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Assessing Unpredictability in Caregiver-Child Relationships: Insights from Theoretical and Empirical Perspectives

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Abstract

There has been significant interest and progress in understanding the role of caregiver unpredictability on brain maturation, cognitive and socioemotional development, and psychopathology. Theoretical consensus has emerged about the unique influence of unpredictability in shaping children's experience, distinct from other adverse exposures or features of stress exposure. Nonetheless, the field still lacks theoretical and empirical common ground due to difficulties in accurately operationalizing and measuring unpredictability in the caregiver-child relationship. In this paper, we first provide an overview of the role of unpredictability in theories of caregiving and childhood adversity and present four issues that are currently under-discussed but are crucial to the field. Focusing on how moment-to-moment and day-to-day dynamics are at the heart of caregiver unpredictability, we review three approaches aiming to address some of these nuances: Environmental statistics, entropy and dynamic systems. Lastly, we conclude with a broad summary and suggest future research directions. Systematic progress in this field can inform interventions and policies aiming to increase stability in the lives of children.

Assessing Unpredictability in Caregiver-Child Relationships: Insights From Theoretical And Empirical Perspectives

Predictability, especially early in life, is instrumental in shaping learning processes and stress-response systems (Doan & Evans, 2020; K. E. Smith & Pollak, 2021a), with important implications for psychosocial functioning across the lifespan (Baram et al., 2012; Doom et al., 2016; Kolak et al., 2018). Accordingly, the fields of developmental psychology and developmental psychopathology are increasingly recognizing the importance of unpredictability in children's lives as a source of environmental adversity (Ellis et al., 2022; McLaughlin et al., 2021; Young et al., 2020), fundamental to understanding the experience of stress throughout development (K. E. Smith & Pollak, 2021a). While existing theoretical and empirical orientations about distal unpredictability (e.g., parental transitions, income variability, residential transitions; Ellis et al., 2022) have grown substantially during the last decade (Young et al., 2020), less research has centered on the specific processes by which the nature of proximal experiences of unpredictability, such as those that may occur within the caregiver-child relationship, shape children's socioemotional and cognitive development (Glynn & Baram, 2019).

Receipt of positive, consistent, and predictable care during early childhood promotes healthy long-term affective and cognitive development (Gee & Cohodes, 2021; Short et al., 2020; Tarabulsy et al., 1996). Contingent and consistent caregiving during infancy fosters attachment security, serving as a source of comfort, safety, and external regulatory support of infants' and children's developing emotional and physiological self-regulation (Feldman, 2021; Lobo & Lunkenheimer, 2020; Yaniv et al., 2021). Animal models suggest that predictability supports the development of hippocampal/limbic and pleasure/reward-related brain circuitry

(Bolton et al., 2018; F. K. Johnson et al., 2018; Molet et al., 2016), with important implications for prefrontal-subcortical development and maturation of the stress response system (Bolton et al., 2019; Tottenham, 2020). This does not pertain exclusively to positive features of caregiving. Predictability of aversive stimuli, such as caregiver separation, has been shown to reduce anxious behaviors in rats (Shi et al., 2021), reduce fear in infants (Gunnar et al., 1986), strengthen threat appraisal (Parritz et al., 1992) and increase perceived control (Maier & Seligman, 1976; Price & Geer, 1972; Wang & Delgado, 2021). Conversely, caregiver unpredictability during infancy has been shown to have lasting adverse effects on neurodevelopment, including disrupting the development of effortful control and memory (Davis et al., 2017; Granger et al., 2021) and dampening stress responses (Noroña-Zhou et al., 2020). Such infant responses to caregiver unpredictability may be considered adaptive for the well-being of the child at the time of the adversity, conferring an immediate survival advantage to environmental demands (Frankenhuis et al., 2020; Nketia et al., 2021). However, they also may convey maladaptive consequences for future health and well-being (Blair & Raver, 2012a, 2012b).

Despite the central roles of caregiver unpredictability in developmental theory, defining, operationalizing, and assessing variation in caregiver unpredictability has proven to be elusive. In this paper we integrate different theoretical and corresponding empirical orientations to provide a set of conceptual and methodological tools for researchers seeking connections between caregiver-child unpredictability and other constructs of interest. Our approach to thinking about unpredictability within the caregiver-child relationship is informed by models of socialization theory that frame caregiver-child interactions as dynamic, bidirectional processes that are shaped by relationship histories yet may be expressed in situation-specific ways (Grusec et al., 2000; Kuczynski et al., 2015). That is, caregiver-child interactions are flexible in the face of changing features of both partners and situations, and the mechanisms that guide socialization and child outcomes across development may be different across varying domains of relationship context, as well as age or developmental stage of the child (Grusec, 2011). Therefore, we expect that caregiver unpredictability is not unidimensional; rather, is likely to be multidimensional. We focus on children's immediate caregiving system across infancy and early childhood because it is the most proximal and primary source of information about the type of environment children can expect concurrently and probabilistically across their lifespan, shaping development accordingly (Bateson et al., 2004; Tottenham, 2020). Hence, unpredictability in this foundational system may confer myriad and enduring consequences.

In this article, we first provide a brief overview of different theoretical perspectives of caregiving and childhood adversity and the role that unpredictability has been posited to play in each of these perspectives. Second, we highlight four under-discussed issues in the field. Third, we present three frameworks and corresponding methods that may improve how we assess variation in child-caregiver unpredictability: Life history theory and environmental statistics, information theory and entropy, and dynamic systems theory. In a fourth and final section, we conclude with a broad summary and suggest potential future directions in the field. Our goal is to synthesize existing issues, theoretical frameworks, methodological tools, and actionable future directions to better equip researchers to understand the role of unpredictability in guiding behavior and affective, cognitive, and neurobiological adaptations in children. Advancing more systematic progress in the study of caregiver unpredictability has the potential for providing more specific targets for interventions seeking to increase stability in the lives of children (Ellis et al., 2009; McLaughlin et al., 2021; K. E. Smith & Pollak, 2021a).

The role of unpredictability in theoretical perspectives of caregiving and adversity

Foundational developmental theories have integrated the importance of predictability and stability in caregiver-child interactions and children's environment. We review four theoretical perspectives that propose environmental or caregiver unpredictability as a determinant feature or dimension of early life adversity. Given the plethora of terms that have been used to consider unpredictability as an aspect of stressful early life experiences, Table 1 outlines our working definitions of key terms that appear repeatedly through the literature and within the current paper, recognizing that many of these definitions are subject to debate within and between disciplines.

Table 1.
Working definitions of constructs included in the manuscript

Construct	Definition
Introduction and theories	
Unpredictability	Stochastic variation (an absence of patterns in the variation) of environmental cues or experiences, including lack of temporal stability of aspects of the environment, and lack of organization, coherence, or consistency of caregiver behavior.
Adversity	A wide range of experiences and contexts that are non-optimal for the developing child and can disrupt physical and psychological health.
Stress	The physiological or psychological response to external or internal stressors or stressful events.
Stressful events/experiences	Acute or chronic induvial or community-based events or experiences that result in physical or emotional stress.
Distal cues	Ecological factors linked to unpredictability.
Proximal cues	Direct experiences of unpredictability.
Inconsistency	Behavioral variability in different aspects of caregiving such as affection or discipline.
Instability	Cumulative number of transitional experiences that challenge families' continuity and cohesiveness through developmental time.
Chaos	General lack of structure or routines in day-to-day experiences and home organization.
Unpredictable schema	A belief that people and the world are uncertain and chaotic.
Harshness	External causes of morbidity and mortality that are relatively insensitive to the decisions/actions of the organism.

Threat	A feature of harshness involving harm or threat of harm imposed by other agents.
Deprivation	A feature of harshness involving lack of necessary resources for survival.
Perceived control	Perceived ability or awareness that the effects of one's actions influence the environment in accord with one's intentions.
Environmental statistics	
Environmental statistics	Ways to quantify the statistical structure of an environment, which is determined by how physical and social parameters vary over space and time, across and within generations, and the extent to which cues (experiences or events) provide reliable information about current and future conditions.
Adaptive plasticity	The degree to which organisms successfully adjust their phenotype to environmental conditions, which will depend on the statistical structure of the environment.
Ancestral cues	Informative cues that signal potential unpredictability to which the human brain is able to detect quickly and adapt efficiently due to the processes of natural selection across evolutionary history favoring those biobehavioral capacities.
Statistical learning	The use of accumulated lived experiences as "raw data" to estimate and developmentally adjust to unpredictability across developmental time.
Level (mean)	Average expression of the parameter across time
Variability	Deviations from a parameter's mean.
Autocorrelation	The degree to which past values correlate with current values of a given parameter.
Stationarity	If a parameter is stationary, the distributional characteristics of a parameter (e.g., mean, variability, and autocorrelation) do not change across time.
Trend	Stable directional changes in variability.
Cycles	Patterns systematically repeating over time (e.g., seasonality).
Self-contingency	An index of the predictability of behavioral rhythms within an individual that is measured by the degree of autocorrelation of moment-to-moment behaviors analyzed by time-series techniques.
Interactive contingency	An index of the predictability of behavioral rhythms across two partners that is measured by the degree of lagged cross-correlation of moment-to-moment behaviors analyzed by time-series techniques.
Informative or reliable cue	Events or experiences that provide information about the current or future state of the environment.
Entropy	
Entropy	The degree of uncertainty or disorder of a random variable.

Entropy rate	Average information required to predict a future observation given a previous observation in a sequence.
Sensory signals	Auditory, tactile, and visual inputs from a caregiver
Fragmentation	Aberrant patterns of care, or the provision of care without a consistent or organized rhythm in rodent models.
First-order stationarity Markov chain	A sequence of behaviors to calculate entropy rate. It is based on the following assumptions: (a) Proximal future states (e.g., at time *t*) depend exclusively on their most recent past state (e.g., *t* -1), such that each sequential transition is independent of preceding and following transitions and (b) the probability distribution is *stationary* or independent of time.
Visit entropy	Transitional probabilities between all visited grids of a state-space grid.
Dynamic systems theory	
Attractors	Recurrent patterns of behaviors that become increasingly coherent and predictable through developmental time.
Phase transitions	System-wide reorganizations in which relative stability and predictability periods are followed by disequilibrium and reorganization.
Perturbations	Exogenous influences on a system or attractor.
State-space grids	A plot representing a dyad's trajectory across a grid of all possible behavioral combinations, where transitions between pre-determined categories of behaviors or affect are plotted for one dyad member (e.g., caregiver) on the x-axis and for the other member
Dyadic contingency	Pairing of caregiver and child states (affect and behavior codes) via temporally dependent sequences, estimated using the average transitional probability between them.
Dyadic variability	The number or rate of transitions between different cells in a state space grid.

Attachment theory

The importance of unpredictability in caregiver-child relationships gained prominence in developmental science about 50 years ago with Bowlby's germinal proposal of humans' biologically programmed need for attachment (Ainsworth et al., 1974; Bowlby, 1969). Caregiver responsiveness and reciprocal interactions with their infants are critical for forming attachment relationships. Under this framework, unpredictability in reciprocal interactions was understood in terms of inconsistent maternal availability, characterized by mothers' non-contingent responses to children's bids, relatively low availability and direct interference during infants' exploration

(Ainsworth et al., 1978; Cassidy & Berlin, 1994; George & Solomon, 1989). Attachment theory, as well as early empirical studies of inconsistent parenting in the 1970s and 1980s (Gardner, 1989; Stern, 1971), and Seligman's learned helplessness theory (Maier & Seligman, 1976), served as the underpinnings for Ross and Hill's conceptual introduction of family unpredictability (2000). In unpredictable families, caregivers were unwilling or unable to provide consistent affective and material nurturance and exercised discipline inconsistently (Ross & Hill, 2004). The adverse effects of caregiver inconsistency were evident in associations with internalizing disorders (Mirabile, 2014), and an unpredictable cognitive schema in children that led to risk-taking: The belief that people and the world are uncertain and chaotic (Cabeza de Baca et al., 2016; Ross & Hill, 2002).

These convergent lines of research suggested that consistency was a solid indicator of appropriate or effective parenting, with the converse, inconsistency, an equivalent to unpredictability, being maladaptive for child well-being. Yet, subsequent research has indicated that a linear translation of consistency to adaptive predictability was inappropriate and too simplistic (Bornstein, 2013). For example, excessive predictability in the context of caregiver-infant interactions (e.g., caregiver responding to cues that were not eliciting of a response) may indicate intrusion or vigilance (Beebe et al., 2020) or a coercive cycle between both partners (Lunkenheimer et al., 2016). Further, inconsistency has proven to be a challenging construct to measure; studies have often conflated inconsistency of maternal availability, nurturance or discipline with overall lower levels of caregiver engagement (Cassidy & Berlin, 1994). Additionally, researchers have rarely considered that specific contextual demands (e.g., the need to elicit child compliance) that may appear to increase or decrease the patterns of consistency of caregiver behaviors may function to allow children to form predictions about their proximal environment (Lunkenheimer et al., 2016). Despite these challenges, attachment theory has provided a framework to explore how variations in the moment-to-moment, microsocial interactions within the dyad may be a significant source of unpredictability for children, with important implications for socioemotional development.

Bronfenbrenner Bioecological Systems theory

In the 1990s and early 2000s, Bronfenbrenner's emphasis on proximal processes and timescales of influence (Bronfenbrenner, 1999; Bronfenbrenner & Evans, 2000), coupled with the emergence of the construct of household chaos (Evans et al., 2005; Wachs, 1996), led to a conceptual integration of environmental unpredictability as a significant determinant of child development (Wachs & Evans, 2010). Environmental unpredictability was defined as temporal and spatial instability in children's lives, spanning from more proximal experiences of the child, such a general lack of routines in day-to-day experiences, to more distal experiences like the accumulation of life events that challenged a family's continuity and cohesiveness through developmental time (Ackerman et al., 1999; Hertzman, 2010; Wachs, 1996). Scales such as the Chaos and Hubbub scale (Matheny et al., 1995) attempted to tap into day-to-day predictability, and the Family Instability Questionnaire (Ackerman et al., 1999; Forman & Davies, 2003) assessed the cumulative number of transitional experiences (e.g., family disruptions, residential instability; Coe et al., 2018). A crucial inference emerged from this work: The frequent and repeated experience of chaos and instability can reflect chronic states of unpredictability with adverse developmental consequences (Doom et al., 2018; Matheny et al., 1995). Repetition, including repeated experiences of unpredictability, informs children's predictions about their future environment, and these influences on children may be different depending on the timing of unpredictability (e.g., early childhood versus adolescence). However, many studies focused on chaos and instability during childhood did not explore the role of unpredictability in the caregiver-child relationship, specifically (for exceptions, see Coe et al., 2020, Davies et al., 2019). This is surprising, considering that Bronfenbrenner and Morris (2006) suggest that the degree of predictability is critical for the quality of caregiver-child interactions, and is therefore an essential property of children's environments which ultimately become a driving force of children's cognitive and socioemotional development. Notwithstanding these issues, a large number of studies have used Matheny and Ackerman's questionnaires assessing chaos and instability, shedding light on how their influences on child development are independent of such other factors as family social and economic resources, although it should be noted that the availability of resources could influence the likelihood of experiencing unpredictability (Wachs & Evans, 2010).

The Integrated Model of Dimensions of Environmental Experience

Unpredictability from a life history perspective (Ellis et al., 2009) and dimensional models of adversity (McLaughlin & Sheridan, 2016) have focused on questions of *why* do different experiences of adversity drive different biobehavioral developmental trajectories and *how* children use information from their proximal environment to concurrently adapt, both neurally and behaviorally, to their immediate environment (Ellis et al., 2022). Regarding the question of *why*, life history theory posits that varying environmental conditions throughout the evolutionary history of our species posed specific selection pressures that required different solutions to increase likelihood of successful reproduction (Ellis et al., 2009). Therefore, natural selection shaped developmental systems capable of detecting and flexibly adapting to specific dimensions of adversity. In both the life history perspective and the dimensional model of adversity, those processes of adaptation reflect the question of *how*, and refer to variations in biological, psychological and behavioral mechanisms that reflect survival strategies, or life history traits (Belsky et al., 1991; Draper & Harpending, 1988; Figueredo et al., 2006). These life history traits are broadly reflective of a coordinated response to cues indicative of a shorter lifespan being likely, leading to an adaptation of faster development, versus cues indicative of a longer lifespan, and hence a slower course of maturation. Faster to slower traits are evident in reproductive strategies such as the timing of puberty, earlier versus later engagement in reproduction, and degree of parental investment in offspring.

Recent efforts to integrate these the life history and dimensions of adversity frameworks have converged on deprivation (e.g., lack of necessary resources for survival) and threat (e.g., harm imposed by other agents) as two features of environmental harshness (Ellis et al., 2022). Both features of harshness can be experienced as predictable or unpredictable depending on the stochastic variations of their cues, which can range from more distal to the child (ecological factors such as variation in household income) to proximal (immediate experiences such as caregiver behavior). Considering the proximal caregiver domain and caregiver-child relationships, unpredictable deprivation could reflect variability in caregiver responsiveness versus neglect, as may occur when caregivers have substance abuse problems (Ross & Hill, 2004) and unpredictable threat could reflect variability in caregiver expression of strong negative affect, as may occur with highly emotionally labile caregivers, or when caregivers have affective disorders with cyclical characteristics (Koenders et al., 2020). Early experiences of these dimensions of adversity have the potential to regulate both immediate and future adaptive biobehavioral responses to the environment (Ellis et al., 2022). When it pertains to caregiving, dimensions of caregiver-related adversity may be better understood as continua (King et al., 2019), occurring to a greater or lesser extent rather than occurring, rather than as a binary.

Similarly, varying degrees of caregiver unpredictability may be evidenced across different aspects of caregiving.

Topological Approach for Conceptualizing Early Adversity

Finally, Smith and Pollak (2021a, 2021b) proposed that specific biobehavioral responses to adversity are determined in part by *features* of the experience of adversity, rather than dimensions or subtypes of adverse events themselves. Among the critical features of adverse experiences is unpredictability, which shapes young children's perceptions of uncertainty and volatility, altering stress response systems and ultimately disrupting biobehavioral development. Whereas Ellis and colleagues focused on whether events were in actuality unpredictable (Ellis et al., 2022), Smith and Pollak (2021a) suggested that what may determine biobehavioral development is whether an infant or child perceives their caregiver as unpredictable, or appraises that their caregiving experiences are unpredictable, even if they are not unpredictable in actuality. Therefore, children's perceptions of the unpredictability of stressful events in their caregiving experiences might drive individual differences in biological and psychosocial development, over and above the impact of exposure to those stressful events (Baldwin & Esposti, 2021; K. E. Smith & Pollak, 2021a, 2021b).

Smith and Pollak's (2021a) focus on children's perception or subjective experience of caregiver unpredictability is an important additional consideration. Yet, it raises questions regarding the integration of developmental timing of unpredictability experiences with maturation of the capacities to form predictions. Within a few months after birth, infants start developing a basic understanding of cause and effect, or the predictability of expected outcomes in their immediate environments (Rochat, 1997; Sherman et al., 2015). This suggests that infants' abilities to perceive the predictability of their caregiver might be evident from very early in life, although the extent to which this is true remains undetermined. Yet, perceiving the predictability of a caregiver's responses to hunger crying or of soothing contact when distressed might not occur along the same developmental course as perceptions of the predictability of maternal mood or emotional expression (Tottenham, 2020). It is plausible that capacities to evaluate those experiences that are more relevant to the basic elements of survival that directly impact infants' biological needs, such as the predictability of feeding patterns, may develop first; again, this hypothesis warrants evaluation. Additionally, both in infancy and across development, it is likely that both the actual experience and the perception of unpredictability guide processes of neural and behavioral adaptations (Gunnar, 2021). Nonetheless, Smith and Pollak's (2021a) introduction of the notion of perception re-centers the conversation on the ubiquitous nature of species tendencies to make predictions and regulate development based on the violation of these predictions (Frankenhuis et al., 2013).

Four Emerging Issues in the Study of Caregiver Unpredictability

Each of the theoretical perspectives considered above, and their supporting empirical research, have shed light on children's biological (Davies et al., 2017; Noroña-Zhou et al., 2020), cognitive (Ross & Hill, 2002; Young et al., 2018), and behavioral outcomes or adaptations (Barbaro & Shackelford, 2019; Coe et al., 2020; Fields et al., 2021) to unpredictable early-life experiences. However, multiple theoretical and measurement issues continue to pose challenges to progress in this field.

As extensively discussed by Young and colleagues (2020), it is theoretically and methodologically challenging to conceptualize unpredictability, its encoding, and its consequences. This is equally true when considering unpredictability in the caregiver-child domain. Informed by socialization theory (Grusec et al., 2000; Kuczynski et al., 2015) and the recognition of caregiver-child relationships as involving dynamic and bidirectional processes of interactions, as applied to the four theoretical foundations of current perspectives on unpredictability, we identify four primary issues to consider when thinking about proximal experiences or cues of caregiver unpredictability and their effects on children's biological and psychosocial development. The goal of highlighting these issues is not to invalidate previous work or provide prescriptive instructions to resolve them. Instead, we aim to increase awareness of four challenges that, when considered, may advance study hypotheses and improve how we assess caregiver predictability.

Issue #1. Statistical and Perceived Caregiver Unpredictability

As highlighted by Smith and Pollak (2021a), events or experiences that are statistically predictable but occur though complex processes might not be experienced as predictable by individuals exposed to those stimuli. The regularity of the phenomena might not be apprehended by individuals experiencing it. Conversely, people may have a mistaken perception of predictability occurring for things that, in truth, are entirely unpredictable. At the heart of the concept of unpredictability are variability, organization, and other temporal and structural dynamics of human experience. Naturally, this challenges a static conceptual representation of unpredictability, introducing the need to consider its temporal complexity. As such, features harnessed under the umbrella term of unpredictability may occur in temporally predictable patterns that children may detect. Seemingly unpredictable experiences, either from the general environment or centered in caregiver-child relationships, might be characterized as more predictable depending on the extent to which (1) variation is patterned across time, for instance, because environmental conditions are autocorrelated (Young et al., 2020) or (2) there are cues other than previous states of the environment that are informative of future experience

(Frankenhuis et al., 2018, 2019). In other words, the extent to which there are trends and patterns within variability, or other informative cues, may affect the ability or likelihood of children to experience their caregiving relationship as more predictable or more unpredictable.

Humans encode, detect, and respond to distal or proximal cues of unpredictability either through ancestral cues or statistical learning (Ellis et al., 2022; Young et al., 2020). Ancestral cues are reliable and informative cues that signal potential unpredictability, to which the human brain is able to detect quickly and adapt efficiently, due to the processes of natural selection across evolutionary history favoring those biobehavioral capacities. These ancestral cues were probabilistically linked to environmental variation through evolutionary time and may or may not be directly or consciously perceived throughout lived experiences (Tooby & Cosmides, 1990). For example, parental transitions (e.g., changes in the caregivers present in the child's life) may be an ancestral cue that individuals use to draw inferences about environmental unpredictability (Ellis et al., 2022), regulating development without requiring repeated experiences.

Statistical learning refers to the use of accumulated lived experiences as "raw data" to estimate and developmentally adjust to unpredictability across developmental time (Young et al., 2020). As noted above, the ability to detect patterns and regularities in the environment and form predictions or "if-then" expectations develops in infancy (Beebe et al., 2010; Saffran, 2020; Sherman et al., 2015). By four months, infants can perceive contingent relations, detect patterns, estimate probabilities of "if-then" sequences, generating some expectations and predictions about their immediate environment (Beebe et al., 2016; Sherman et al., 2015). By six months, infants can discriminate among simple emotions, recognize them from bodily movements, and learn the social efficacy of their vocalizations in caregivers' behaviors (Goldstein et al., 2009; Sherman et al., 2015). By eight months, they can compute conditional probabilities in language learning (Aslin et al., 1998) and temporal sequences of visual stimuli (Gopnik & Schulz, 2004). As infants approach 12 months, they can represent the intentions of others (Sherman et al., 2015). Extracting contingencies and regularities promotes learning, reduces uncertainty, and gives children a sense of perceived control or influence over their environment (Saffran & Kirkham, 2018). Conversely, an absence of reliable "if-then" sequences or patterns of contingency and regularity would threaten the development of these competencies. Thus, through informative cues (ancestral cues) or repeated exposures to transitions, changes, or inconsistency (statistical learning), it is possible that unpredictability may become *predictable* for some children. That is, children may learn to "expect the unexpected," or to understand their caregiver relationships, and by extension their broader social worlds, as unpredictable.

Yet, are ancestral cues of predictability, or evidence for statistical predictability of any environmental factor, necessarily predictable through a child's eyes? Specifically, informative cues or the statistical predictability of experiences may be consciously undetectable to the individual having those experiences. As mentioned beforehand, the topological approach to early adversity underscores the importance of perceptions of unpredictability as a driver of individual differences in biobehavioral development (Smith & Pollak, 2021a; 2021b). Models of decision-making and reinforcement learning differentiate between expected uncertainty, understood as variability in reward outcomes that are random, ubiquitous and unavoidable, and unexpected uncertainty, or the "subjectively" perceived uncertainty due to tractable changes in rewards. Individuals' capacity to perceive uncertainty depends on whether unpredictable events actually change the environment (e.g., by changing rewards) and internal stored information (e.g., lived experiences), leading to significant changes in behavior as a result of learning (Soltani & Izquerdo, 2016).

How, when, and to what extent young children can unconsciously or consciously track, perceive or interpret unpredictable events remains relatively unexplored. Munakata and colleagues (*under review*) have considered these issues with respect to children's statistical learning and cognitive development, suggesting that the timescale of unpredictability might be fundamental to understanding whether, and how, children perceive and respond to unpredictability. Proximal unpredictability occurring in the scale of seconds (e.g., unpredictability of maternal sensory signals) might not involve traceable changes in the environment and therefore might be harder to perceive or recognize consciously. Conversely, proximal unpredictability that is more easily traceable, occurring on a timescale of hours and days (e.g., unpredictability of daily routines), or distal unpredictability across months and years (parental transitions) might be easier to perceive. Therefore, it is possible that perceptions of unpredictability (understood from a statistical learning perspective) might vary across timescales, in addition to differences stemming from experiences indicating unpredictability in our evolutionary past (ancestral cues; Ellis et al., 2022).

Issue #2. Domains and Specificity of Caregiver Unpredictability

Is a caregiver being unpredictable all that "matters", or do the varying ways or domains in which the caregiver is unpredictable confer different cues for children's adaptation? It is possible that caregiver unpredictability and its impact on development might vary as a function of the particular caregiver behaviors being considered, and the valence of such behaviors. Davis' pioneering observational work on caregiver unpredictability (Davis et al., 2017) has exclusively centered on sensory inputs to the infant (e.g., touch or vocalizations), which are not equivalent to or interchangeable with other inputs, such as caregivers' emotional expressions or responses to infants' bids or needs (Buhler-Wassmann & Hibel, 2021). Researchers have not yet considered whether caregiver unpredictability is domain-general, expressed similarly across different inputs or features of caregiving, or domain-specific, evident in specific inputs or valences (McLaughlin et al., 2021). Of course, both aspects of caregiver unpredictability may be possible, but they could have different implications for children's neurodevelopment. Regarding valence, unpredictability may not pertain exclusively to aversive experiences (e.g., maternal negative mood, rejection or punitive behavior; Cohodes et al., 2021; Glynn et al., 2018). Rewarding experiences (e.g., positive maternal affect, praise or face-to-face communication) might be unpredictable as well (Frankenhuis et al., 2013; Lunkenheimer et al., 2020), and may convey distinct implications for children's adaptations.

Empirical work simultaneously examining different ecological levels (proximal to distal cues), behavioral inputs, or affective valences of unpredictability is scarce. Indications that the impact of unpredictability on neurodevelopmental adaptation may vary as a function of these differences primarily emerge from animal research. For example, rodent models of early life adversity have found that limiting dams of bedding and nesting resources induces unpredictable caregiving to pups (Baram et al., 2012; Molet et al., 2014; Rice et al., 2008). Most notably, dams spend the same time nursing or licking and grooming their pups as do dams without limited resources, but they do so in more disorganized and shorter bouts compared to controls (Davis et al., 2017; Molet et al., 2016). Gallo and colleagues (2019) repeated the same paradigm while assessing dams' behaviors continuously across the circadian cycle. This microanalytic analysis revealed that approximately half the dams subject to limited bedding and nesting also developed abusive-like behavior to their pups in the form of occasional maternal kicking, in addition to unpredictable care. Unpredictability in the absence of kicking predicted more anxiety-like behaviors in the pups during adulthood, whereas unpredictability accompanied by kicking predicted more risk-taking behaviors (e.g., further wondering in an open field, entering the light side of a box faster than pups not subjects to kicking and controls). To the extent that rodent dam kicking can be interpreted as negatively valenced unpredictability, these results underscore the importance of considering the complexity of the caregiver context, as the different ways unpredictability can be expressed might impact development differently (Luby et al., 2020).

Studies have yet to examine whether distal cues of unpredictability beyond the caregiver-child dyad correlate with or influence unpredictable patterns within the caregiver-child relationship, as would be expected from socialization theories that position the caregiver-child relationship as the most proximal and primary source of information about safety and availability of environmental resources during infancy and early childhood (Bronfenbrenner & Morris, 2006; Cohodes et al., 2021; Short et al., 2020). Exposure to social and non-social distal unpredictable events such as residential instability (McCoy, 2012) and marital partner transitions (Hartman et al., 2018) *might* increase the likelihood that a child will experience unpredictability in their most proximal environment, that is, within the dyad. However, this might not be the case (Lu et al., 2022), as caregivers facing external challenges that interfere with care might draw on different sources of resilience to provide consistent and contingent care to the child (e.g., social support, Masten et al., 2021). Further, caregiver unpredictability and distal experiences of unpredictability may lead to distinct behavioral outcomes based on adaptive learning (Munakata et al., *under review*). When the availability of resources or opportunities in the environment is unpredictable (or volatile), it may be the case that the best way to maximize rewards is to take them the moment they are available; thus, these aspects of unpredictability could foster impulsivity and other present-oriented behaviors (Fenneman & Frankenhuis, 2020; Munakata et al., *under review*). On the other hand, when there is unpredictability in action-outcomes, such as a caregiver's responses to a child's behavior, it may be adaptive to seek more information before acting; thus, this feature of unpredictability could foster greater inhibitory control and more future-oriented behaviors (Munakata et al., *under review*).

Thus, the ways in which caregiver unpredictability across socialization contexts or domains, involving varying behaviors and affective valences, and expressed over different ecological levels (proximal and distal cues) are related to each other, and the extent to which they do they lead to convergent or distinct neurodevelopmental adaptations in children, remain as open questions pending further investigations.

Issue #3: Developmental Timing of Caregiver Unpredictability

The developmental effects of unpredictability might vary as a function of the relative sensitivity of the developing system and the time in which unpredictability is experienced (Cohodes et al., 2021; Luby et al., 2021). For instance, the provision of an unpredictable caregiver's sensory signals during infancy promotes neurobiological vulnerability to memory impairments and is associated with problems in effortful control (Davis et al., 2017; Granger et al., 2021). Infancy is a sensitive period for sensory signals, as they shape specific visual, somatosensory, and stress-responsive hypothalamic brain synapses, circuits, and regions (McLaughlin & Gabard-Durnam, 2022). However, it is unknown whether early childhood continues to be a period sensitive to sensory unpredictability, specifically, or whether caregiver unpredictability in other domains of behavior might be pernicious at this age. During infancy and early childhood, caregivers play a fundamental role as co-regulators of infants' physiological and affective needs, and consistent, predictable care fosters secure attachment and promotes infants' and children's expectation of control or influence over the environment (Cassidy et al., 2013; Gunnar et al., 1984). Thus, unpredictable or inconsistent maternal mood and affect might undermine the quality of dyadic interactions in ways that are particularly salient for the development of attachment security and self-regulation (K. C. Johnson et al., 2014; Mohr et al., 2019).

It has been suggested that the first five years of life may be a sensitive period for unpredictability, with distal unpredictability having more profound effects on children's development of life history related traits and behaviors (Simpson et al., 2012). Studies conducted in early childhood have shown that caregivers behaviors may mediate the impact of distal unpredictability on child characteristics (Belsky et al., 2012, Ellis et al., 2022; although see Li & Belsky, 2022). Conversely, studies conducted with older children and adolescents show that distal unpredictability might have more direct influences on older children, augmenting perceptions of volatility, uncertainty, and uncontrollability of the immediate or extended environment (Cabeza de Baca & Albert, 2019; Ellis et al., 2022, Hanson et al., 2017; Harms et al., 2018). During infancy and early childhood, caregivers might be more able to shield young children from recognizing distal unpredictability; older children and adolescents have more direct contact with the social realms outside the home, potentially making it more difficult for parents to maintain a sense of predictability within an unpredictable environment. Therefore, unpredictability in different spheres of life may have impacts on developmental processes at distinct periods of life, although this supposition requires further investigation.

Issue #4. Is Caregiver Unpredictability an Individual or Dyadic Construct (or Both)?

The degree to which a caregiver-child relationship is unpredictable may be attributable to either or both of the partners: The caregiver might be unpredictable, the child might be unpredictable, or both might be unpredictable. Alternatively to these individual and additive possibilities, unpredictability might be an emergent quality of the dyad, where the particular partners together form unpredictable patterns of interacting with each other in their day-to-day experiences (Beebe et al., 2016, 2020). To date, caregiver unpredictability has often been studied as a univariate construct focused solely on the caregiver's behaviors or signals to the infant or child (Davis et al., 2017, 2019). However, starting in infancy, caregivers establish affective and behavioral patterns contingent on reciprocity or back-and-forth exchanges between the caregiver and the child (Beebe et al., 2016; Feldman, 2021; Provenzi et al., 2018). Infants also display a wide range of emotions, with their emotional variability influencing caregivers' behaviors (Montirosso et al., 2010). Beyond infancy, children increasingly become more active agents in day-to-day co-regulation processes (Feldman, 2015), contributing to dyadic patterns of behavior and affect (Lobo & Lunkenheimer, 2020; Lunkenheimer, Hamby, et al., 2020). Feldman (2021) posits that, from the neonatal period to adulthood, caregiver-offspring affective and behavioral moment-to-moment coordination should be evaluated from the perspective of each individual *and* from the perspective of the dyad as a unit (e.g., self- and interactive contingency). More specifically, theories of socialization conceptualize children as taking an active role in shaping their caregivers' behavior (Kuczynski et al., 2015), and infants' and children's characteristics such as temperament and problem behaviors have been shown to decrease caregivers' sensitivity and consistency (Hastings et al., 2019; Zvara et al., 2018). This suggests that infants' or children's characteristics might also influence the likelihood that caregivers' behaviors might be unpredictable, or could set in motion a pattern of mutual unpredictability, where both partners contribute to a relationship context that is unpredictable (Kuczynski et al., 2015). However, both dyadic unpredictability and whether caregiver unpredictability can be influenced by children's characteristics remain relatively unexplored questions in empirical research.

Three Theoretical and Empirical Approaches to Characterize Unpredictability

Each of these issues presents important challenges for measurement models and analytic approaches that account for such complexity. How to develop standardized quantifications and measures of caregiver unpredictability is just as challenging as the conceptual question of defining it (Hodson, 2021). As distinct sources of adversity tend to co-occur, assessing the specificity of caregiver unpredictability with human samples continues to be a significant hurdle. Further, even if measures representing the construct of caregiver unpredictability are developed, these might vary across sociocultural groups (DeJoseph et al., 2021). In a psychology field saturated by "new" constructs (Hodson, 2021), establishing convergent and discriminant validity with other adversity constructs, and testing what is versus is not unpredictability across different communities and developmental stages, will provide a better understanding of causal mechanisms and targeted interventions that foster predictability (Eronen & Bringmann, 2021; Hodson, 2021). In the following sections, we present three major approaches that, collectively, provide some insight into each of these challenges.

Life History Theory and Environmental Statistics

Evolutionary biology and life history theory suggest that species can support a range of phenotypes in response to environmental conditions, increasing the likelihood of survival and reproduction (Ellis et al., 2017; Nettle et al., 2013; Young et al., 2020)**.** There are no "single best" strategies to adapt to the environment successfully. Instead, these vary as a function of both social and physical parameters of the environment, such as food and housing availability, neighborhood safety, and caregiver sensitivity (Ellis et al., 2017; Frankenhuis et al., 2013).

Adaptation is understood in terms of the coordination between life history strategies (e.g., timing of puberty) and varying environmental conditions with specific statistical structures (Ellis et al., 2022). The statistical structure of an environment is determined by how physical and social parameters vary over space and time, across and within generations, and the extent to which cues (experiences or events) provide reliable information about current and future conditions (Frankenhuis et al., 2019; Young & Frankenhuis, 2020). Adaptive plasticity requires environments that are both variable and predictable (Scheiner & Holt, 2012). If the environment is stable across generations, then there is no reason for plasticity to evolve, as there is a “single best” strategy. However, if changes in the environment are highly unpredictable across ontogeny, then early conditions are a poor guide to future conditions, and so plasticity may not be adaptive (Nettle et al., 2013).

To date, several studies have used the life history model to compare the effects of environmental harshness and unpredictability during development (Young et al., 2020; Wu et al., 2020). In Western societies, cues of harshness include low socioeconomic status, direct and indirect experiences of violence (i.e., witnessing someone get shot, gang activity), and abusive or neglectful parental practices (Usacheva et al., 2022). Conversely, cues that signal environmental unpredictability typically have been operationalized as frequent changes in physical or structural conditions of harshness, such as residential transitions (housing instability), inconsistent parental employment status (job instability), and caregiver’s sequential partners in the home (family instability; Bjorklund & Ellis, 2014). Research on familial and ecological conditions reflective of these ancestral cues (Ellis et al., 2022) has shown that, over and above absolute levels of harshness experienced, distal unpredictability predicts a variety of adverse child and caregiver outcomes in Western societies. These include more externalizing behaviors (Doom et al., 2016;

Hartman et al., 2018), lower emotional control (Szepsenwol et al., 2021), earlier and more frequent sexual risk-taking (Brumbach et al., 2009; Usacheva et al., 2022) , poorer quality of adult relationships (Barbaro & Shackelford, 2019), and diminished parental investment or quality of relationship with offspring (Belsky et al., 2012; Szepsenwol et al., 2015).

Since the life history model has not been precise about how to operationalize unpredictability, Young and colleagues (2020) proposed to quantify environmental unpredictability using environmental statistics, which is particularly relevant to the challenge of *statistical and perceived unpredictability* (issue #1). Indeed, describing unpredictability in statistical terms could potentially reduce ambiguity and encourage measurement precision and knowledge accumulation among different research groups interested in unpredictability (Frankenhuis & Walasek, 2020; Haslbeck et al., 2019; Young et al., 2020). Their focus has mainly been on quantifying unpredictability of physical features of the environment or distal cues. We posit that environmental statistics also can be used to quantify *caregiver* unpredictability, while acknowledging that it may be more challenging to apply this framework to aspects of the social environment (for discussion of social environmental statistics in other domains than caregiving, such as social dominance, see Frankenhuis et al., 2019; Fawcett & Frankenhuis, 2015).

Evolution and development are processes of adaptation operating on different timescales (Frankenhuis et al., 2019). We restrict our focus to individuals detecting and developmentally adjusting to environmental unpredictability across developmental time; we do not discuss how species genetically adapt to unpredictability across evolutionary time. Further, predictability is relative to a spatial and temporal scale (Burgess & Marshall, 2014; Fenneman & Frankenhuis, 2020). Here, we will focus exclusively on temporal unpredictability of caregiver behavior and affect within the lifetime of children. Our perspective is more aligned with the statistical learning approach to encoding unpredictability, wherein learning and development is guided by an individual's ability to generate models of the statistical structure of the environment through an ongoing computational process using lived experiences as raw data.

Temporal features of predictable environments. Young and colleagues (2020) attempted to refine the field's definition of unpredictability (*stochastic variations or changes in harshness*; Ellis et al., 2009) by encouraging researchers to describe this definition in formal statistical terms. As alluded to in issue #1 (*statistical and perceived unpredictability*), seemingly unpredictable environments might be characterized as less versus more predictable depending on the extent to which variation is patterned across time, for instance, because present conditions are similar to the near future (Young et al., 2020). Predictability will increase when it can be characterized by regular patterns allowing for predicting future behaviors (Ram & Gerstorf, 2009). In statistical terms, the degree of predictability of any parameter will depend on patterns with respect to time and the parameter's autocorrelation.

In the caregiving context, variability refers to deviations from a caregiver's mean (average expression of the parameter across time). This is often denoted as "within-person variance," and is indicated by indices of intraindividual variability of behaviors or affect across different timescales (e.g., from seconds to years; Ram & Gerstorf, 2009). For example, if variability in caregiver's sensitivity is high, it means that it varies widely from very sensitive to insensitive across time. However, this will not necessarily reflect unpredictability, as caregiver's sensitivity might be contingent upon identifiable factors associated with the passage of time (Lazarus et al., 2021). Repeatedly measured variables often exhibit non-stationarity, such that distributional characteristics (e.g., mean, variability, and autocorrelation) might change across time (Molenaar & Campbell, 2009). This can produce consistent or predictable patterns of variability, which can be divided into two general groups: trends and cycles (Lazarus et al., 2021). Trends capture stable directional changes in variability. For instance, over the course of a day, variability of caregivers' positive or negative affect has been shown to increase or decrease depending on daily routines, stress, or time spent with their children (Erbas et al., 2018; Kerr et al., 2021; Musick et al., 2016). Over the course of weeks, variability in caregivers' daily feeding strategies with young infants initially increased as different types of food were introduced but then decreased after a few weeks (van Dijk et al., 2012). Over the first 6 months postpartum, daily maternal sleep variability was found to decrease as infants' sleep schedules stabilized and dyads settled into new routine, which predicted greater maternal emotional availability (Bai et al., 2020). Variability can also be seasonal or cyclical, with patterns repeating over time. Such is the case for seasonal affective disorder, which has an annual recurring pattern (Smetter et al., 2021), major depressive disorder, which is highly recurrent but waxes and wanes over periods of weeks to months (Burcusa & Iacono, 2007), or even generalized anxiety disorder, which varies day-to-day in periodic fluctuations (Fisher & Newman, 2016). Therefore, rather than reflecting caregiver unpredictability, time-dependent variability may represent stable fluctuations with consistent temporal patterns.

Even if the variability of caregivers' behaviors or affect is high and does not change as a function of time, it can still be predictable if the degree of autocorrelation is high. This means that present conditions (exhibitions of behavior or affect) are similar to those in the near past and in the near future (Fawcett & Frankenhuis, 2015; Ram & Gerstorf, 2009). In the context of an individual, higher autocorrelations implies that if a person deviates from their mean at a particular occasion, this deviation is likely to persist for a longer time (Wang et al., 2012).

Conversely, if autocorrelation is weak, then deviations from the mean are independent of each other and may change abruptly, indicating higher unpredictability. For example, Ebner-Priemer and colleagues (2015) examined the variability and autocorrelation of hourly affect levels in individuals with borderline personality disorder. In comparison to healthy participants, these individuals had heightened variability and lower autocorrelation of positive emotions, meaning they transitioned abruptly from positive to negative mood states. However, these same individuals had higher autocorrelation of negative moods, such that negative mood states tended to persist for longer. Thus, autocorrelation differed within the same individual, depending on mood valence (Ebner-Priemer et al., 2015). Moreover, results varied depending on the time intervals between measures (Ebner-Priemer et al., 2006).

Consequently, when using autocorrelation to evaluate the degree of unpredictability in caregivers' behaviors, researchers should consider three sets of questions. First, at what time scale is caregiver unpredictability operating, and what time intervals of observation are appropriate for capturing this process of interest (Lazarus et al., 2021)? Second, repeated observations of the same person are rarely ever truly independent; in other words, some degree of autocorrelation is typical or expected (Ram & Gersthoff, 2009). Therefore, what degree of autocorrelation in a caregiver’s affect or behaviors would be considered normative, and conversely, how low would an autocorrelation need to be before the caregiver’s actions would be considered unpredictable? Third, and as discussed in *issue* #2, whether we should expect an autocorrelation to be domain-general, stable across different domains of behaviors or situations for a given caregiver, or to be more domain specific, as indicated in the work of Ebner-Priemer and colleagues (2015), remains an open question.

One way in which autocorrelation has been applied to the study of caregiver's unpredictable behaviors and interactions is in Beebe and colleagues' examinations of the contingency of caregiver-infant communication and the development of infant attachment (Beebe et al., 2012b., 2010, 2011, 2012a). These studies use a micro-temporal approach using real-time interactions coded at 1-second intervals, as the development of attachment is hypothesized to emerge from moment-to-moment communication patterns that can vary across different modalities (e.g., gaze, vocal and facial affect, touch; Beebe et al., 2012b). The authors use time-series methods to partition predictability at the level of the person (self-contingency) and at the level of the dyad (interactive contingency). Self-contingency is an index of the predictability of behavioral rhythms within an individual and is measured by the degree of autocorrelation of moment-to-moment behaviors. Across studies, links between maternal predictability (self-contingency) and insecure attachment formation varied across communication modalities. For instance, although mothers of future disorganized infants moved and gazed less predictably (low autocorrelation between behaviors at time t and time $t-1$), they were highly predictable in their facial affect (high autocorrelation; Beebe et al., 2012b). Infants with insecure-resistant and disorganized attachment were themselves more unpredictable than secure babies, exhibiting low self-contingency across various communication domains (Beebe et al., 2010). Beebe and colleagues have proposed that self-contingency, that is, predictability of individual behavior, is one of the most critical organizing features of early dyadic communication. They contend that each individual's moment-to-moment predictability, as well as predictability of the dyad's contingent behaviors, should be considered when examining caregiver-infant interpersonal communication (Beebe et al., 2010, 2016). However, self-contingency is also partly organized by the partner. Mothers coordinated their behaviors to their infants, and unpredictable infants increased maternal self-unpredictability (Beebe et al., 2016; Beebe et al., 2012b). Therefore, examining caregiver unpredictability as a univariate construct might miss a piece of the puzzle: its dyadic component.

Altogether, variability can be decomposed into different parts that will determine its unpredictability: The absence of patterns with respect to time and low autocorrelation. Applying this framework to social aspects of the environment such as caregiver-child relationships is more complex, since caregiving both influences and arises from characteristics of the child. Thus, the statistical structure of the caregiving environment – its levels, variability, and autocorrelation – might vary depending on the time period chosen to measure, across different domains of behavior (*issue #2*), and the co-determination of unpredictability between both members of the dyad (*issue #4*, Frankenhuis et al., 2019).

Cue reliability in predictable environments. Individuals can encode unpredictability using both ancestral cues of environmental qualities and statistical learning, including caregiving (Burgess & Marshall, 2014; Young et al., 2020). Considering the former, reliable environmental cues are events or experiences that provide information about the current or future state of the environment (Frankenhuis et al., 2018). Within the life history framework, the human brain evolved to quickly detect and efficiently respond to reliable cues for setting up developmental trajectories. To have shaped our species' physiological and psychological mechanisms of development, caregiver-related experiences would have needed to occur with sufficient frequency across human evolution (Frankenhuis & Amir, 2022). Within current relationships, these same caregiver-related experiences then would convey information that could shape children's biobehavioral developmental trajectory accordingly. For instance, across evolutionary time, the presence of a responsive caregiver might have been an ancestral cue of a safe environment for the child, which when experienced today, would confer a slower life history trajectory (Frankenhuis et al., 2013; Gee & Cohodes, 2021). However, it is difficult to know what constituted "responsive caregiving" in our evolutionary history, or what other aspects of caregiving were most meaningful for infants and children in eons past (Frankenhuis & Amir, 2022). As another example, parent partner transitions – such as frequently changing paternal figures – is frequently suggested as an environmental cue of unpredictability (Ellis et al., 2022). Whether stable two-parent family structures were consistently the norm throughout our evolutionary history, though, is an open question (Frankenhuis & Amir, 2022).

From a statistical learning perspective, the *regularity* of dyadic contingent exchanges may be an informative cue of environmental predictability to the child. Across the first year, infants' developmental changes across cognitive capacities support the formation of mental models about their caregiving system (Beebe et al., 2016; Sherman et al., 2015). Contingent exchanges between caregivers and children might be sources of information about the environment, as infants depend on their caregiver to regulate all their primary needs (Beebe et al., 2010). For instance, a responsive caregiving environment may produce an association between "needs + needs-are-met," fostering infants' mental representation of security that contributes to a rule of regulation regarding the caregiver (Cassidy et al., 2013; Tottenham, 2020). Conversely, a non-contingent environment may create the association between "needs + needs-are-not-met," promoting a rule of non-regulation. With repetition, these associations may contribute to an affective schema or mental model that contributes to children's ability to forecast caregivers' behavior (Thompson et al., 2003; Tottenham, 2020).

Overall, children may use caregiver's quality of care as a cue to estimate environmental unpredictability (Belsky et al., 2012; Frankenhuis et al., 2019). However, how do infants and children encode these parental cues to generate expectations of their environment? From a statistical learning perspective, Frankenhuis, and colleagues (2013) proposed that infants may use social contingency analysis, that is, conditional probabilities of needs + needs-are(-not)-met, as informative cues to estimate caregivers' profiles of quality of care (also Cassidy et al., 2013). The higher the cue reliability, the better children can adjust to the current state of their environment and leverage positive autocorrelation to adjust to future states of the environment (Walasek et al., in press; Young et al., 2020). However, stochastic variations in caregiver contingency profiles would likely decrease cue reliability, increasing unpredictability (Bjorklund & Ellis, 2014; Frankenhuis et al., 2013). Thus, fluctuations in caregivers' contingent responses to infants and children may be a cue to environmental unpredictability (Ellis et al., 2009). Visual habituation and exploration paradigms (e.g., violation-of-expectations methods, infant-triggered-video) have been used successfully to examine infants' expectations about caregiver-infant interactions (Biro et al., 2015; Jin et al., 2018; S. C. Johnson et al., 2010). These and other kinds of procedures evaluating social information processing could be adapted to examine infants' and young children's perceptions of social contingencies.

Still, there are some caveats to consider when applying such an approach. As highlighted in the previous section, caregivers' cues may not only influence but also *be influenced* by infants or children (Fawcett & Frankenhuis, 2015). Further, individual differences in infants' and children's proficiency for detecting contingencies may influence perceptions of unpredictability (Frankenhuis et al., 2013; S. C. Johnson & Chen, 2011; Jozefowiez, 2021). Yet, experiences of early life stress such as variation in caregiver responsiveness may alter contingency detection and learning in infants and children (Harms et al., 2018).

Summary and Implications. Environmental statistics can be used to quantify variation in caregiver unpredictability across different dimensions and timescales ranging from moment-to-moment to developmental time (Frankenhuis et al., 2018, 2019; Young et al., 2020). Particularly relevant to the theory and measurement of unpredictability, this approach may increase precision (Haslbeck et al., 2019) and knowledge accumulation (Smaldino, 2020) across research groups focusing on *different dimensions or levels of unpredictability* (issue #2), as statistical concepts can be applied to any source of intensive longitudinal data (see below). By using this approach, the field could reconcile different research findings and refine or update theory in light of new evidence (Borsboom et al., 2021; Frankenhuis & Walasek, 2020), strengthening the validity of the broad construct of unpredictability.

Nonetheless, a collection of challenges requires further attention as the field moves forward and attempts to apply environmental statistics to caregivers' behaviors. These include consideration of which time intervals are appropriate to capture caregiver unpredictability from a statistical learning perspective, what is typical and atypical of a caregiver's behavioral autocorrelation, what are the individual differences in children's ability to detect temporal patterns or cues, and how do these statistics unfold within a dyad where each partner influences and is influenced by the other. Regardless of these challenges (or "realistic noise"; Frankenhuis et al., 2019, p. 8), we believe environmental statistics are invaluable tools in dyadic research. For example, intensive and naturalistic measures of dyadic interactions that can produce time-series data are increasingly being used in tandem with larger longitudinal studies, including mobile eye tracking (Pérez-Edgar et al., 2020), wearable physical proximity monitors (Salo et al., 2021), and sound-activated audio recording devices (Gilkerson et al., 2017). As an example of research using the latter, King and colleagues (2021) found that six-month infants who experienced inconsistent adult speech and conversational turns across 8-hours of a typical day at home had higher symptoms of psychopathology during toddlerhood, even after accounting for speech quantity and caregivers observed sensitivity. Similarly, Werchan and colleagues (2022) found that three-month infants living in homes with noise exposure characterized by low autocorrelation (e.g., low predictability) had less sustained attention. Environmental statistics could be applied to such naturalistic time-series data to advance our understanding of dyadic rhythms and to formally quantify unpredictability. We highlight other directions for future research using environmental statistics to measure and understand caregiver unpredictability in Table 2. For example, pairing formally quantified unpredictability with visual habituation paradigms that probe to infants' or young children's expectations about their caregiver (S.C. Johnson et al., 2010), might provide insightful information on the degree to which *statistics of the environment* correspond (or not) to *perceptions of unpredictability* (issue #1). In the next section, we review a burgeoning area of research that is already advancing our understanding of unpredictability in the caregiver-child relationship by using the concept of entropy.

Table 2

Future directions on caregiver and caregiver-child unpredictability

Method	
Environmental statistics	1. Identify specific neurodevelopmental and behavioral adaptations to "objective" caregiver unpredictability as indicated by environmental statistics versus adaptations to children's "subjective" perceptions of their caregiver's unpredictability, as evaluated using developmentally-appropriate measures (e.g., visual attention paradigms, questionnaires). 2. Using environmental statistics and naturalistic data, investigate whether proximal experiences of volatility (e.g., noise exposure) and unpredictability in action-outcomes (e.g., responses to children utterances) differentially impact emotional and cognitive development.

Entropy	1. Expand animal models manipulating proximal (e.g., fragmentation) and distal (e.g., transient food insecurity, Lin et al., 2022) unpredictability to identify causal effects on behavioral, physiological, and brain development while controlling for genetic and other environmental factors. 2. Leverage existing longitudinal and panel studies with caregiver mood data and use causal inference methodologies (e.g., marginal structural models) to determine whether (1) distal unpredictable experiences (e.g., income volatility) are related to caregiver mood entropy and whether (2) proximal and distal cues of unpredictability lead to distinct neurodevelopmental changes from infancy to adolescence.
Dynamic Systems Theory	1. Examine the emergence and consolidation of individual and dyadic unpredictability employing an attractor framework (e.g., accounting for phase transitions) and state-space-grid methodologies from infancy to early childhood. 2. Explore differences in children's biobehavioral regulation as a result of unpredictability in differently-valenced aspects of caregiving, including rewarding (e.g., praise, encouragement, responsiveness) versus aversive experiences (punitive and harsh behaviors).
Integrative directions for future research	1. Compare and contrast the nature of proximal caregiver unpredictability across the three different methods in the same samples to (1) identify shared and unique features and (2) evaluate whether the unique features captured by each method differentially influence cognitive, emotional, and neural development. 2. Identify sensitive periods for cognitive and emotional neurodevelopment to different "types" of caregiver unpredictability (e.g., sensory signals during infancy, affect and mood during early childhood) and evaluate the extent to which there is continuity or discontinuity in caregiver unpredictability across time, aspects, and situations. 3. Use acute societal stressors (e.g., natural disasters, massive layoffs) as natural experiments to determine whether the (1) distal unpredictability causally increases the likelihood of caregiver unpredictability (individual or dyadic) and (2) whether the timing of distal and caregiver unpredictability has distinct impacts in neurobehavioral adaptations across development. 4. Identify environmental and individual factors strongly linked to likelihood of caregiver and caregiver-child unpredictability to include in screening, intervention or policy relief efforts.

Shannon's Information Theory and Entropy of Maternal Sensory and Mood Signals

One specific body of unpredictability research has focused on how patterns of care, or the provision of care without a consistent or organized rhythm, shape children's behaviors and neurobiology (Baram et al., 2012; Chen & Baram, 2016). A guiding premise of this work is that unpredictability of maternal sensory signals and mood influence the development of emotional and cognitive circuitry with important implications for children, adolescents, and even adult psychopathology (Davis et al., 2017; Glynn & Baram, 2019; Howland et al., 2020). Accordingly, this line of research has termed this approach to care as unpredictability of sensory signals in humans, or fragmentation in rodent models (Davis et al., 2017). To quantify unpredictable maternal signals or fragmentation, this body of research uses *entropy* and *entropy rate*, a common approach for characterizing the randomness of stochastic processes. Entropy represents the uncertainty or disorder of a random variable. Entropy rate extends entropy to sequences, quantifying the average information required to predict a future observation given a previous observation. Several types of entropy exist and can characterize univariate and multivariate continuous and discrete processes (Namdari & Li, 2019; Shannon, 1948). Originally from thermodynamics, entropy has been applied in physics, finances, physiology, and developmental psychology (Dishion et al., 2004; Lichtenberg & Heck, 1986; Montirosso et al., 2010).

Although entropy is used here as a measure, it is not an atheoretical construct. In 1948, Claude Shannon at the Bell Telephone Laboratories proposed a mathematical theory of the engineering of communication, giving rise to information theory (Shannon, 1948). Shannon and Weaver (1949) suggested that the engineering (e.g., patterns of information) of communication is also relevant to the semantic aspects (e.g., meaning, content, valence) of communication. From this perspective, information is not equal only to its meaning, but also to the degree of randomness of an ensemble of messages that any given source will produce. An ensemble is considered random when the structure of a message is completely free, and redundant when the structure is determined by its own patterns, and the degree of randomness is quantified using entropy, with higher values indicating more unpredictability (Shannon & Weaver, 1949). Below, we present three different ways in which entropy has been used to characterize organization and predictability in caregiver and caregiver-child interactions.

Quantifying Entropy Rate of Maternal Sensory Signals. Caregiver unpredictability has been quantified using entropy rate of maternal sensory signals during infancy (Davis et al., 2017, 2019), using cross-species research to explore causal physiological mechanisms by which unpredictability influences infant and child development. Using the limited bedding and nesting rodent model to induce unpredictability in dams, studies have found that pups raised with unpredictable dams have enhanced anxiety-like behaviors and anhedonia manifested by a lower preference for peer play (Bolton et al., 2018; Curley & Champagne, 2016). Unpredictable maternal signals shape dopaminergic processes in response to social play and predict aberrant functional connectivity between reward and fear circuits (Bolton et al., 2018; Molet et al., 2016), resulting from corticotropin-releasing factor (CRF) expression neurons in the central nucleus of the amygdala (Bolton et al., 2018; Molet et al., 2016). Goodwill and colleagues (2019) found that fragmented care produced an early emerging, female-specific anhedonia depressive phenotype that persisted until adulthood, while anxiety-like behaviors were promoted in juvenile mice male when unpredictable dam removal was paired with limited bedding and nesting (Heun-Johnson & Levitt, 2016; Schmidt et al., 2010). This was predicted by increased amygdala-prefrontal cortex and amygdala-hippocampus connectivity (F. K. Johnson et al., 2018). Fragmented dam behaviors also lead to memory-related disruptions in pups through structural changes in the hippocampus related to elevated basal corticosterone levels (Rice et al., 2008), dendritic atrophy, hyperexcitatory synapse in the hypothalamus, and augmented CRF expression in the hippocampus (Singh-Taylor et al., 2015).

These studies suggest that fragmented maternal care in rodents regulates the development of different biological systems that underlie internalizing-like behaviors (e.g., reward circuits) and memory-related disruptions through structural changes in the hippocampus. In humans, unpredictability of sensory signals, that is, the unpredictability of auditory, tactile, and visual inputs from a caregiver, has been calculated from a semi-structured 10-minute play episode. Infants experiencing higher unpredictability at six months had worse effortful control at one year of age, and this association persisted until 9.5 years of age (Davis et al., 2017, 2019), even after accounting for socioeconomic status and maternal sensitivity. Mirroring findings in rodent models, infants who experienced more unpredictability had poorer performance on a hippocampus-dependent memory task four years later (Davis et al., 2017). Unpredictability during infancy partially mediated the relation between maternal sensitivity and children's cognitive development (Davis et al., 2017). In this sample, impaired memory function continued during late childhood and pre-adolescence and was mediated by an imbalance of corticolimbic circuitry, developing increased connectivity between the amygdala and orbitofrontal cortex at the expense of hippocampus – orbitofrontal cortex connectivity (Granger et al., 2021).

In these studies of rodents and humans, caregiver unpredictability was quantified using entropy rate of maternal behavior. In rodents, entropy rate captured the degree of certainty in predicting dam's behaviors towards her pups (e.g., licking and grooming, nursing), and in humans, entropy rate reflected the certainty in predicting caregiver's next sensory behavior based on their current behavior (e.g., vocalization, touch). Greater certainty indicates a more organized process, whereas greater uncertainty indicates a more disorganized process. There is a subtle but important distinction between entropy rate and autocorrelation with regard to their dependency on time[1]. When applying autocorrelation to caregiver behavior, one measures the extent to which caregiver behavior at time *t* depends or is correlated to earlier behaviors (*t-1, t-2, t-3... t-n).* Conversely, entropy divides caregivers' behaviors into discrete states that *can* be independent of time, such that current behavior *t* depends only on *t-1* (Feutrill & Roughan, 2021).

Another convergent feature of these studies of rodents and humans is that maternal behavior was recorded continuously as time-series on a second-to-second basis. Entropy rate of dams' behaviors was measured by assessing seven behaviors continuously during 50-minute windows twice a day for eight days, and entropy rate of human maternal sensory signals was measured during 10-minute free play sequences, in which the caregiver's visual, auditory, and touch behaviors were coded continuously. In both rodents and humans, this sequence of behaviors was modeled as a first-order stationary Markov chain (Vegetabile et al., 2019). The following assumptions are central to this Markov model: (a) Proximal future states (e.g., at time *t*) depend exclusively on their most recent past state (e.g., *t* -1), such that each sequential transition is independent of preceding and following transitions. Therefore, the best guess of the next caregiver behavior is based solely on her current behavior. (b) The probability distribution is *stationary* or independent of time (Lichtenberg & Heck, 1986; Vegetabile et al., 2019), such that the probabilities of occurrence of different outcomes are the same from the beginning to the end of the sequence. Because of these two assumptions, the Markov chain can be expressed as a transitional probability matrix, which can be used to estimate the entropy rate of the whole

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[1] Autocorrelation examines temporal dependency of continuous processes with "long term memory" (e.g. current behavior *t* can depend from behavior that happened a long time ago, *t-5*). Conversely, entropy examines its organization by dividing the process into discrete states that *can* be independent of time, such that the dependence on past observations is low or non-existent, having "short term memory" (e.g., current behavior *t* depends only on *t-1;* Feutrill & Roughan, 2021). To quantify entropy, a probability distribution is needed.

sequence of behaviors, that is, the average predictability of the sequence (Namdari & Li, 2019; Vegetabile et al., 2019). To our knowledge, entropy findings have been replicated across two independent cohorts, linking unpredictable patterns of maternal sensory signals with worse effortful control years later (Davis et al., 2017, 2019). By very closely matching the task demands and coding processes for rodent studies that involved experimental manipulation to those of the human study that did not involve experimental manipulation, convergent findings across these two approaches indicates a greater likelihood of potential causal mechanisms at play in humans as seen in the experimental task with rodents.

When attempting to translate this approach to observational data across a range of interaction tasks, researchers need to consider threats to internal and external validity imposed by the two assumptions detailed above. To date, sensory unpredictability has been measured using 10-minutes of free play with a standard set of toys in a carefully controlled laboratory setting. This method balances task duration, valence, and setting to comply with the assumption of stationarity (Vegetabile et al., 2019). However, suppose that the interaction paradigm researchers are interested is a frustrating timed task for caregivers and children (e.g., a 5-minute impossible puzzle task). Behaviors will likely vary as a function of time, since caregivers and children might get frustrated and change the range of their behaviors as they rush to complete the activity. Thus, the probability distribution at the start of the activity is likely different than at the end, affecting the entropy rate and undermining internal validity. Further, the external validity of this approach, that is, the extent to which entropy findings can be generalized to “the real world” is yet to be explored. External or ecological validity is a well-known issue for carefully controlled laboratory tasks that are, by their nature, not reflective of naturalistic settings. Hence, more research is needed to establish the ecological validity of unpredictability as elicited or observed in laboratory tasks. For instance, caregivers who appear to evince less predictable behavior in a lab setting might be more predictable in their familiar home environment, with their own set of toys and their regular schedule. Conversely, in day-to-day interactions, caregivers' attention often is divided among multiple competing goals, taking considerable amounts of self-regulation (Monn et al., 2017), possibly increasing unpredictability over levels observed in controlled lab settings with fewer distractions. Overall, predictability might be activity- and context-dependent, such that caregiver's entropy rate might vary depending on the nature of the activity they are performing and the environment they are in (Vegetabile et al., 2019).

It is important to stress that this body of works examines sensory signals, as infants' brains are especially susceptible to this type of input (Luby et al., 2020). As such, entropy rate is estimated only in one member of the dyad (the caregiver) since it is calculated on a univariate sequence of sensory inputs to the child. Sensory signals are not necessarily comparable to other domains of caregiving, such as affect or regulatory behaviors. In fact, it is unclear whether the persistent impact of unpredictable patterns of caregiver sensory signals during infancy are a result of early disruptions exclusively and/or due to stability of caregiver unpredictability, either in sensory signals or in affective or regulatory behavioral interactions, as described in the issue of *timing* (#3) and *domains and specificity* (#2). Focusing on affect and regulatory behaviors naturally raises questions regarding their *dyadic* nature (#4). Caregivers develop affective and behavioral patterns as early as infancy, based on a back-and-forth with the child (Beebe et al., 2016; Feldman, 2021; Provenzi et al., 2018). Infants experience a wide spectrum of emotions, and their emotional variability influences caregivers' affect and behaviors (Montirosso et al., 2010). Beyond infancy, children increasingly become more active agents in daily co-regulation processes (Feldman, 2015). Therefore, is sensory unpredictability stable throughout development and related to affective or behavioral interactions between caregivers and their children? In other words, is unpredictability domain-general, being continuous throughout development and expressing similarly across different features of caregiving?

Quantifying Entropy of Dyadic Interactions Using State-Space Grids. Unpredictability of dyadic interactions has been measured by applying Shannon's entropy to state-space-grids (Coburn et al., 2015; Dishion et al., 2004; Lougheed et al., 2020; Sravish et al., 2013). State-space-grids (SSGs) were introduced to analyze socioemotional behavior in a dynamic system framework and have primarily been used to analyze dyadic interactions in real-time (Granic & Hollenstein, 2003; Hollenstein, 2007, 2013; Lewis et al., 1999). Using real-time observations, SSGs plot a dyad's trajectory across a grid of all possible behavioral combinations (Granic & Hollenstein, 2015). These grids are a graphical representation of a dyadic state-space, where transitions between pre-determined categories of behaviors or affect are plotted for one dyad member (e.g., caregiver) on the x-axis and for the other member (e.g., child) on the y-axis (see Figure 1). Each cell of a grid represents a specific combination or a joint state between caregiver and child. Any time the dyad moves around each cell, a line is drawn from the previous point to the next, ultimately "drawing" a trajectory representing content or valence (occurrences and duration in joint states of behaviors or affect) and structure (patterns of change) of a particular interaction (Granic & Hollenstein, 2015).

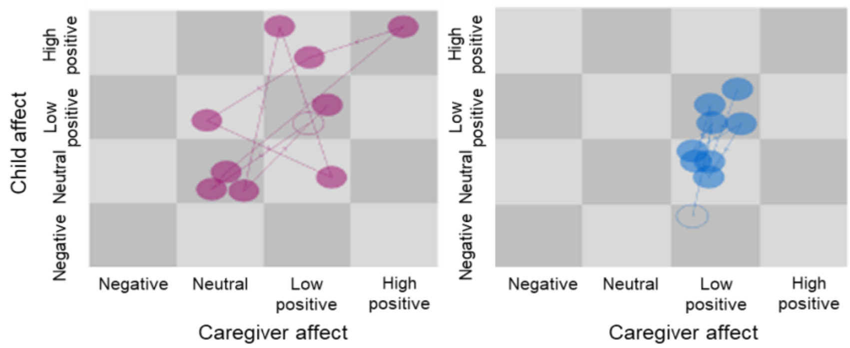

Figure 1
Example of state space grids of affect of two caregiver-child dyads. The left grid represents a relatively flexible dyad (more variability) and the right a relatively rigid dyad (less variability). Caregiver affect is plotted on the x-axis and child affect on the y-axis. Any time there is a change in either person's affect, a new point is plotted, and a line is drawn connecting the new point to the previous point.

Current SSG programs estimate *visit entropy*, calculated using transitional probabilities between dyadic states under the same assumptions as the entropy rate of sensory signals: stationarity and first-order sequences (Dishion et al., 2004; Granic & Hollenstein, 2015; Hollenstein, 2007). Entropy is often used as an index of dyadic flexibility/variability, which is supposed to capture how members in a dyad adapt to each other's behaviors (Hollenstein, 2007; Sravish et al., 2013; van Dijk & van Geert, 2015). Only two studies have examined caregiver-infant interactions using entropy, with inconsistent results. Entropy was positively related to mutual reciprocity and dyadic adaptive regulation during a 5-minute frustrating task (Coburn et al., 2015) and to infant negativity during a still-face paradigm (Sravish et al., 2013). Altogether, dyadic unpredictability can be measured using entropy of SSG, examining the role of both mother and child as equal contributors to shifts between states. However, researchers should refrain from making the a priori assumption that dyadic entropy is adaptive or apply it to tasks where the probability distribution is likely to change over time.

Quantifying Entropy of Maternal Mood. Researchers also have adopted a distinct approach to studying the entropy rate of maternal mood (Glynn et al., 2018; Glynn & Baram, 2019), by applying Shannon's entropy to mood questionnaires. Each individual's responses to a specific questionnaire are transformed into a probability distribution based on the frequency of each response choice (see Glynn et al., 2018 for details). Maternal mood unpredictability, measured by applying Shannon's entropy formula to mothers' mood questionnaires, was hypothesized to indicate mood unpredictability (Glynn et al., 2018). Prenatal mood entropy was positively associated with intraindividual variability of maternal daily negative affect reported with EMA (convergent validity). It was unrelated to the entropy of a physical activity questionnaire (discriminant validity), discarding the alternative explanation of entropy being a tendency to answer all questionnaires in an unpredictable manner (2018). Prenatal mood entropy predicted children's greater negative affectivity and poorer cognitive development at 12 months, 24 months, and 7 years of age (Glynn et al., 2018; Howland et al., 2021). Further, it was associated with child-reported anxiety and depressive symptoms at 12 years, even after accounting for possible confounds such as SES, cohabitation with the child's father, and prenatal and postnatal average mood levels (Glynn et al., 2018). Thus, maternal mood entropy appears to be a distinct risk factor – possibly, affective unpredictability – that confers myriad risks to children's healthy development. To provide an empirical example of the validity of using this method of examining entropy of maternal mood as indicative of affective unpredictability, we used archival data assessing depressive symptoms in young mothers via questionnaires and examined the relation of mood entropy to emotion dysregulation and ecological momentary assessments of mothers' daily positive and negative emotions; please see supplemental material for results.

Exactly what mood entropy reflects and how it increases risk for psychopathology or disrupts cognitive development is unclear. It has been suggested that it might reflect trait-like mood instability and lack of emotional clarity (Glynn et al., 2018). It might also indicate some degree of disorganization on caregiver's representation of the self, which could possibly extend to their representation of their child, thereby hindering the caregiver-child relationship (King, Salo, et al., 2021). Additionally, the fact that prenatal mood entropy is prospectively associated with developmental outcomes over and above postnatal experience suggests that the underlying biological substrates of this mood profile might influence the intrauterine environment (Demers et al., 2021) or that there might be genetic underlying characteristics that contribute to the variance both in caregiver mood entropy and children's development (Hannigan et al., 2018).

Summary and Implications. Ample evidence supporting specific effects of entropy of maternal sensory signals in offspring's biobehavioral development is found in rodent models (Bolton et al., 2018; Gallo et al., 2019; Molet et al., 2016; Risbrough et al., 2018) and in humans (Davis et al., 2017, 2019; Noroña-Zhou et al., 2020;). To a lesser extent, some of these findings are also common to entropy of maternal prenatal mood (Glynn et al., 2018; Howland et al., 2021). These associations remain even after adjusting for quality and quantity of care (e.g., maternal sensitivity) from infancy through early adolescence. Robust cross-species findings, replicability across cohorts, and initial replicability of mood entropy with our data (see supplements) are only some of the strengths of this line of work. Nonetheless, more research is needed to explore issues of *domains and specificity* (issue #2), *timing* (issue #3), and its *dyadic* nature (issue #4), extending caregivers' sensory unpredictability to behavioral and affective domains beyond and test whether the child's influence is relevant to caregiver entropy (Montirosso et al., 2010).

Future work should aim to establish ecological validity of entropy by testing short-term reliability and continuity across contexts of observation, including settings (e.g., lab and home) and situations (e.g., playing, daily routines). Maximizing ecological validity by measuring behaviors in a way that is more similar to the "real world" will increase the match between measures and the broader construct of interest (unpredictability) as it occurs in day-to-day life (Gunther et al., 2022). To avoid statistical violations, researchers should make well-informed decisions about time constraints and task demands for each observation and by testing the stationarity of the behavior sequence (or states when using visit entropy) if treated as an ordinal times series (Keller et al., 2007). Dyadic unpredictability could also be measured using mutual information and transfer entropy, which measure the information flow between two-time series and has been used to evaluate the degree of unpredictability between caregivers and children's physiology (Callaghan et al., 2021; Namdari & Li, 2019). Table 2 includes more specific directions for future research in the realm of entropy, such as including cues of distal unpredictability to current animal models focusing on fragmentation. Altogether, this body of work has substantially increased our knowledge of the neurobiological and behavioral effects of early unpredictability, introducing new measures for characterizing caregiver unpredictability. In the final section, we review dynamic systems theory and its corresponding methods as a novel and potential way to assess caregiver unpredictability.

A Dynamic Systems Approach to Unpredictability in the Caregiver-Child Relationship

According to dynamic systems theory (DST), variability and organization are intrinsic properties of development, providing theoretical and corresponding methodological instruments to describe the nature of dyadic interactions (Lunkenheimer et al., 2011). We propose that key DST concepts presented below can be applied to examine the degree of unpredictability of caregiver-child interactions, allowing us to distinguish valence and content of behaviors from their patterns and organization to evaluate *domains and specificity* (issue #2) in *individuals or dyads* (issue #4). It is important to note that, in contrast to prior work, DST has not been explicitly used to measure unpredictability.

DST suggests that system variability (e.g., intraindividual variability, dyadic variability) is a driving force of change and a crucial source of information throughout development. Self-organizing systems become "patterned forms emerging from variability" throughout time (Lewis, 2011, p. 1). A self-organizing system will naturally generate internal order, developing recurrent patterns of behaviors that become increasingly coherent and predictable through developmental time (Granic & Patterson, 2006). These patterns are called *attractors* that a system will frequently gravitate to, increasing its stability and predictability. Behaviors converge in attractors in real-time, at a scale of seconds to minutes, but the emergence and consolidation of an attractor occur over developmental time, across months and years (Lewis et al., 1999). Altogether, a signature of a dynamic system is its stability - the extent to which multiple patterns of behaviors range from unstable to stable. When patterns are stable, they will tend to be more predictable and resist change (Granic & Hollenstein, 2015). However, these stable, predictable patterns need to dissolve and reorganize to move development forward (Smith & Thelen, 2003). *Phase transitions* are system-wide reorganizations in which relative stability and predictability periods are followed by disequilibrium and reorganization. During a phase transition, real-time behavior is highly variable and sensitive to *perturbations* from the external environment (Granic & Hollenstein, 2015).

Using Attractors to Characterize Unpredictability in the Caregiver-Child Relationship. Dyads are inherently dynamic and flexible across situations and developmental stages, yet self-organizing, ultimately stabilizing into a limited range of coherent interactions and behavioral patterns (Fogel, 2011). These emergent, predictable patterns of interactions or behaviors represent an attractor. Attractors can vary in domain and valence, leading to different outcomes in children and dyadic relationships. Examples include positive feedback loops between infants cooing and maternal mirroring that foster the emergence of conversational exchanges and creative play (Lavelli & Fogel, 2013), child-directed speech in lower income households decreasing from the beginning to the end of a month as financial pressures increase (Ellwood-Lowe et al., 2021), or coercive cycles of children's non-compliance and caregiver hostility (Granic & Patterson, 2006).

Attractors can also vary in depth (strength), and we posit that shallow (weak) attractors could indicate a higher degree of unpredictability in the caregiver-child relationship. If attractor strength is weak, patterns of behaviors should be unstable across contexts and exhibit high degrees of variability without discernible patterns of change (Hollenstein, 2007). Using sensitivity of real-time interactions as an example, the sensitive behaviors of more unpredictable caregivers might be intermittent, varying in their duration of expression, or across contexts that are potentially eliciting of sensitivity (Ainsworth et al., 1974; Lewis et al., 1999).

DST indicates that shallow attractors are more reactive to perturbations (Granic & Hollenstein, 2003). Therefore, more unpredictable caregivers would take longer to self-organize or return to a baseline state after a perturbation. Several DST studies have used an A-B-A design; B represents the introduction of a perturbation to examine changes from a positive or neutral to negative, and back to positive or neutral contexts (Hollenstein et al., 2013; Lunkenheimer et al., 2016). Dyadic paradigms often introduce a stressor as a perturbation (e.g., "you have one minute to finish the activity," a scary object, inoculations). For instance, Sravish and colleagues (2013) used the still face paradigm to observe changes in dyadic affective variability in free play before and after the perturbation of maternal unresponsiveness. Variability increased significantly following the still face for all dyads, but it did so more strongly for depressed caregivers. Thus, caregiver depression was related to a shallow attractor state for dyadic affect.

It is important to note that change is a necessary part of development and periods of heightened unpredictability might be normative. Dyadic patterns may destabilize during phase transitions and become more variable, eventually settling into a new predictable pattern (Granic & Hollenstein, 2015). For example, dyadic interactions might become more erratic and unstable during the transition from infancy to toddlerhood, as this is a period of rapid and multifaceted motoric, linguistic, cognitive and socioemotional maturation (Lewis et al., 2004). Under these conditions, it is functional and adaptive for caregivers to adjust their behaviors in response to changes in their toddlers. Thus, repeated samples of behaviors may be needed to discern whether increased variability or shallow attractors are transitory products of the developmental stage or change, rather than an enduring characteristic of the dyad. Altogether, conceptualizing unpredictability in the caregiver-child relationship as a collection of shallow attractors is one way to operationalize the construct of unpredictability, providing a specific set of indices that may better characterize variation in unpredictability. This attractor framework can be applied to any data with intensive repeated measures, including video recorded observational data and ecologically momentary assessments.

Exploring Dyadic Unpredictability Using State-Space Grids. To increase our understanding of dyadic unpredictability specifically, we propose that variations in dyadic unpredictability could be captured by combining contingency and dyadic variability measures under a DST framework using SSGs (Lobo & Lunkenheimer, 2020; Lunkenheimer, Skoranski, et al., 2020). Contingency is the consistent pairing of caregiver and child states (affect and behavior codes) via temporally dependent sequences (Cole et al., 2009; Harrist & Waugh, 2002; Lobo & Lunkenheimer, 2020). Contingency is estimated using the average transitional probability between a specific pair of behaviors or expressed affect within a dyad (e.g., the probability that a child follows a command after a caregiver provides a command). Higher probabilities indicate more robust contingency or predictability of behavior between both partners (Lunkenheimer et al., 2017). In a dyad exhibiting a high degree of contingent affect-behaviors, current states are reliable cues to future states for *both* members. In a dyad exhibiting a low degree of contingent affect-behaviors, current states are not reliable cues to future states for both members. Thus, contingency allows children and caregivers to develop expectancies of sequences of events and coherent day-to-day experiences (Beebe et al., 2016; Cassidy et al., 2013). Conversely, dyadic variability is operationalized *as the number or rate of transitions* between different cells in a SSG. In SSGs, dyadic variability is presented as an index of dyadic flexibility, wherein caregivers and children vary in their behaviors to respond to each other's needs and goals (Hastings & Grusec, 1998; Hollenstein, 2007). For the current purposes, variability is a more preferable term than flexibility, which has positive connotations in socialization theory. Variability is a value-free term that evokes fewer a priori assumptions about its adaptive or maladaptive disposition (Lunkenheimer, Skoranski, et al., 2020).

We propose that contingency and variability may be considered simultaneously to represent dyadic unpredictability. As such, the degree of unpredictability is best represented by an interaction of low contingency and high variability, which would characterize dyads with high behavioral variability coupled with a low probability of contingency of their behaviors. Although one could argue that variability and contingency on their own might constitute indices of unpredictability, the principles of environmental statistics and entropy suggest the contrary. Variability is not necessarily random, as trends and autocorrelation might increase predictability. Considering contingency on its own, if dyadic behavior is low in contingency, any given behavior from either partner is an unreliable cue of future behavior within the dyad. However, even with low contingency, making the best guess of the next dyadic behavior is easier for dyads with low behavioral variability, in comparison to dyads with high variability. Therefore, dyads exhibiting a greater number of behaviors (higher variability), none of which is a consistent or reliable indicator of the subsequent behavior (low contingency), could be prone to interactions that rarely settle into a predictable pattern (Busuito & Moore, 2017). An empirical example illustrating this joint consideration of contingency and variability is provided in the supplemental materials.

Summary and Implications. DST concepts and methods, such as attractors and SSGs, serve as a lens to examine caregiver unpredictability, or more precisely, unpredictability in the interactions and relationships between caregivers and children. This framework describes patterns and variation of behaviors and can be flexibly used to examine individuals or dyads (Hollenstein, 2007; van Dijk & van Geert, 2015). Rather than focusing on the presence or absence of specific behaviors, DST centers on their organization: How, when, and where do they unfold. In addition, patterns are not bounded to the valence and overall quantity or intensity of these behaviors and can be examined independently. This method can tap both the content (e.g., sensitivity, positive versus negative affect) and the patterning of behavior, regardless of content (e.g., the latency of responses, temporal patterns; Granic & Hollenstein, 2015). As expressed in issue #2 (*domains and specificity*), it is not clear whether the detrimental impact of unpredictability differs based on the valence of experience (e.g., aversive or rewarding). For instance, dyadic variability impacts preschool children differently depending on the valence of the content, predicting increased emotional lability in children when positive affect content is low or higher self-regulation when positive content is high (Lobo & Lunkenheimer, 2020; Lunkenheimer, Skoranski, et al., 2020). Focusing exclusively on interaction patterns, without regard to interaction contents, may obscure the meaningful contribution of precisely what is being communicated and experienced within these patterns (King et al., 2021). Examining the unique contribution of patterns, and the combination of both patterns and contents of caregiver or dyadic unpredictability, are future steps for the field that may be facilitated by using DST methodologies. Although these propositions are yet to be tested, we highlight how DST can be integrated to future research on caregiver unpredictability in Table 2.

Altogether, DST offers more fine-grained perspectives to examine the temporal and complex nature of moment-to-moment interactions (Hollenstein, 2007; Lewis, 2011). When this data is collected longitudinally, DST can examine how these unfolding patterns of real-time unpredictability embed into a higher-order dynamic system of interactions that alter children's development (Granic & Hollenstein, 2015). Empirically, however, integrating and collecting this combination of repeated and intensive data is challenging and expensive (Spencer et al., 2011). Studies with such designs exist (Buhler-Wassman & Hibel, 2021; Glynn et al., 2018; Lunkenheimer et al., 2020; A.B. Miller et al., 2017) but may not have the statistical power to examine complex models and deliver robust between-person findings, especially if true effects in the population are small (J. Miller & Ulrich, 2016; Oakes, 2017).

Conclusion

There has been considerable progress in understanding the role of unpredictability on brain maturation, cognitive and socioemotional development, and psychopathology. Theoretical consensus has emerged about its unique influence in shaping children's experience, distinct from other sources of adversity. Nonetheless, the field still lacks theoretical and empirical common ground given difficulties in precisely conceptualizing and accurately operationalizing and measuring environmental and caregiver unpredictability. Four issues were presented; First, concepts that fall under the umbrella of unpredictability may occur in temporally predictable patterns (Young et al., 2020). Yet, how children perceive these experiences and make meaning of unpredictability is unknown (K. E. Smith & Pollak, 2021a). Second, it is important to consider the specificity of unpredictability in the caregiver-child relationship, as it might vary within and between individuals depending on valence (i.e., positive or negative), input (i.e., sensory or affect), and levels (i.e., caregiver unpredictability or caregiving within an unpredictable environment). Third, its characterization and effects will likely change in concert with the dyad's development (Cohodes et al., 2021; Gee & Cohodes, 2021). Fourth, unpredictability is likely a product of each individual's predictability as well as interactive patterns between caregiver and child (Beebe et al., 2016). Focusing solely on caregivers without taking the its dyadic nature into account may obscure how unpredictability unfolds during development. Each of the issues increase theoretical and measurement complexity, particularly when we aim to establish construct validity and reconcile different research findings and refine or update theory in light of new evidence (Borsboom et al., 2021; Frankenhuis & Walasek, 2020).

The three empirical approaches reviewed in this paper can inform each other to advance theory and research on caregiver unpredictability, particularly when considering the four issues identified in this paper. We highlight concrete, integrative directions across these three approaches for future research in Table 2. Considering issue #1 (*statistical and perceived caregiver unpredictability*), environmental statistics and entropy are ways to model the statistical properties of children's proximal environments. When we pair these methods with visual habituation paradigms that probe infants' or young children's expectations about their caregiver (S.C. Johnson et al., 2010) or with reliable retrospective measures of perceived unpredictability such as the Questionnaire of Unpredictability in Childhood (Glynn et al., 2019), we can probe whether both aspects map onto each other within the same caregiver or dyad. Identifying whether, which and when children perceive (report, habituate) unpredictability in caregivers who display "truly" (observed and statistically demonstrated) unpredictable behaviors might enlighten several questions about the developmental biobehavioral implications of experiences and/or cognitions of unpredictability (Baldwin & Esposti, 2021; Danese & Widom, 2020; Rivenbark et al., 2020). Assessing how children perceive and construct their experiences of unpredictability might provide further insights into our understanding of its effects on behavior and mental health throughout the lifespan, while understanding these may be the longer-term sequelae of children's conditional adaptations that allowed them to survive or succeed in their proximal environments (Amso, 2021; K. E. Smith & Pollak, 2021a).

Regarding issue #2 (*domains and specificity of unpredictability*), using each of these approaches to model unpredictability at multiple levels and across different aspects of the caregiving environment might advance our knowledge of the *why* and *how* of unpredictability. Regarding the *why,* did developmental systems evolve to respond and adapt to different forms of unpredictability in similar or different ways? For example, using environmental statistics with naturalistic data of language and noise exposure, researchers could probe into the distinct behavioral outcomes of a volatile environment indicated by noise exposure (Werchan et al., 2022) from unpredictability in action-outcomes indicated by the inconsistency of child-initiated conversational turns (King et al., 2021). Whereas the former fosters present-oriented behaviors such as impulsivity, the latter fosters future-oriented behaviors such as information seeking (Fenneman & Frankenhuis, 2020; Munakata et al., *under review*). Therefore, both might be adaptive depending on the type of unpredictability that is experienced. Regarding the *how*, do the neurodevelopmental consequences of unpredictability vary as a function of the domain of unpredictability? We proposed to extend the concept of entropy to include different features of the caregiving context such as affect and behavior, and the integration of DST methods to disentangle both patterns and content of caregiver or dyadic unpredictability. Using these methods in tandem might unveil the extent to which caregiver unpredictability and its impact on neurodevelopment is domain-general, expressing similarly across different inputs or features of caregiving, or domain-specific, evident in specific inputs or valences. Altogether, using these approaches might help us understand *why* and *how* unpredictability and its impact on development varies between and within caregivers or dyads as a function of the particular inputs and the valence of such inputs (Lunkenheimer, Skoranski, et al., 2020).

In relation to issue #3 (*timing of unpredictability*), implementing these quantitative approaches within longitudinal designs might inform how children calibrate development to both immediate environments concurrently and broader contexts in the future (Ellis et al., 2022). Such approaches could take into account the continuity or discontinuity between different aspects of proximal cues of unpredictability (e.g., entropy of caregiver mood) and their relation to distal cues of unpredictability (e.g., caregiver's job loss), and could identify whether there are sensitive periods for the adverse effects of unpredictability in distinct aspects of maternal or dyadic behavior (e.g., sensory signals versus emotional cues). Finally, state-space grids and dynamic systems theory are particularly adept for disentangling the extent to which unpredictability is an emergent dyadic quality across time, as highlighted in issue #4.

Overall, comparing and contrasting the quantification of unpredictability across these different methods using the same sources of information will clarify whether they provide distinct or complimentary perspectives to better understand variation in caregiver and caregiver-child unpredictability. As with other domains of the caregiving environment, unpredictability might be better understood as a continuum (King et al., 2019, King, 2021) where both very high and very low degrees of predictability may lead to maladaptive outcomes, as several studies converge on an optimum midrange model (Beebe et al., 2016; Granic & Lougheed, 2015; Lobo & Lunkenheimer, 2020; Lunkenheimer, Hamby, et al., 2020). Paraphrasing King and colleagues

(2019, p. 3), understanding unpredictability as binary and trait-like within a caregiver (i.e., predictable vs. unpredictable) will likely obscure the impact of less extreme but potentially significant variations in unpredictability within and between dyads. Accurately measuring unpredictability will allow us to properly investigate which external and internal factors foster caregiver unpredictability, opening different avenues for intervention.

In the context of DST, we could also think about unpredictability from outside to within: Unpredictable events such as residential or intimate partner transitions are *perturbations in a system* – a dyad or a caregiver. Families experiencing disadvantage are those most likely to lack stable, predictable, and well-structured environmental conditions (Pollak & Wolfe, 2020; Yoshikawa et al., 2012). Future work should integrate and attempt to bridge both macro and micro perspectives: caregiver unpredictability in the cultural and societal context in which this relationship is unfolding. The reason is two-fold. First, dyads do not exist in a vacuum, but in complex ecological niches with unique environmental demands that the dyad has to adapt to (Bronfenbrenner, 1999; Nketia et al., 2021). Focusing solely on the dyad may contribute to biased interpretations about the nature of caregiver unpredictability and how children develop in response to such environments, while ignoring structural determinants that may be driving caregiver unpredictability (Hastings, Guyer, & Parra, 2022). This could perpetuate deficit-based approaches and victim blaming, normalizing the experience of dominant groups in developmental science (Western, educated, industrialized, rich, and democratic samples) and placing the burden on the caregiver to change (Colegrove & Adair, 2014; Nketia et al., 2021). Since WEIRD populations represent only a thin slice of societies, greater attention to diversity and variation in caregiver unpredictability within and across cultures can provide insights into the ways in which “adverse” caregiving is socially constructed and processed, influencing well-being and psychopathology in the developing child (Frankenhuis & Amir, 2022).

Second, studying dyads in a vacuum will obscure the role and responsibility of society and public policy to support children and caregivers (Humphreys et al., 2021). Therefore, as the field moves forward, care must be taken to ensure measures of caregiver unpredictability are not only reliable but also ecologically valid and culturally sensitive (DeJoseph et al., 2021; Humphreys et al., 2021), considering the demands of the dyad environment and the cultural and societal structures in which the dyad is embedded. For example, Liu and Fisher (2022) highlight the COVID-19 pandemic as an example of an unpredictable event that strongly impacted the caregiving environment. Similarly, massive forced migration and large-scale natural disasters expected from climate change might increase a sense of unpredictability and helplessness for caregivers and their children (Masten et al., 2021). Applying methodological and quantitative approaches to examining unpredictability within caregiver-offspring relationships in the context of the pandemic and the climate crisis could be highly informative for understanding the nature of the effects of distal and proximal unpredictability in caregivers and their children. Even after periods of crisis, elucidating protective policy pathways to ensure caregiver stability, such as universal child allowance (Shaefer et al., 2018), universal health coverage (Doan & Evans, 2020), and “grid” resilience to disasters (e.g., restoring power to maintain communications, household temperature, supply chains, and internet systems to support social and education continuity; Masten 2021) may enhance prevention efforts that put systems in place to ensure continuity and stability in children’s lives.

In this article, we identified three approaches to address the conceptualization and measurement of caregiver unpredictability. Evolutionary approaches suggest that adaptation varies as a function of social and non-social parameters of the environment, such that social phenomena like caregiver unpredictability can be formally quantified with environmental statistics: Trends, autocorrelation, and cue reliability. Information theory and the concept of entropy quantifies unpredictability within caregivers. DST provides conceptual and methodological tools to characterize and measure unpredictable patterns of caregiver-child interactions beyond their content or valence. These approaches can be examined using real-time interaction paradigms (Davis et al., 2017; Feldman, 2021; Lunkenheimer et al., 2016), ecologically momentary assessments (J. J. Li & Lansford, 2018; Ram & Gerstorf, 2009; Williams et al., 2020), or other intensive naturalistic measures of dyadic interactions (Gilkerson et al., 2017; Pérez-Edgar et al., 2020). These are increasingly being used in tandem with traditional longitudinal studies (Chiang & Lam, 2020) and can be leveraged to examine how these unfolding patterns of unpredictability in typical family-based settings embed into higher-order repertoire of interactions that alter children's development. Nonetheless, each of these novel approaches has theoretical and statistical limitations to consider, challenging data collection procedures, and labor-intensive data processing. Rather than focusing on novel paradigms or analytic approaches, we attempted to expand methods that are currently being proposed and used in developmental science. Consistency in terms, metrics and statistical approaches will make comparison and integration across different working groups more manageable and likely to occur, reducing ambiguity and encouraging knowledge accumulation among different research groups interested in unpredictability (Frankenhuis & Walasek, 2020; Haslbeck et al., 2019; Young et al., 2020).

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Supplemental Material

S1. Testing Entropy of Maternal Mood

Currently, no published studies other than those referenced in the paper (Glynn et al., 2018; Howland et al., 2021) have used entropy of maternal mood. Therefore, we tested the feasibility and replicability of this method with data from a longitudinal study of Mexican heritage mothers living in Northern California (NICHD R01HD087367). We tested (1) discriminant validity with entropy of mother's rating of neighborhood quality; and (2) convergent validity, the extent to which mood entropy was correlated with difficulties with emotion regulation and momentary measures of positive and negative mood variability. Sixty-four young Latina mothers (*M*age=23.67, *SD*=2.54) completed mood questionnaires at a home visit and then completed a six-day ecologically momentary assessment (EMA) protocol of daily mood variability. During the home visit, mothers reported their depressive symptoms using the Center for Epidemiologic Studies Depression Scale (CESD; Radloff, 1977), their emotion dysregulation with the Difficulties in Emotion Regulation Scale (DERS; Kaufman et al., 2016), and ratings of neighborhood quality with the Neighborhood Quality Evaluation Scale (NQUA; Kim et al., 2008). After the home visit, mothers completed a six-day EMA protocol. Assessments were delivered three times a day for six days via a smartphone application (metricwire[R]) and included positive and negative emotions. Entropy for each questionnaire was calculated using an R function to calculate mood entropy (Glynn et al., 2018). EMA mood variability was calculated as the intraindividual standard deviation across 18 occasions for positive and negative emotions[2], after testing for time trends in the data.

[2] We acknowledge that better measures exist to quantify the temporal dimension of variability (e.g., RMSSD; Wang et al., 2012), but these need complete data to be correctly computed. On average, mothers completed 12.42 reports out of a total of 18.

Table S1 shows correlation coefficients and Bayes Factors of discriminant and convergent validity associations and Figures S1.1 and S1.2 show pairwise scatterplots. As seen in Fig. S1.1, mood entropy was not correlated with mothers' evaluation of neighborhood quality. Further, mood entropy was correlated with emotion dysregulation and daily mood variability. As seen in Fig. S1.1 and S1.2, emotion dysregulation and intraindividual standard deviation of negative and positive emotions were correlated with entropy of depressive symptoms (although BF was slightly lower than 3 for negative emotions, p = .03).

Table 1
Correlation coefficients and bayes factors for the validity of mood entropy

	CESD Entropy	
	R	BF
Neighborhood entropy	0.18	0.74
DERS	0.63	**>1000**
IAV negative emotions	0.28	***2.58***
IAV positive emotions	0.36	**13.90**

Bayes Factors (BF) indicate the strength of evidence in favor of the alternative hypothesis. Bayes Factors ranging from 1 to 3 are considered "anecdotal"; Bayes factors ranging from 3 to 10 are considered "moderate", and from >10 "strong" or "very strong" (Kass & Raftery, 1995; Quintana & Williams, 2018). R is the bayes correlation coefficient. CESD = Depressive symptoms. DERS = Emotion dysregulation. IAV = Intraindividual variability.

Figure S1.1. *Pairwise scatterplots between depressive symptoms entropy and indices of neighborhood quality and emotion dysregulation.*

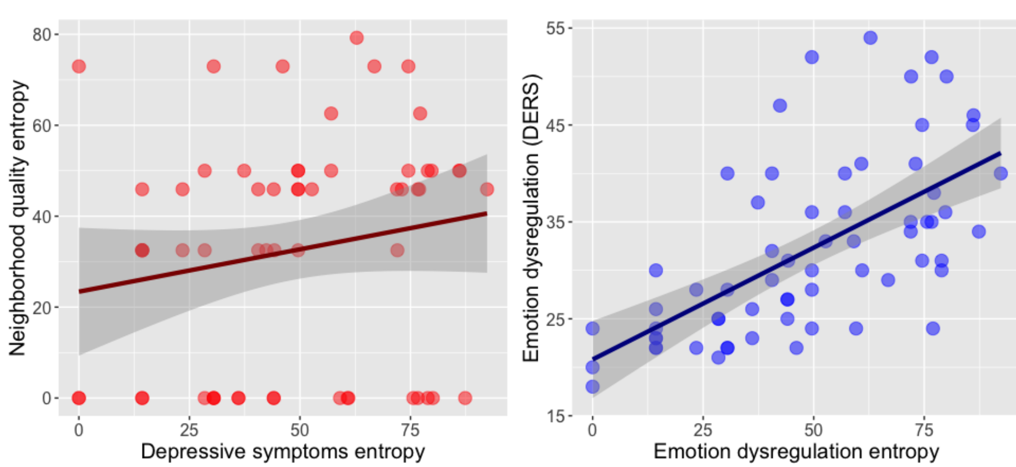
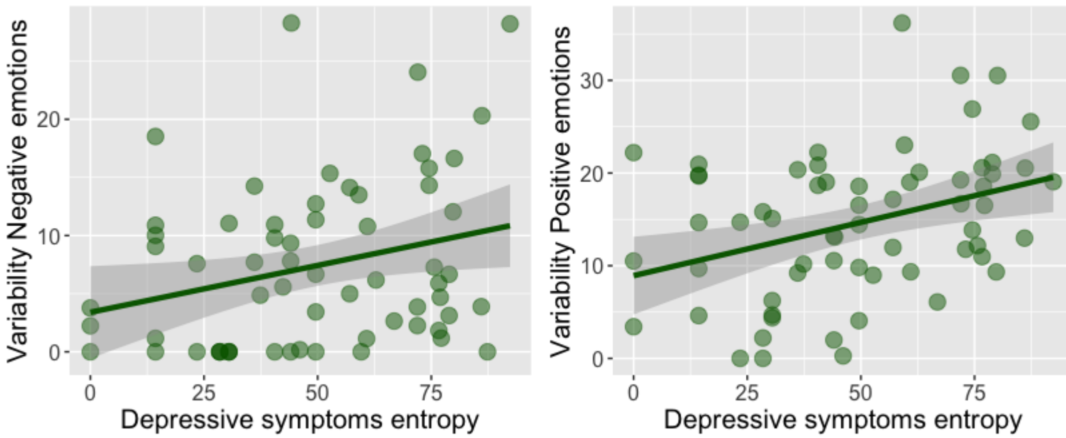


Figure S1.2. *Pairwise scatterplots between depressive symptoms entropy and intraindividual variability in negative and positive emotions acquired through ecologically momentary assessments.*

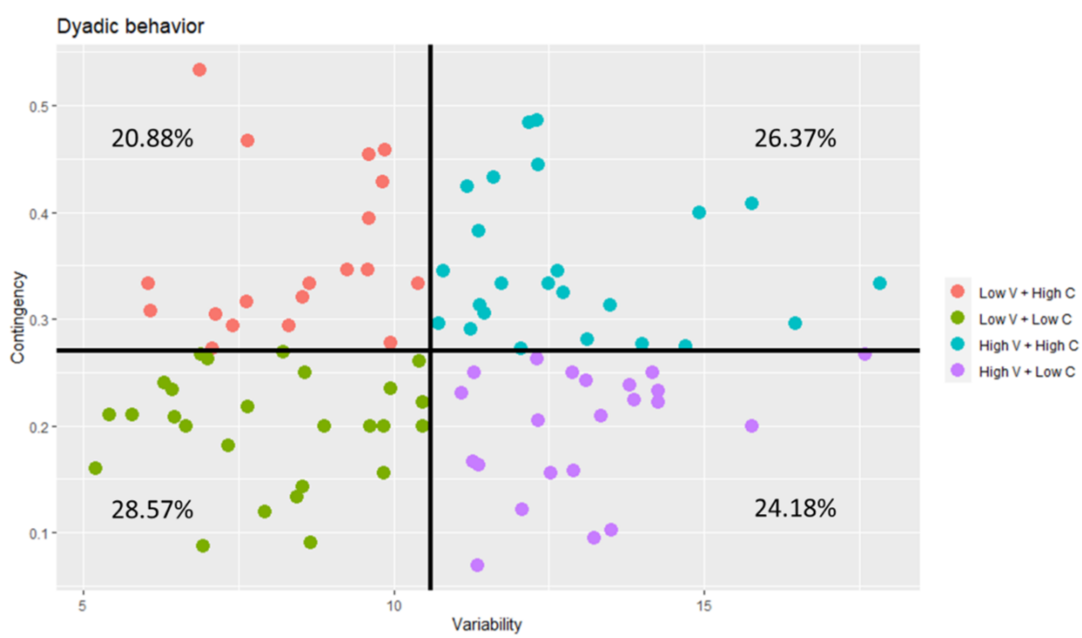


S2. Testing the Feasibility of using State-Space-Grids to Measure Dyadic Unpredictability

In our manuscript, we proposed that contingency and variability may be considered simultaneously to represent dyadic unpredictability. As such, the degree of unpredictability is best represented by an interaction of low contingency and high variability; dyads with high behavioral variability coupled with a low probability of contingency of their behaviors

We attempted to assess the feasibility of this hypothesis using data representing behavioral variability and contingency in 100 mother-preschooler dyads from a low-risk community sample (*M*age = 3.42 yrs, 86% White, 79% married, median family income = $65,000) who completed a free play task, a clean-up task, and a puzzle task that escalated in difficulty (For more details about the sample, tasks, and measurements, see Lobo & Lunkenheimer, 2020, data shared courtesy of the authors). Figure S2 presents a two-dimensional model of the relations between contingency and variability in this sample. Approximately 24.18% of mothers in this sample scored above the mean in variability, meaning that the number of dyadic transitions was higher than average, and below the mean in contingency, indicating a lower consistency between caregiver and child behavior. This lower-right quadrant of the figure could be seen as indicative of relative unpredictability. Of course, the degree of unpredictability increases as dyads move further above the mean for variability and further below the mean for contingency. Only 9% of mothers in this sample scored +0.5 *SD* in behavior variability, and -0.5 *SD* in contingency. Thus, only a small proportion of mothers fell into a profile potentially reflecting a high degree of unpredictability. Nevertheless, this is not entirely unexpected. Dyads tend to self-organize into predictable and integrated interactions even without explicit instructions to do so (Fogel, 2011; Lewis, 2011). Thus, dyadic unpredictability, operationalized as this combination of low contingency and high variability, should be expected to be atypical in this sample, although this does not diminish the importance of dyadic unpredictability's implications for children's development.

Figure S2. *Scatterplot of the relations between dyadic behavioral variability (V) and contingency (C). Vertical and horizontal lines indicate the mean for variability and contingency, respectively. Low and high correspond to under and above the mean. High variability and low contingency could be considered an index of dyadic unpredictability..*



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