model building fashion, these paths were initially all constrained to zero and then systematically unconstrained one path from dyadic reciprocity to EF and from vagal functioning to EF at a time. Model fit indices were compared to determine which model best reflected the data.

RESULTS

Preliminary Analyses

Raw descriptive statistics and correlations among primary study variables were examined using SPSS version 26 and are presented in Table 3. None of the primary study variables were skewed or kurtotic (>2 or >7, respectively). Twenty-four-week RSA and dyadic reciprocity were not significantly correlated with maternal country of birth, number of years in the United States, maternal age, economic hardship, or infant temperamental regulation. Dyadic reciprocity at 24 weeks was positively correlated with maternal age, $r = .169$, $p = .018$, and negatively with child sex, $r = -.209$, $p = .003$, such that mother-daughter child dyads exhibited higher dyadic reciprocity than mother-son dyads. RSA at 24 weeks was marginally positively correlated with child sex, $r = .139$, $p = .053$), such that males were more likely to have a higher baseline RSA value than females.

Missing Data. Independent samples *t*-tests and chi-square tests of association revealed missingness at the 1-, 1.5-, 2-, 3-year lab visits (but not the 24-week visit) was associated with maternal age, such that younger mothers were more likely to be missing, and with maternal country of origin, such that children of mothers who were born in the United States were more likely to have missing data at these time points. Missingness at the 6-year lab visit was likewise associated with maternal country of origin. Missingness was otherwise not associated with number of other children, maternal number of years in the United States, prenatal household income, or child biological sex (all *p*s > .05).

Primary Analyses

Aim 1: Measurement model of child executive function at 6 years. Table 3 also presents descriptive statistics and zero-order correlations for the variables examined as potential indicators of child executive function at 6 years. Inter-item correlations between potential indicators ranged from absolute values of .01 to .48. The tripartite (Figure 3a) and bifactor models (Figure 3c) were not tested due to insufficient shifting-specific indicators (e.g., only HTKS trials 21-30 was thought to reflect shifting).

Nested factor models (see Figure 3c for conceptual model). The nested factor model was tested with all eight indicators loading on a general factor, three tasks loading onto an updating-specific factor (e.g., working memory) – HTKS trials 1-10, HTKS trials 11-20, and digit span backwards, – and three tasks loading onto an inhibition-specific factor – HTKS trials 21-30, CPT commission errors, and reaction time for CPT commission errors. This model fit the data well (χ^2(N = 200; df = 12) = 13.53, p = .332; RMSEA= .03, 90% CI [.00, .08]; CFI = .993; SRMR = .032) but two of the three indicators for the inhibition-specific factor were not significant: CPT commission errors (p = .474) and reaction time for CPT commission errors (p = .202). The inhibition-specific factor was subsequently removed from the model. Without need for the inhibition-specific factor, the reaction time for commission errors derived from the CPT was excluded from subsequent models because it did not correlate well with any of the other performance-based tasks (*r*s = -.01 to -.09).

A second nested factor model was tested in which seven indicators loaded on a general factor and the same three tasks loaded onto an updating-specific factor. Factor loadings were significant across both factors and ranged from .309 (lowest) to -.663 (highest) on the general factor and from .448 to .674 on the updating-specific factor, but the model did not fit the data well (χ^2(*N* = 200; df = 11) = 35.05, *p* < .001; RMSEA= .11, 90% CI [.07, .14]; CFI = .854; SRMR = .077). Based on model modification indices, a correlation was added between proportion of commission errors and reaction time for correct hits on the CPT which significantly improved model fit (χ^2(*N* = 200; df = 10) = 3.933, *p* = 95; RMSEA= .00, 90% CI [.00, .00]; CFI = 1.00; SRMR = .023). As shown in Figure 5, HTKS trials 1-10 (β = .375), HTKS trials 11-20 (β = .567), HTKS trials 21-30 (β = .647), CPT omission errors (β = -.433), CPT commission errors (β = -.592), reaction time for CPT correct responses (β = -.663), digits backwards (β = .309) loaded significantly onto the common EF factor. For the updating-specific factor, HTKS trials 1-10 (β = .492), HTKS trials 11-20 (β = .674), and digits backwards (β = .448) all had significant loadings, all *p*’s < .01.

Unidimensional model (see Figure 3d for conceptual model). The unidimensional model with all 7 indicators and without correlations between residual indicator variances reflected a less than adequate fit of the data (χ^2(*N* = 200; df = 14) = 47.759, *p* < .001; RMSEA= .11, 90% CI [.08, .145]; CFI =.80; SRMR = .10). All indicators significantly loaded onto the general EF factor (all *p*s < .01), with loadings ranging from -.411 (lowest) to .772 (highest). Similar to the nested factor model, a correlation was added between proportion of commission errors and reaction time for correct hits on the CPT based on model fit indices. This addition significantly improved model fit (χ^2(*N* = 200; *df* = 13) = 10.099, *p* = .69; RMSEA= .00, 90% CI [.00, .06]; CFI = 1.00; SRMR = .04). As shown in Figure 6, HTKS trials 1-10 (β = .626), HTKS trials 11-20 (β = .818), HTKS trials 21-30 (β = .682), CPT omission errors (β = -.393), CPT commission errors (β = -.283), reaction time for CPT correct responses (β = -.383), digits backwards (β = .549) loaded significantly onto the common EF factor, all p's < .01.

Model comparison. Based on a chi-square difference test using the Satorra-Bentler scaling correction factors for MLR, the nested model did not fit the data significantly better than the unidimensional model (χ^2 (*N* = 200; *df* = 3) = 5.19, *p* > .05; critical value at $\alpha_{.05}$ = 7.81). Thus, the more parsimonious model, the unidimensional structure, was retained as the final model of EF.

Measurement invariance. Fit indices for tests of measurement invariance for the unidimensional model are reported in Table 4. Configural, metric, and scalar invariance were established, indicating psychometric equivalence of the factor structure of EF at child age 6 years across males and females within the current sample.

Initial validation of executive function unidimensional model. As reported in Table 5, The extracted EF factor score was positively correlated with maternal education, *r* = .219, *p* = .002, and negatively correlated with child sex, *r* = -.258, *p* < .001, such that children of more highly educated mothers and females were more likely to have a higher EF factor score than mothers who completed less education. Contrary to expectation, the EF factor score was not significantly correlated with prenatal family economic hardship, *r* = -.132, *p* = .06, or the ORC factor at child age 6 weeks, *r* = -.026, *p* = .71.

As hypothesized, the EF factor was positively correlated with child performance on the Block design, $r = .29$, $p < .001$, and Vocabulary, $r = .37$, $p < .001$, subtests of the WISC-IV. The EF factor was more strongly negatively correlated with child T scores on the Behavioral Regulation Index (BRI) of the BRIEF-2 parent-report, $r = -.14$, $p = .049$, compared to the Cognitive (CRI), $r = -.13$, $p = .06$, and Emotion Regulation Indices (ERI), $r = -.14$, $p = .06$. Within the BRI, the EF factor score was more highly negatively correlated with the self-monitor scale, $r = -.16$, $p = .031$, than the inhibit scale, $r = -.12$, $p = .09$. Of the two scales that comprise the ERI, the EF factor score was more highly correlated with the shift scale, $r = -.18$, $p = .011$, than the emotional control scale, $r = -.08$, $p = .27$. Significant negative correlations were present for plan/organize, $r = -.17$, $p = .019$, and task-monitor scales, $r = -.14$, $p = .047$, of the CRI but not for initiate, working memory, or organization of materials.

Aim 2. The univariate LCS model for dyadic reciprocity converged with no errors but model fit was poor, $\chi^2(N = 287; \text{df} = 13) = 84.927$, $p < .001$; RMSEA= .14, 90% CI [.11, .17]; CFI = 0.00; SRMR = .56. After visual inspection of individual histograms suggested skewness in the data, Box-Cox transformations (Box & Cox, 1964; Osborne, 2010) were applied to dyadic reciprocity variables. Using the Box-Cox transformed data marginally improved model fit, $\chi^2(N = 287; \text{df} = 13) = 27.078$, $p = .012$; RMSEA= .06, 90% CI [.03, .09]; CFI = 0.32; SRMR = .12. Parameter estimates are reported in Table 6. The constant change and initial mean level were nonsignificant, but both had significant variance (ps < .05). Results also indicated significant proportional change (prior level on later change) in dyadic reciprocity across time, $\beta = -1.373$, $S.E. = .215$, $p < .001$. However, given the inadequate fit based on a number of indices, results of the univariate

LCSM for dyadic reciprocity should be interpreted with caution.

The univariate LCS model for RSA fit the data adequately based on select indices, $\chi^2(N = 274; \text{df} = 7) = 10.59$, $p = .158$; RMSEA= .04, 90% CI [.00, .09]; CFI = .95; SRMR = .12. Because the RSA model will be used in conjunction with the dyadic reciprocity model in Aim 3, Box-Cox transformations were also applied to the raw RSA data across time points. Using the Box-Cox transformed data improved model fit, $\chi^2(N = 274; \text{df} = 7) = 4.734$, $p = .692$; RMSEA= .00, 90% CI [.00, .06]; CFI = 1.00; SRMR = .06. Parameter estimates are reported in Table 6. The initial mean level and constant change were nonsignificant, but there was significant variance in the initial mean level ($p < .001$). The proportional change in RSA was nonsignificant, β = .858, *S.E.* = 3.874, $p = .825$.

Covariate effects. Preliminary analyses revealed significant correlations between dyadic reciprocity and child sex, dyadic reciprocity and maternal age, and RSA and child sex. These covariates were entered as predictors of the initial mean level parameter in the respective LCSMs. Predictive paths to the constant change parameter were nonsignificant and removed for parsimony. The inclusion of child sex and maternal age in the LCS model for dyadic reciprocity marginally improved model fit, $\chi^2(N = 322; \text{df} = 22) = 39.928$, $p = .011$; RMSEA= .05, 90% CI [.02, .08]; CFI = .45; SRMR = .10. Older mothers, β = .024, *S.E.* = .012, $p = .037$, and mother and female child dyads, β = -.391, *S.E.* = .139, $p = .005$, exhibited more dyadic reciprocity at child age 24 weeks. On the other hand, child sex was not a significant predictor of the initial mean level or constant change of RSA and was removed from the model.

Predictors of missingness. The inclusion of maternal country of birth was considered as a covariate due to its relation to missingness at multiple time points. However, maternal country of birth correlated highly with maternal age in the dyadic reciprocity model ($r = .70$, $p < .001$) and was not a significant predictor over and above the significant influence of maternal age; thus, maternal country of birth was removed from the univariate dyadic reciprocity model for parsimony. The inclusion of maternal age was also considered as a covariate in the univariate model for RSA and marginally predicted the initial mean level of child RSA at 24 weeks, $\beta = .021$, *S.E.* = .011, $p = .053$. The inclusion of maternal age did not result in a significant decrease in model fit, $\chi^2(N = 274; df = 10) = 7.265$, $p = .700$; RMSEA= .00, 90% CI [.00, .05]; CFI = 1.00; SRMR = .06, nor did it result in a change in the direction or significance of the proportional or constant change parameters.

Aim 3. The univariate LCS models for dyadic reciprocity and RSA were combined into a bivariate LCS model. In addition to the proportional and constant change parameters previously specified in the univariate models, bidirectional coupling parameters were added as a part of the bivariate extension to examine prior level on later change (e.g., prior level of RSA on later change in dyadic reciprocity *and* prior level of dyadic reciprocity on later change in RSA). The bivariate LCS model, using the Box-Cox transformed variables and without the inclusion of covariates, fit the data well only on select indices, $\chi^2(N = 287; df = 38) = 55.812$, $p = .03$; RMSEA= .04, 90% CI [.01, .06]; CFI = .82; SRMR = .098. In order for model estimation to terminate normally, the variance of the constant change in RSA was fixed at 0.1.

Constant and proportional change parameters. The initial mean level and constant change of both dyadic reciprocity and RSA were nonsignificant (see Table 6).

Results revealed significant variance in both initial mean level (β = .483, S.E. = .108, *p* < .001) and constant change (β = 0.148, S.E. = 0.066, *p* = .025) of dyadic reciprocity. The initial mean level for RSA also varied significantly (β = 0.418, S.E. = 0.097, *p* < .001). Prior level of RSA on later change in RSA was significant, β = .425, *S.E.* = .125, *p* = .001, and prior level of dyadic reciprocity on later change in dyadic reciprocity was also significant, β = -1.355, *S.E.* = .213, *p* < .001.

Bidirectional coupling parameters. Prior level of dyadic reciprocity on later change in RSA was nonsignificant (β = 0.015, S.E. = 0.063, *p* = .817; see Table 6). Prior level of RSA on later change in dyadic reciprocity was also nonsignificant (β = -.153, S.E. = 0.095, *p* = .110).

Aim 4. Given the insignificant coupling parameters in the bivariate LCS model, the insignificant proportional change parameters in the univariate LCS model of RSA, and the poor fit of the univariate LCS model of dyadic reciprocity, paths were not extended out from any of these models to the EF factor extracted from Aim 1. Instead, a piecewise latent growth model (LGM) was estimated to test the hypothesis that the rate of change in resting RSA between 1 and 2 years would be most predictive of child EF at 6 years. Because equal time intervals are not a requirement in latent growth models, data from home visits 1, 2, and 3 (infant ages 6, 12, and 18 weeks) were also included to replicate the finding more closely by Jewell et al. (2018) of accelerating resting RSA change from 6 weeks to 2 years of age. Raw data were used, and two separate linear growth factors were estimated representing the slopes of RSA from infant age 6 through 24 weeks (times 1–4) and from child age 1 to 2 years (times 5-7). Time 1 (infant age 6 weeks) was set as point 0 within the analyses and Time 5 (point 4) represented the breakpoint/knot. The first growth trajectory was constrained to [0, 1, 2, 3, 7, 7, 7] and the second growth trajectory to [0, 0, 0, 0, 0, 1, 2]. The intercept along with both linear growth factors were regressed on the EF factor score from aim 1, controlling for child sex and maternal country of origin (related to missingness).

The piecewise LGM for resting RSA data had modest fit, $\chi^2(N = 322; \text{df} = 35) = 50.91$, $p = .04$; RMSEA= .04, 90% CI [.01, .06]; CFI = .89; SRMR = .07. Both growth factors were significant; meaning, resting RSA increased in a linear fashion up to infant age 24 weeks ($\beta = .154$, S.E. = 0.012, $p < .001$) and an even steeper increase was evident after 1 year ($\beta = .546$, S.E. = 0.057, $p < .001$). The variances for the intercept and the first growth factor were significant, indicating interindividual variability. The variance for the second growth factor was nonsignificant, indicating individual growth trajectories post-infancy did not significantly differ from one another. See Figure 7 for a graphical depiction of the model estimated means. Neither growth factor nor the intercept significantly predicted child EF at 6 years (*p*s > .50), after controlling for maternal age and child biological sex.

Similar to the univariate LCS model reported in Aim 3, the fit statistics for the piecewise LGM for dyadic reciprocity were exceedingly poor across most indices (e.g., CFI = 0.00). Neither the use of the MLR estimator, box-cox transformed data, the extension to earlier time points (infant ages 12 and 18 weeks), nor the removal of the 1.5-year time point (more equal time intervals once removed) improved model fit to the point of usability. This problem may be attributable, in part, to fluctuating mean levels and low intercorrelations of dyadic reciprocity across time (see Table 3). To approximate testing of the original hypothesis that change in dyadic reciprocity from 2.5 to 3 years would be predictive of individual differences in EF at child age 6 years, a multiple regression model was estimated in M*plus* v. 8.4 using MLR. The EF factor score was regressed on dyadic reciprocity at 3 years, controlling for dyadic reciprocity at 2 years, child biological sex, and maternal country of origin. The model had adequate fit to the data, $\chi^2(N = 322; df = 3) = 3.74$, $p = .29$; RMSEA= .03, 90% CI [.00, .10]; CFI = .95; SRMR = .03. Dyadic reciprocity at 3 years significantly predicted child EF at 6 years ($\beta = .170$, S.E. = 0.08, $p = .036$) after accounting for covariates.

DISCUSSION

Executive function (EF) has emerged as a growing construct of interest for psychologists given concrete ties to self-regulated and purposeful behavior. The hierarchical and complex nature of EF development has posed challenges for accurate and replicable measurement, with varying levels of unity and diversity evident at each developmental stage (e.g., Friedman & Miyake, 2017; Miyake & Friedman, 2012). Studies of within-group differences in development of EF among low-income Mexican American children, in particular, are scant. A large part of the difficulty with measurement stems from a lack of available assessments to capture EF abilities reliably and accurately prior to age 5, which is known to be a period of rapid developmental change (Anderson & Reidy, 2012; Carlson et al., 2005; Zelazo et al., 2003). As such, in addition to developing a measurement model for EF in middle childhood for a low-income Mexican American sample, this study aimed to elucidate dynamic change processes among measurable developmental correlates of EF during infancy and early toddlerhood as predictors of later higher-order EF abilities. Drawing from developmental theory and a model of neurovisceral integration (Thayer et al., 2009; Thayer & Lane, 2000), surges in neurocognitive regulatory abilities may be supported by both previous and concurrent changes in physiological functioning and engagement in reciprocal social relationships. Utilizing recent methodological innovations, the current study moved beyond traditional growth models to evaluate possible points of attenuation and acceleration in dyadic reciprocity and vagal functioning over time as well as dynamic associations between these unfolding developmental processes. Results suggested that, in this sample, EF was best modeled at child age 6 years as a unidimensional construct. Findings also supported the importance of earlier dyadic reciprocity for later EF, but there was a lack of evidence supporting the theorized link between EF and earlier vagal functioning and codevelopment of vagal functioning and dyadic reciprocity.

Executive Function

The transition into formal education is a salient developmental period in which to study EF because children must rely on EF skills to self-regulate attention, behavior, and emotions when facing new challenges presented by the school environment. The latent structure of EF has been posited to change across development, with support for both a unidimensional model (Wiebe et al., 2008) and models with component-specific factors (Lehto et al., 2003; McAuley & White, 2011) found during middle childhood. In the current sample, results supported the application of a single EF latent construct to describe variation in Mexican American children’s scores at 6 years of age on 7 tasks that tap into aspects of EF, and this unidimensional model applied equally to girls and boys. Interestingly, the nested factor model with an updating-specific factor also evidenced excellent fit. Greater differentiation of skills becomes more evident as early foundational skills emerge into the more complex forms of working memory, inhibitory control, and set shifting commonly seen in adulthood.

If we situate the current findings in the context of the *unity/diversity* framework (Friedman & Miyake, 2017; Miyake & Friedman, 2012), the inclusion of the common EF and updating-specific factors left no inhibition-specific variance as evidenced by the nonsignificant loadings on the inhibition-specific factor. Neurodevelopmentally, 7 years of age has been posited to represent a pivotal period of differentiation of children's executive abilities (e.g., decreasing unity and increasing diversity; Shing et al., 2010). Though there was support for an updating-specific factor at 6 years of age, the nested factor model did not fit the data significantly better than the unidimensional model and perhaps reflects the approach towards this pivotal period of differentiation but not arrival. This finding highlights the importance of testing competing models, with the most parsimonious model being retained as the standard of practice in the field. The excellent fit of the nested factor model, if tested in isolation, would have resulted in the selection of a less parsimonious model. In sum, the findings of the current study are in line with metanalytic evidence supporting a unidimensional structure of EF during middle childhood (McKenna et al., 2017).

One of the forefront contributions of the current study to the literature is the extension of support for a unidimensional structure to a sample of Mexican American children from low-income families. The dearth of literature investigating EF development amongst populations that are *both* non-White and non-economically advantaged is striking. This is important given the role of cultural experiences, socioeconomic status, and exposure to a multilingual environment during infancy and early childhood are posited to affect EF development (Tran, Arredondo, & Yoshida, 2019) but have yet to be extensively studied. Some studies of cultural similarities and differences in EF components exist (e.g., Howard et al., 2020; Lan et al., 2011), though these are generally few and far between. Even less explored are *within*-group differences in EF development. Thus, this study represents the first step in building confidence in the appropriate application of a unidimensional structure to a low-income Mexican American population in preparation for future work examining culturally specific predictors of these differences (e.g., bilingualism, acculturation, etc.) purely *within* a single understudied population, rather than between cultural groups.

Results also point to several avenues for future research, including the integration of child bilingualism into developmental models of EF. Dual language use is thought to afford certain cognitive advantages to bilingual children (Barac & Bialystok, 2012). As such, the transition to a formal school environment is a particularly meaningful developmental period during which to examine the underlying structure of EF abilities in this population because, for many, it signifies a transition from a Spanish-dominant home environment to an English-dominant classroom. Studies with aims such as these will go far to uncover information key to tailoring intervention and prevention programs to non-Western, low-income samples.

Expected relations emerged between the unidimensional EF model and parent-reported indices of EF at 7.5 to 9 years, providing initial validation of the latent variable model. Interestingly, associations between the parent-reported subscales thought to most directly map on the performance-based EF tasks used in the model were generally nonsignificant (e.g., working memory and inhibit subscales). Rather, the significant associations were driven by the self-monitor, shift, plan/organize, and task-monitor subscales which alludes to ongoing discourse in the field regarding possible differences in the underlying processes captured via parent-report versus performance-based measures. Formal parent-report questionnaires are purported to measure “real-world” everyday applications of EF skills by providing parents with concrete examples whereas performance-based lab measures attempt to gather more process-specific information (Chevignard et al., 2012). Perhaps, the absence of the more directly hypothesized subscale-level associations (based on overlap in naming conventions) reflects differences in a structured testing environment compared to an unstructured home setting. The addition of teacher report of child EF skills in the school setting would be an avenue for future research since the school classroom is often perceived as more structured than a home setting but less structured than a one-on-one testing environment. If teacher report of child EF skills was more closely associated with the factor structure compared to parent-reported skills, it may suggest that, at this age, parents may not be placing as high of demands on a child’s working memory and inhibitory control as what they encounter in the school setting and testing environment making difficulties may be less apparent at home. Nonetheless, the associations that emerged were unvaryingly in the expected directions and impart a sense of ecological validity in addition to the high internal validity achieved by the lab-based measures. The unidimensional EF model was also positively associated with scores on tests of both fluid and crystalized intelligence, a finding that is complementary to previous research (e.g., Brydges et al., 2012; Friedman et al., 2006) and provides additional validation of this EF measurement model within the current study.

The latent variable approach to modeling EF has been the standard of practice since Miyake and colleagues (2000) described the advantages over traditional analytic methods (e.g., excluding variance due to error, greater reliability, more “pure” measure of underlying construct, etc.). Over the past two decades, the widespread use of CFAs for representing performance across a battery of EF tasks has yielded excellent model fit as is the case in the current study; both the unidimensional and nested models tested in the current study had excellent global fit. Insofar as correlations between tasks (ranging from .17 to .53) suggest the CFA was able to successfully extract a relatively small amount of shared variance across tasks, other researchers counter that weak correlations between tasks imply less shared variation to be extracted to define the construct of interest which may undermine the use of the resulting latent variables as predictors or outcomes. Indeed, Willoughby and colleagues (2014) critically evaluated the use of the CFA method with EFA tasks and highlighted the importance of modest to high correlations among EF tasks for maximal reliability. Emanating from the psychometric literature on reflective versus formative measurement, Willoughby and colleagues (2014) also raised the question of whether performance-based EF tasks should be construed as causal or effective indicators of the latent construct. The answer to this question may bear both conceptual and statistical weight. Conceptually, an effective indicator model assumes that “performance on each EF task is necessarily an interchangeable indicator of true ability (Willoughby et al., 2014, p. 80)”. However, the neurobiology of EF suggests a U-shaped relation between EF and the neural circuitry of the prefrontal cortex that varies as a function of individual ability, developmental history (e.g., levels of catecholamines), and the complexity of preceding EF tasks (Willoughby et al., 2014). If so, a summation of performances across tasks as assumed by the causal indicator model may be a more accurate characterization of EF ability. Further evaluation of the most accurate characterization of EF indicators using vanishing tetrad tests (Bollen, Lennox, & Dahly, 2009) would be prudent to affirm whether indicators should be modeled as causal or effective from a statistical standpoint. For models in which the latent constructs of EF are represented using effect indicators, akin to the current study, many tasks are needed per construct. Although the current study utilized 7 indicators, which is on par with many studies of EF development, there were a lack of tasks mapping on to the set-shifting component of EF which limited the type of model structures examined.

Longitudinal Development of Dyadic Reciprocity

Developing EF abilities are thought to be supported by reciprocal interactions between parents and children from an early age. From birth, social interactions with caregivers expose children to “a *field of mutual influences* between the infant’s regulatory abilities and the parent’s attuned response in gradually shaping development (Feldman, 2017, p. 1008).” As children develop, they become increasingly more active participants in social interactions with their caregivers. The current study sought to investigate possible points of attenuation and acceleration in the growth in dyadic reciprocity over time with the expectation that greater opportunities for reciprocal interaction would be present once the child was able to interact with their caregiver both verbally and nonverbally. Across all time points, mean levels of dyadic reciprocity were found to be moderately high. Although there are no reference points for which to compare proportional change, previous studies using the same CIB coding system to index dyadic reciprocity during both free play and teaching interactions have reported similar average levels of dyadic reciprocity during the first year of life: an average mean of 3.39 across 3 and 6-month interactions (Feldman, 2015). Mean levels of the current study for the 1- and 2-year time points (*M*s = 3.61 & 4.07) were higher than the average reported by Feldman (2015) across the 1st and 2nd years (*M* = 3.12). The highest mean level for dyadic reciprocity in the current study was indeed recorded at the 3-year time point, which, consistent with hypothesis, may reflect higher levels of reciprocal interactions due to the child's increasing verbal expressiveness.

Results of the univariate LCS model demonstrated an effect of prior level on later change in dyadic reciprocity across time (e.g., proportional change) such that there was a deceleration in dyadic reciprocity growth across the timepoints assessed. To date, this is the first study to examine proportional change in dyadic reciprocity during infancy and early childhood. A larger body of research is needed to determine with greater confidence whether this finding is consistent across different samples and measurement periods (e.g., 3-month time intervals). Several possible explanations are offered for this deceleration in dyadic reciprocity growth over time. First, drawing from the parent-infant biobehavioral synchrony literature, the first year of life is a crucial sensitive period of bond formation between parent and child (Feldman, 2012). Though growth in synchronous parent-child behavioral interactions may continue throughout early childhood as attachment processes further develop, the steepest rates of growth may be seen during this key early infancy period. Compared to the 24-week home visit, dyadic reciprocity was more stably interrelated across laboratory visits with correlations ranging from .24 to .35. Thus, the deceleration of growth over the timepoints assessed in the current study may reflect establishment and stabilization in attachment processes, though this hypothesis remains to be tested.

Second, although the brain bases of executive functions and vagal functioning have received considerable attention in the developmental literature, the brain basis of social interaction during early human development has received comparatively little (Redcay & Schilbach, 2019). The field of social neuroscience has recently begun to elucidate the neural correlates of dyadic reciprocal social interaction components (e.g., joint attention, communication, social decision-making; Redcay & Schilbach, 2019). There is reason to posit shared underlying connectivity between advances seen in cognitive development that facilitate engagement in social interaction (e.g., being able to seamlessly integrate socially important stimuli such as body language, tone of voice, content of speech to inform an appropriate response), yet this thinking has yet to be mapped onto neuroanatomical structures or pathways beyond general associations with reward systems. Further advancing our knowledge of the timing of growth in underlying structures and strengthening of these developing systems may provide another possible explanation for the deceleration found in dyadic reciprocity from 24 weeks through 3 years.

Longitudinal Development of Vagal Functioning

Commonalities in brain systems supporting both cognitive and physiological regulation make the longitudinal development of vagal functioning of interest to EF researchers. Consistent with prior research (e.g., Alkon et al., 2011; Bar-Haim, Marshall, & Fox, 2000), the moderate stability found in resting RSA between 24 weeks and 2 years suggests that patterns persist over time (e.g., a child with high resting RSA at one time point is also likely to have high resting RSA at subsequent time points) and support the conceptualization of resting RSA as a biomarker of trait-like differences in regulatory style that become entrenched early in life. In terms of developmental change, growth in vagal functioning was expected to accelerate across the timepoints assessed. Contrary to this expectation, the univariate LCS model of RSA did not yield significant constant or proportional change parameters. This finding, or lack thereof, was surprising given prior concordance between theory (e.g., Calkins, 1997; 2007) and empirical research with Latino children (e.g., Alkon et al., 2011; Jewell et al., 2017). These prior studies demonstrated linear growth in RSA over infancy and early childhood.

As noted in the introduction, LCS models conceptualize change over time differently than traditional longitudinal growth models. As demonstrated by the piecewise growth model of RSA, there is indeed linear change when change is conceptualized as a static process and a function of time and, as hypothesized, greater accelerations in this growth were evident during later time periods compared to infancy. Of note, equally spaced time points are not an assumption for piecewise growth models as they are for LCS models and additional time points were able to be included which provided more information regarding these growth patterns over time that were not available in the LCS model. The ability to capture the hypothesized proportional change in the LCS model, in particular, was likely depreciated as a function of this assumption. Further, the inclusion of two successive phantom variables placed an added computational burden on this already exceedingly complex model.

Though several studies have examined developmental change in resting RSA from infancy through later childhood, few have investigated accelerations and decelerations in growth rates during this early sensitive period. Previous research has documented a slowing in rates of change of resting RSA from 2 to 15 years of age, with a plateau around age 10 (Dollar et al., 2020). Measurement of RSA in this impressive longitudinal study by Dollar and colleagues did not, however, extend downward to include the infancy period. Importantly, from birth to three years of age marks an important sensitive period for autonomic nervous system development characterized by rapid myelination that slows down after age 3 (Alkon et al., 2011). The current study extends prior research by documenting a significant increase in resting RSA from 1 to 2 years of age that is distinct from growth occurring during early infancy (e.g., between 6 and 24 weeks). Taken together, development of resting RSA may be best characterized by a logistic equation or sigmoid growth curve; slow increases initially during early infancy are followed by significantly greater positive accelerations from late infancy into early middle childhood, which is then followed by a slowing of growth in middle childhood until a child reaches near-adult like stabilization in vagal functioning around age 10. Extensive longitudinal research studies with ethnically diverse samples are needed to affirm this hypothesis and denote an important avenue for future research.

Interwovenness of Dyadic Reciprocity and Vagal Functioning Across Early Development

Dyadic reciprocity within caregiver-child interactions was hypothesized to support emerging physiological regulatory abilities and physiological regulatory abilities were similarly hypothesized to support a child’s ability to successfully engage in a reciprocal manner during interactions with their caregiver. The dynamic parameters of interest (e.g., proportional change and coupling coefficients) were nonsignificant and, thus, results failed to support the hypothesized reciprocal relations between dyadic reciprocity and RSA. The theorized reciprocal relations between these constructs would suggest a positive association such that greater RSA facilitates greater social engagement and vice versa. There were only three significant intercorrelations between dyadic reciprocity and RSA. RSA at child age 1 year was negatively correlated with dyadic reciprocity at child ages 1.5 and 2 years and RSA, whereas RSA and dyadic reciprocity were positively correlated at 2 years. Perhaps, the negative associations found with earlier child RSA reflect an infant's relatively limited ability to flexibly engage with their environment, as compared to post-growth surges, such that their mothers were required to provide substantially more external co-regulation and greater coordination of reciprocal actions. However, the interpretability of these associations is limited, and consideration must be given to inconsistencies in directionality and temporal proximity that would indicate these findings are of a more spurious nature. Resting RSA is posited to index an individual's ability to flexibly engage with their environment (Porges, 2007; Thayer & Lane, 2000). Greater infant resting RSA measured at birth has previously been found to predict greater dyadic reciprocity during the first year of life, with resting RSA posited to serve "as a biomarker of system maturation that taps into the underlying substrate that supports regulatory function (Feldman, 2015, p. 1018)." The lack of interwovenness of dyadic reciprocity and RSA over time in the current study fails to add support for this theory. Given the generally inconsistent and nonsignificant correlations, the nullification of interwovenness is not likely attributable to the complexities necessitated by and introduced via the statistical model (e.g., transformations, missing data).

The allocation of internal resources can facilitate a child's social functioning in the moment (e.g., following rules, responding appropriately) through vagal regulation (Porges, 1995). "*In the moment*", however, may be the crux of this theory and pulls at the dynamic nature of social interactions. Indeed, most of the documented empirical links involve RSA *during* interactions. Emotional expressivity during social interactions necessitates use of facial, head, and neck muscles which are also supported by vagal influence (Whedon et al., 2018). Thus, vagal augmentation (e.g., increased PNS influence) is commonly recorded during social interactions with positive engagement states. Greater PNS influence during a task may allow for greater responsivity to social cues (Whedon et al., 2018). If vagal regulation in the current study had been measured in a dynamic fashion *during* the parent-child interaction task, it is possible that stronger associations between RSA and dyadic reciprocity would have emerged both within and across time.

Developmental Correlates of Executive Function

Although there was no evidence suggesting a joint influence of RSA and dyadic reciprocity on developing EF, change in dyadic reciprocity was individually predictive of later EF. However, the theorized link between physiological functioning and EF was not supported by the data. Conceptually, there are several mechanisms by which the mutual influences of child physiological functioning and parent-child reciprocity may underpin EF development. Children who were more effective cardiac regulators were also expected to be more effective cognitive regulators given theory supporting the integration of relevant neurophysiological systems (e.g., the neurovisceral integration hypothesis; Thayer et al., 2009; Thayer & Lane, 2000) and prior empirical evidence linking higher resting RSA with concurrent parent-report of effortful control (Chapman et al., 2010) and greater EF task performance within the same experimental session (Marcovitch et al., 2010). Though higher resting RSA is thought to reflect a more trait-like adaptive regulatory style (Beauchaine, 2001), as illustrated in the previously mentioned studies, results of the current study failed to support a *prospective* extension of integrated neurophysiological systems underlying RSA and EF. There are several possible reasons why resting RSA did not emerge as a developmental correlate of EF. First, the temporal gap between RSA measurement periods and measurement of EF was substantial. Across the 4 years between the last RSA measurement at 2 years of age and eventual EF measurement at 6 years of age, dramatic increases in EF are known to occur (Carlson et al., 2005; Zelazo et al., 2003). During this point of rapid development, more proximal measurement may be needed for the establishment of a direct link. There may also be mediators that indirectly link resting RSA *prior* to surges in neurocognitive development to EF abilities *post* surge. Receptive and expressive language in toddlerhood, for example, were shown to link biological functioning during infancy with social and cognitive functioning in childhood (Whedon et al., 2018). Third, RSA reactivity measured during performance-based EF tasks tapping into attention, working memory, and inhibitory control processes has been more consistently related to concurrent EF ability during childhood (e.g., Marcovitch et al., 2010). Reductions in PNS influence on the heart are commonly found to facilitate sustained attention, likely by means of reallocation of neural resources to the prefrontal cortex (e.g., Calkins et al., 2002). Porges (1992) also highlighted the metabolically costly working memory demands implicated in sustaining active attentional control.

Reciprocal exchanges within caregiver-child interactions provide opportunities to practice integrating executive skills in support of social engagement. Greater latent change in dyadic reciprocity between 2.5 and 3 years was hypothesized to be the most predictive of EF abilities at 6 years of age based on the sophistication of verbal ability around 2 – 3 years of age affording more opportunities for reciprocal exchange (e.g., both verbal and nonverbal). In line with this hypothesis, greater dyadic reciprocity at 3 years was found to predict greater EF at child age 6 years even after accounting for dyadic reciprocity at 2 years, child biological sex, and maternal country of origin. This finding supports incorporation of the dynamic back-and-forth exchange during social interaction into intervention and prevention programs marketed to facilitate EF development among children. In recent years, we have witnessed a surge of computer-based training programs for EF in pop-culture. Given the current findings, socially based interventions may be more developmentally appropriate, especially during early childhood and especially given the positive carryover effects into other domains (e.g., language development, interpersonal functioning).

Strengths and Limitations

The current study has many strengths. First, few intense longitudinal studies span from the prenatal period through the first decade of life and have collected as rich and frequent behavioral and physiological data as the parent project from which this study derives. Second, the unique sample of the current study affords the opportunity to examine continuity and change in developmental processes across time among an understudied population in the literature and can serve to elucidate the role of factors specific to this population that may influence these processes over time (e.g., maternal country of origin). Third, measurement models of EF among Mexican American populations during the transition to school have not been well documented which represents a large gap in the literature given the importance of executive function skills for behavioral adjustment at school age (Ponitz et al., 2009) and academic success (Willoughby, Wylie, & Little, 2019). Further, longitudinal, multi-method investigations of EF development among ethnic and culturally diverse populations often focus on between-group comparisons (e.g., compared to non-Hispanic, White children from middle class families) rather than within-group differences (e.g., White & Greenfield), like in the current study. Fourth, the use of the univariate and bivariate LCS models exemplify how novel statistical approaches can be used to shed new light on important research questions in developmental science by placing an emphasis on time-sequential within-person change and ability to predict intraindividual change at a given point in time.

Interpretations of the current study's findings should be considered in light of several limitations. First, the limited number of set-shifting tasks imposed restrictions on the types of EF factor structures that could be empirically tested. Second, the sample size is relatively small for the complex bivariate LCS model. In addition, the unavailability of RSA data at the 3-year time point imparted a greater amount of missing data upon the model than initially anticipated. This issue may have further complicated model estimation above and beyond the phantom variables for both dyadic reciprocity and RSA specified at the 2.5-year time point to keep the time lag constant. Third, I was unable to evaluate potential reciprocal associations between EF and dyadic reciprocity. Children with higher EF may evoke greater parental responsiveness in addition to greater parental responsiveness promoting child EF development (Merz et al., 2018). Fourth, the fit of the univariate LCS model for dyadic reciprocity did not fit the data well and these results must be interpreted cautiously. Lastly, the uniqueness of the sample may limit the generalizability of results beyond low-income Mexican American populations.

Summary and Conclusions

Elucidating developmental correlates of EF remains an important research objective with meaningful practical implications in both clinical and research settings. Understanding processes that support EF development among minority populations is an important public health endeavor above and beyond their centrality to child health promotion programs (Pentz & Riggs, 2013) given that, by 2050, thirty percent of all Americans under 18 years old are projected to be Latinx, making Latinxs the fastest growing ethnic minority group in the United States (U.S. Census Bureau, 2017). Heeding the call for increased attention to EF development among non-White, low-income samples, the present study investigated the structure of EF among Mexican American children at 6 years of age through testing single and complex multifactor models. Results of this dissertation provide support for a unidimensional model of EF among this unique sample. Although results from the dissertation project failed to support the hypotheses that dynamic associations exist between RSA and dyadic reciprocity across infancy and early childhood and that greater RSA promotes EF development in middle childhood, they provide empirical evidence in support of reciprocal social interactions laying the groundwork for emerging EF abilities. This finding highlights the importance of including dyadic measures of parent-child contingencies in studies of EF development and, from a clinical perspective, the potential use of relationship-based, dyadic intervention and prevention models to support crucial development of EF skills central to everyday adaptive functioning.

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65 APPENDIX A

TABLES AND FIGURES

Table 1. *Sample Demographics* (*N* = 322)

	Min	Max	Mean	SD	%	*n*
Mother's Age	18	42	27.79	6.48		322
Mother's Education	0	18	10.14	3.21		322
Mother's Country of Birth						
United States					14	44
Mexico					86	278
Child's Gender						
Male					45.7	145
Female					54.3	172
Marital Status						
Married and living together					30	96
Living with partner but not married					45	147
Never married and not living with a partner					15	49
Number of other Biological Children Estimated Total	0	9	1.98	1.68		320
Income						
≤ $5,000					14	44
$5,001 – 10,000					19	61
$10,001 – 15,000					28	87
$15,001 – 20,000					12	37
$20,001 – 25,000					13	40
≥ $25,001					14	45

Table 2. *Mother-Child Teaching Task Descriptions*

	TT 1	**TT 2**	**TT 3**	**TT 4**
24 weeks	Remove pegs from a peg board and place them back. 	N/A	N/A	N/A
1 year	Take shapes out of box. 	Roll ball back and forth. 	Make a tower out of blocks. 	Pop-up animals. 
1.5 years	Fit different size rings onto peg to make a tower. 	Nested cups. 	Fit shapes into shape box. 	Fit farm animal puzzle pieces into place on backdrop. 
2 years	Make a tower from blocks. 	Fit insect puzzle pieces into place. 	String big wooden beads. 	Put foam rings onto the correct color peg on pegboard. 
3 years	Make a chain from a barrel of monkeys. 	Stack different shaped pegs on a pegboard. 	N/A	N/A

Note: TT = Teaching Task

Table 3. *Descriptive statistics and zero-order correlations among primary study variables*

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. DR 24 wks	--																	
2. Child RSA 24 wks	.12	--																
3. DR 1yr	-.11	-.04	--															
4. Child RSA 1 yr	.01	**.36**	-.16	--														
5. DR 1.5 yrs	.18	.07	**.26**	**-.38**	--													
6. Child RSA 1.5 yrs	.02	**.33**	-.08	**.50**	.02	--												
7. DR 2 yrs	.09	-.06	.10	**-.38**	**.35**	-.02	--											
8. Child RSA 2 yrs	.05	**.39**	.07	**.29**	.12	**.39**	**.25**	--										
9. DR 3 yrs	.16	<.01	.02	-.08	**.24**	**-.29**	.15	.02	--									
10. HTKS trial 1	.12	.01	.07	.03	-.06	-.02	.12	.09	.12	--								
11. HTKS trial 2	.12	-.16	.04	**-.26**	.16	-.12	.10	**-.17**	.16	**.33**	--							
12. HTKS trial 3	.03	.04	.07	>.01	**.26**	-.08	.03	-.04	**.21**	**.24**	**.43**	--						
13. DSb	.15	-.11	.01	-.03	-.04	-.10	.04	-.01	.10	**.34**	**.42**	**.29**	--					
14. CPT RT for com. errors	.12	-.03	-.13	.09	-.03	**.21**	.04	.07	.15	-.01	-.04	-.09	-.02	--				
15. CPT RT for correct hits	<.01	-.07	-.04	-.17	-.12	.09	-.09	-.08	**-.28**	**-.24**	**-.24**	**-.31**	**-.19**	**.23**	--			
16. CPT com. errors	-.02	.02	-.03	.02	.03	**.21**	.02	-.01	**-.18**	**-.17**	-.21	**-.25**	-.13	**.48**	**.53**	--		
17. CPT om. errors	.01	**.19**	-.03	.15	-.06	.06	-.09	.15	-.07	**-.23**	-.23	**-.28**	**-.19**	**.21**	**.25**	**.22**	--	
18. EF factor	.14	-.12	.08	-.03	.08	-.09	.13	-.03	**.19**	**.72**	**.90**	**.72**	**.63**	-.12	**-.46**	**-.34**	**-.33**	--
Mean	3.12	3.08	3.61	3.65	4.33	4.24	4.07	4.75	4.49	12.9	12.2	10.2	7.75	.87	.79	.08	.13	.00
S.D.	.80	.86	.60	.94	.59	.98	.83	1.20	.74	7.54	4.98	5.80	3.50	.32	.17	.10	.13	4.08

Note. All ages refer to child age. Correlation coefficients presented in bold are statistically significant, $p < .05$. RSA – Respiratory Sinus Arrythmia. HTKS – Head Toes Knees Shoulders; CPT – Continuous Performance Test; RT – reaction time.

Table 4. *Measurement invariance by gender for the unidimensional model of executive function (N = 200)*

Model	χ^2 (*df*)	CFI	RMSEA (90% CI)	SRMR	Model comp	$\Delta\chi^2$ (Δdf)	ΔCFI	ΔRMSEA	ΔSRMR	Decision
M1: Configural	37.61 (26)	.93	.07 (.00-.11)	.08	-	-	-	-	-	
M2: Metric	46.10 (32)	.92	.07 (.00-.11)	.11	M1	8.53 (6)	-.01	.00	.03	Accept
M3: Scalar	53.34 (38)	.91	.06 (.00-.10)	.12	M2	7.38 (6)	-.01	.01	.01	Accept

Note. $N = 200$; females $n = 108$; males $n = 92$; All χ^2 tests were nonsignificant.

Table 5. *Initial Validation Results for EF Factor*

	M Edu	Sex	EHS	ORC	Block Design (WISC-IV)	Vocabulary (WISC-IV)	BRIEF 2 BRI	BRIEF 2 CRI	BRIEF 2 ERI
EF	.219	-.258	-.132	-.026	.29	.37	-.14	-.13	-.14
p value	.002	<.001	.06	.71	<.001	<.001	.049	.06	.06

Note. EF = Executive Function; M Edu = Maternal Education; EHS = Economic Hardship Scale; ORC = Orienting/Regulatory Capacity from the IBQ.

Table 6. *Parameter Estimates for Univariate and Bivariate Latent Change Score Models*

Model	Parameter	B	SE B	*p*
Univariate LCSM for DR				
	Initial Mean Level	.002	.069	.980
	Constant Change	-.005	.043	.903
	Proportional Change	**-1.373**	**.215**	**<.001**
Univariate LCSM for RSA				
	Initial Mean Level	-.007	.060	.912
	Constant Change	.006	.072	.936
	Proportional Change	.858	3.874	.825
Bivariate LCSM				
	Initial Mean Level (DR)	.002	.069	.981
	Constant Change (DR)	-.007	.043	.863
	Proportional Change (DR)	**-1.355**	**.213**	**<.001**
	Initial Mean Level (RSA)	-.009	.060	.881
	Constant Change (RSA)	.004	.041	.925
	Proportional Change (RSA)	**.425**	**.125**	**.001**
	DR → RSA Coupling	.015	.063	.817
	RSA → DR Coupling	-.153	.095	.110

Note. LCSM = Latent Change Score Model; DR = Dyadic Reciprocity; RSA = Respiratory Sinus Arrythmia. Bold indicates statistical significance.

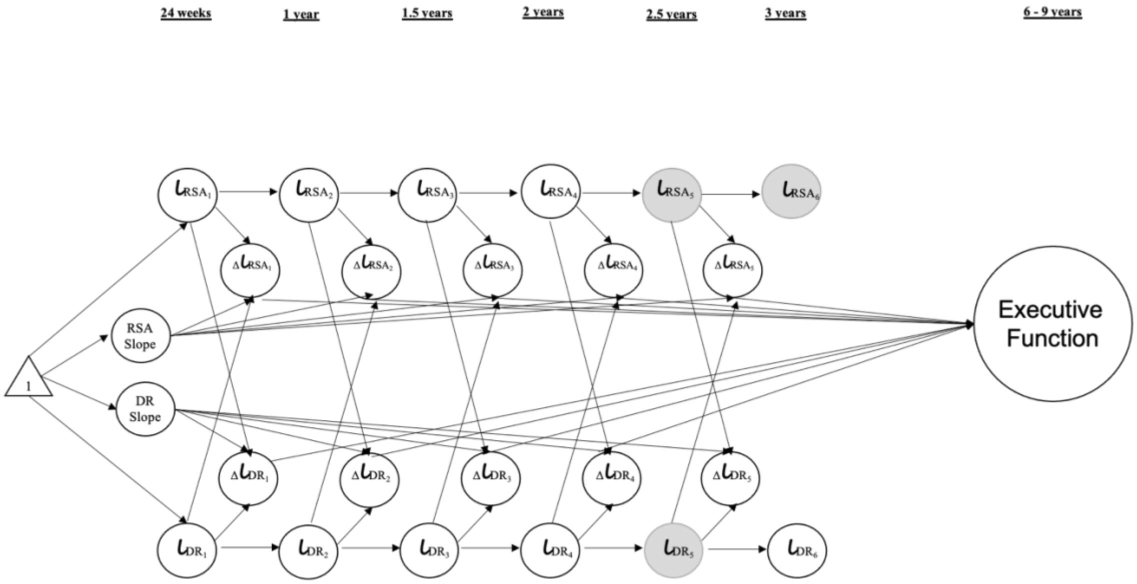

Figure 1. Conceptual Model of EF as a Function of Latent Change in Dyadic Reciprocity and Baseline RSA. Grey circles indicate a phantom variable. DR = Dyadic Reciprocity; RSA= Respiratory Sinus Arrythmia.

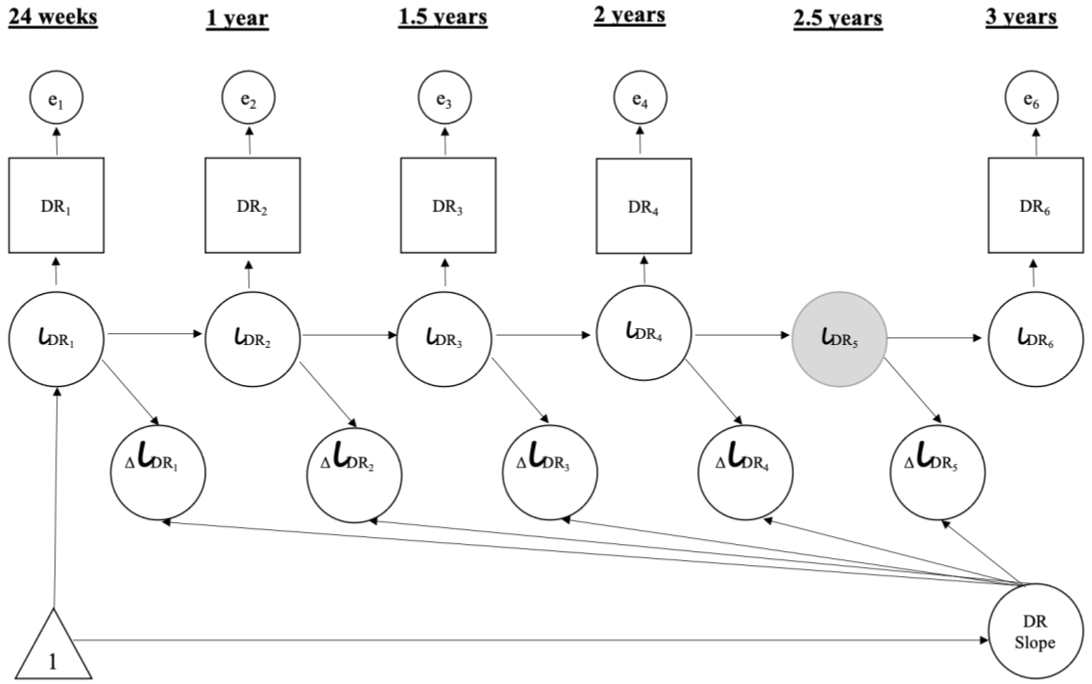

Figure 2. Univariate Latent Change Score Model for Dyadic Reciprocity (DR). Grey circle indicates a phantom variable. e = error.

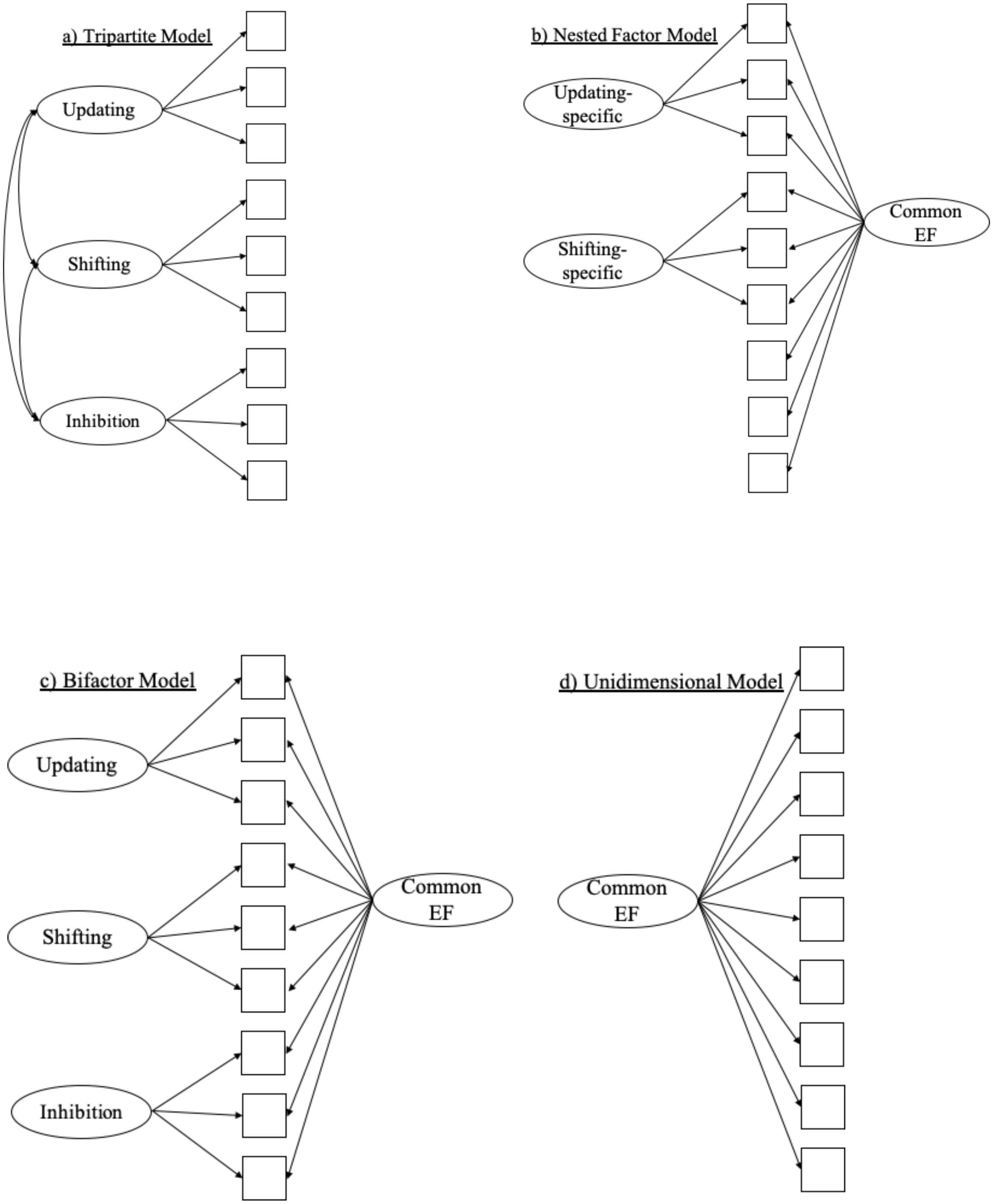

Figure 3. Possible EF Factor Models.

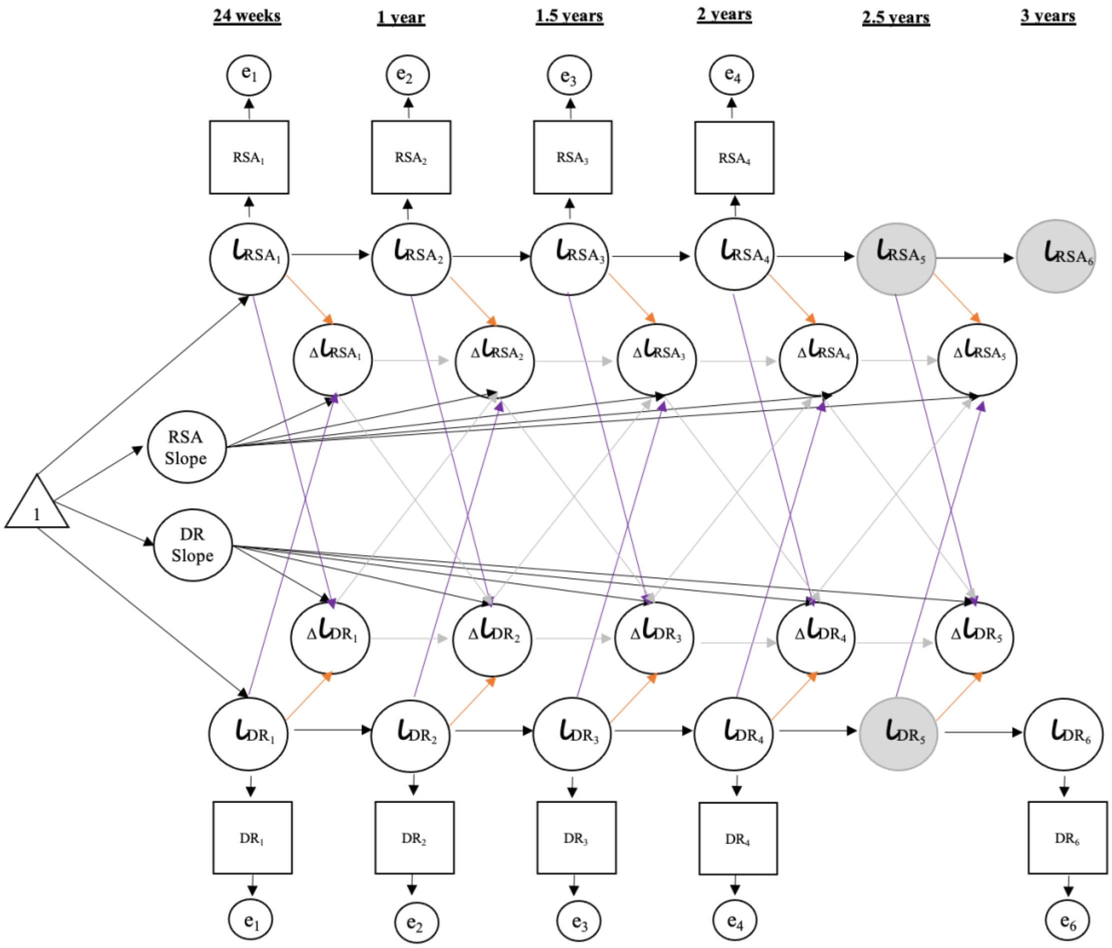

Figure 4. Bivariate Latent Change Score Model. Grey circle indicates a phantom variable. Orange paths represent the proportional change parameter and purple paths represent the bidirectional coupling parameter. e = error; RSA = Respiratory Sinus Arrythmia; DR = Dyadic Reciprocity.

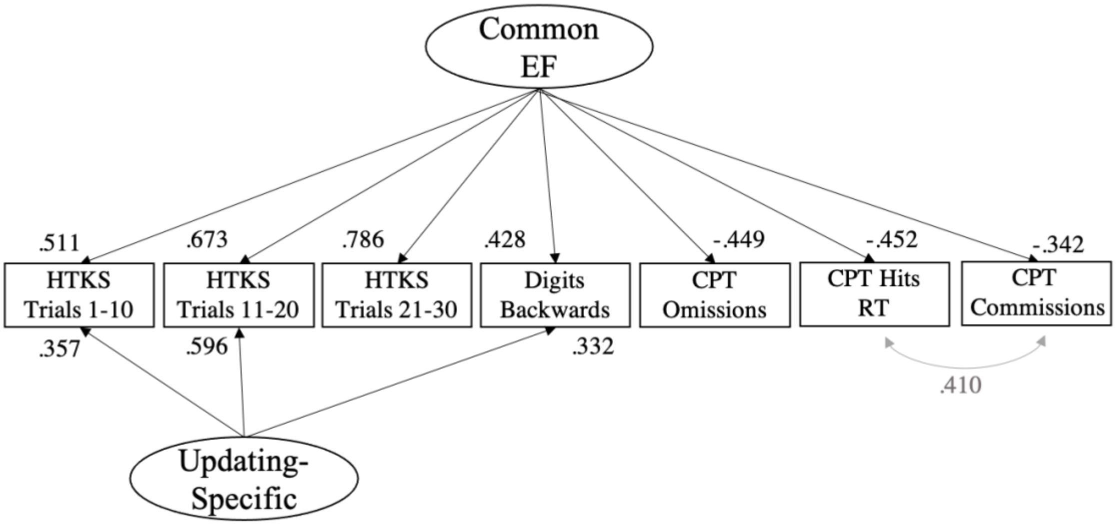

Figure 5. Nested Factor Model of Executive Function at Child Age 6 Years.

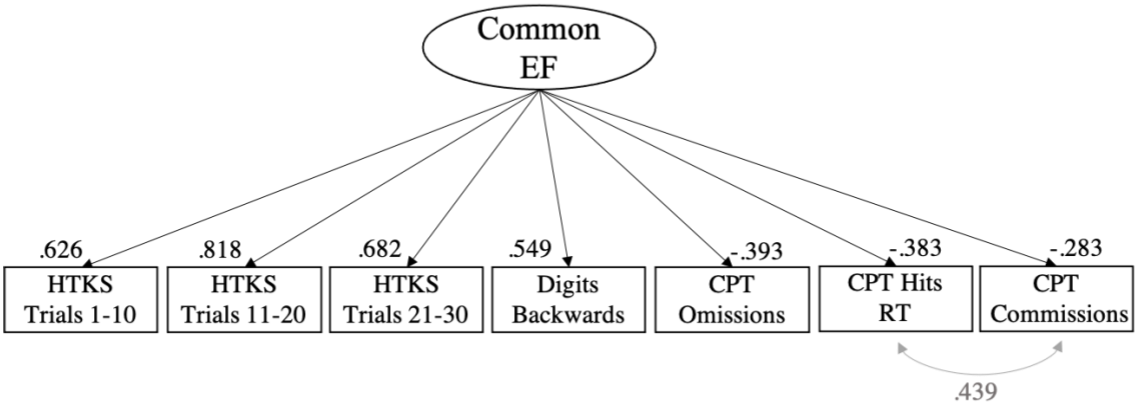

Figure 6. Unidimensional Model of Executive Function at Child Age 6 Years

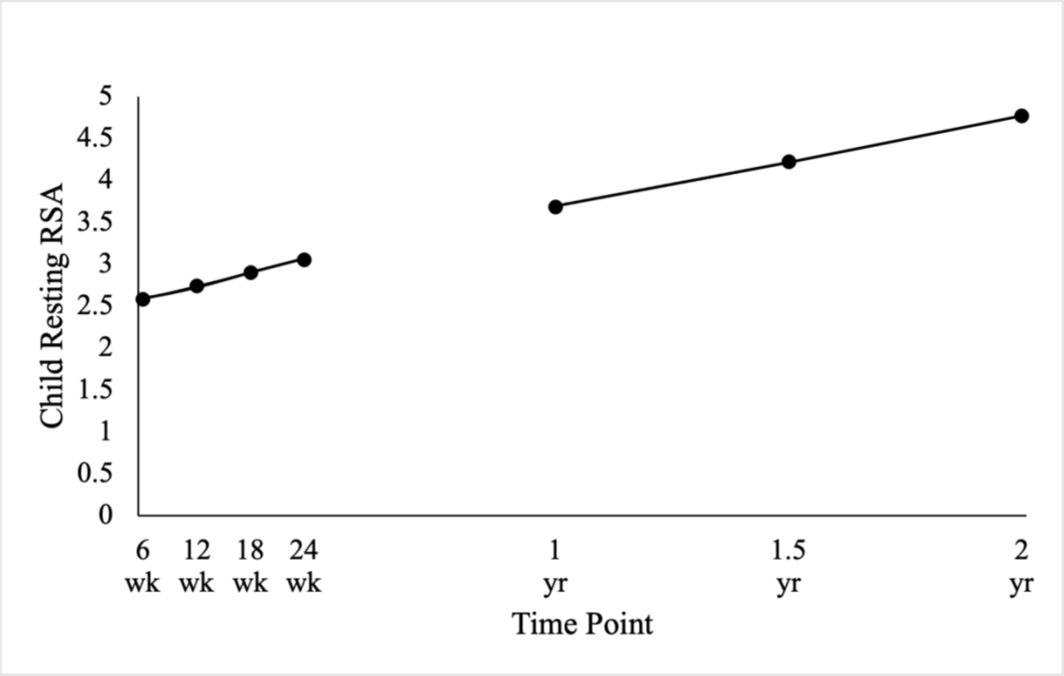

Figure 7. Model Estimated Means for Piecewise Latent Growth Model for Resting RSA from 6 Weeks to 2 Years.