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Authors

Munakata, Yuko
Placido, Diego
Zhuang, Winnie

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What's Next? Advances and Challenges in Understanding How Environmental Predictability Shapes the Development of Cognitive Control

Yuko Munakata,
Diego Placido,
Winnie Zhuang
Department of Psychology and Center for Mind and Brain, University of California, Davis

Abstract

Forming predictions about what will happen next in the world happens early in development, without instruction, and across species. Some environments support more accurate predictions. These more predictable environments also support what appear to be positive developmental trajectories, including increases in cognitive control over thoughts and actions. Such consequences of predictable environments have broad-reaching implications for society and have been explained across ecological, psychological, computational, and neural frameworks. However, many challenges remain in understanding the effects of environmental predictability, including adaptive responses to unpredictable environments and the mechanisms underlying the effects of predictable environments on developmental trajectories. Future work addressing different dimensions of predictability -- across time scales, locations, actions, people, and outcomes -- and their interactions will advance the ability to understand, predict, and support developmental trajectories.

"Prediction is very difficult, especially about the future." This quote has been attributed to multiple people, including the physicist Niels Bohr, and may have originated from an unidentified Danish humorist. While the statement highlights a fundamental truth, predictions -- guesses about what will happen in the future -- are nonetheless formed early and often. After brief exposure to new sights and sounds in the environment, even infants detect statistical regularities and use them to form expectations about what will happen next and react when their expectations are violated (Canfield & Haith, 1991; Emberson et al., 2015). Such predictions are formed in the absence of any instruction across development, across species, and across visual, auditory, tactile, and motor domains (Santolin & Saffran, 2018). Forming predictions and detecting the differences between them and actual events (i.e., prediction errors) may provide an essential signal that drives curiosity and learning (Gruber & Ranganath, 2019; O'Reilly et al., 2020).

However, when it comes to supporting the formation of accurate predictions, not all environments are created equal -- with apparent consequences for cognitive development.

Corresponding author: Yuko Munakata, ymunakata@ucdavis.edu, Center for Mind and Brain, 267 Cousteau Place, Davis, CA 95618.

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For example, some households may be structured in ways that make it harder for developing children to assess future events or outcomes, due to irregular routines (e.g., no morning routines, family plans rarely work out, inconsistent disciplines), disorganized environments (e.g., high levels of commotion inside the home, difficulty finding things when needed), high household transience (e.g., frequently moving residence, people coming and leaving, irregular personal relationships), inconsistency in parental mood, and inconsistent safety and security (e.g., food or financial insecurity, not feeling safe at home). More predictable environments appear to support multiple facets of brain and cognitive development (Ugarte & Hastings, in press). For example, greater exposure to predictable routines (e.g., eating meals as a family, consistent bedtimes) during adolescence predicts higher adult levels of cognitive control – processes that regulate thoughts, actions, and emotions in support of flexible, goal-directed behavior (Andrews et al., 2021). Such developments may have broad consequences given the role of cognitive control in academic, behavioral, health, and other outcomes (Munakata & Michaelson, 2021).

Of course, correlation is not causation: predictable environments might not influence cognitive development but the two could be linked via confounding factors. For example, if children's nutrition is better supported in more predictable environments, nutrition could drive developments in cognitive control rather than predictability (e.g., Jirout et al., 2019). Attempts to control for such potential confounds can yield high false positive rates (Westfall & Yarkoni, 2016). In addition, shared genes could explain both variations in the predictability of parents and the development of cognitive control in their children, leading to correlations between the two without a causal link (e.g., Jami et al., 2021).

However, experimental studies highlight how predictable environments causally influence cognitive control and cognitive development more generally. For example, when children (and adults) receive information about upcoming tasks, they engage cognitive control proactively in anticipation of the task more often when the information accurately predicts the future task than when the information is made unreliable (Chevalier et al., 2020). Moreover, causal links between predictability and cognitive processes hold across longer time scales. When the predictability of maternal sensory signals during the first days of life is experimentally manipulated in non-human animals, by limiting bedding and nesting materials which leads to unpredictable behavior in mother rodents (Ivy et al., 2008), spatial memory and other processes in the offspring are later disrupted in adolescence (Davis et al., 2017) and beyond (Birnie & Baram, 2022). In children, the same measure of predictability of maternal sensory signals in the first year of life predicts children's memory and cognitive control years later (Davis et al., 2017, 2019). This parallel between experimental and correlational work highlights how early unpredictability in the environment might shape cognitive development.

Such consequences of predictable environments have broad-reaching implications explained across ecological, psychological, neural, and computational frameworks. According to Life History Theory, early environments funnel individuals and populations to assume a developmental speed and behavioral repertoire that maximizes genetic fitness and survival in those environments. Resource-rich, predictable environments promote slow life histories and behavioral tendencies that support future-oriented planning and investment,

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while unpredictable and resource-scarce environments promote fast life histories that emphasize present-oriented behaviors (Pepper & Nettle, 2017). At the psychological level, predictability is critical for learning and generalization (Kolb et al., 2001): individuals rely on predictable action-outcome pairings to appropriately orient attention and select reward-maximizing responses. These effects are seen in the increased speed and accuracy in psychological tasks with predictable signals and outcomes (Chevalier et al., 2020). Further, in unpredictable environments, individuals may learn that attempts to learn from prediction errors – violations of expectation – are unhelpful, which could have cascading effects on future learning. Similarly, the effects of predictability on learning also transpire at the neural level, where predictable inputs allow neurons to anticipate and adaptively prepare for future outcomes and rewards (Hollerman & Schultz, 1998). Finally, computational models that learn to maximize rewards based on prior reward histories have shown how unpredictability leads to behavioral adaptations consistent with many of the above frameworks (Fenneman & Frankenhuis, 2020).

While predictable environments thus appear to shape cognitive development in sensible ways, many issues must be addressed to more fully understand the influences of predictability and inform intervention. For example, one potential challenge to the story presented thus far is that unpredictable environments *increase* certain cognitive control processes. Compared to adults raised in predictable environments during childhood, adults raised in unpredictable environments showed greater updating of information into working memory (Young et al., 2018) and more successful task-switching, but less inhibitory control (Mittal et al., 2015). Similarly, instability in early caregiving is associated with greater childhood cognitive flexibility (but less inhibitory control; Fields et al., 2021). In addition, children who spent more time in less-structured activities that may seem relatively unpredictable (such as free play and outings, where adults provide few if any guidelines or instructions) showed more successful task-switching (Barker et al., 2014; Stucke et al., 2022); conversely, children who spent more time in activities structured by adults that may seem relatively predictable (such as adult-led lessons and practices) showed less successful task-switching (Barker et al., 2014). Longitudinal work with genetically-informative samples is consistent with children's early experiences causally affecting later cognitive control (Barker et al., 2021). These findings highlight that predictability is not universally linked with increased cognitive control.

Understanding these potentially conflicting influences of predictability may require delineating dimensions of predictability, regarding when, where, who, and what (Figure 1). For example, a child's experience could be predictable or unpredictable on a timescale of seconds (e.g., in terms of transitions from moment to moment in maternal input across visual, auditory, and tactile modalities, as in Davis et al., 2017) or on timescales of minutes, hours, or days (e.g., in terms of family plans for the next morning or weekend). Similarly, predictability for a child may vary across spatial locations, from more proximal locations like the home to increasingly distal locations across the neighborhood, community, and beyond. *Who* is doing *what* may also vary, influencing the nature of predictable or unpredictable signals -- from a child forming predictions while observing the environment (as captured in statistical learning studies), to a child acting on the environment and predicting outcomes of those actions, to a child interacting with other people and forming

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predictions about how they will behave. As a child develops, the types of predictability and unpredictability experienced will change, to include longer time scales, more distal settings, and a greater range of child actions and interactions. Predictable or unpredictable experiences along these dimensions may engage distinct mechanisms and shape distinct outcomes.

Considering these dimensions of predictability can offer a new perspective on seemingly conflicting findings, such as the links between children's unstructured time and greater cognitive control (Barker et al., 2014, 2021; Stucke et al., 2022). Less-structured activities for children might seem less predictable from an adult's perspective in terms of who is doing what, because adults have less say in what children are doing. From this adult perspective, it may seem surprising that less-structured time is linked with greater cognitive control. However, less structured time might support more predictability from the child's perspective, because children have more agency in determining their own goals and how they will pursue them; the outcomes of their actions may be more predictable than the directives from an adult that come during more structured time. From this child perspective, the link between less-structured time and greater cognitive control appears compatible with effects of predictability (see also Doebel & Lillard, 2023).

Different types of predictability may also interact to shape outcomes. For example, disorganized home environments predict lower levels of cognitive control in children, but this effect depends on external influences from outside the home, specifically children's time in childcare; children who spend less time in childcare show a stronger relationship between home predictability and cognitive control (Berry et al., 2016). This interaction could reflect an offsetting effect from higher predictability in the child care setting, although other interpretations are possible and remain to be tested (e.g., a dose-response relationship between home unpredictability and cognitive outcomes).

Beyond single interactions like the household-childcare example, developing a whole, multidimensional profile of the unpredictability experienced across development may illuminate our understanding of shaping forces and outcomes. For example, each child experiences different levels of unpredictability at different points among the three dimensions of time, space, and actions (Figure 1), leading to a unique landscape of multicolored points and unique changes across development. This profile may shed light on relationships between dimensions of unpredictability and their contributions to cognitive outcomes. Such approaches have been taken to understand multiple dimensions of poverty (DeJoseph et al., 2021) and adversity (McLaughlin & Sheridan, 2016) and their impacts on children. With a rich dataset that contains markers of unpredictability across spatial, temporal, and social domains, psychometric analyses can be conducted to probe and identify the dimensional structure of unpredictability and links with developmental outcomes (Young et al., 2020).

The full multidimensional profile of predictability likely includes additional informative dimensions beyond time, space, and actions. For example, the type of outcome being shaped (such as task-switching vs. inhibitory control) may provide insight into why unpredictability increases certain aspects of cognitive control (Young et al., 2018). Predictable environments

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may support children in planning ahead and maintaining those plans; these experiences may in turn support developments in goal maintenance, which has been argued to support a broad range of cognitive control processes including inhibitory control (Friedman et al., 2008). In contrast, unpredictable environments may lead children to update goal-relevant information and switch tasks more frequently, leading to observed increases in working memory updating, task-switching, and cognitive flexibility (Fields et al., 2021; Mittal et al., 2015; Young et al., 2018). In some cases, such increases are only observed under conditions that draw attention to unpredictability in the world, which may highlight the context-dependent nature of these developments and adaptations. Thus, predictable environments may support aspects of cognitive control that require maintaining goals across delays and distractions (stability), while unpredictable environments support aspects of cognitive control that require relaxing goals and adaptively updating (flexibility) (see Dreisbach & Fröber, 2019 for a discussion of stability-flexibility tradeoffs in cognitive control).

Dimensions of predictability can also provide insight into how unpredictability could increase both present-oriented and future-oriented behaviors. For example, computational simulations of adaptive learners have shown that two forms of environmental variation promote different behaviors: unpredictability in environmental structure, or volatility, promotes more present-oriented behaviors such as rapid updating and high learning rates, while unpredictability in action-outcomes promotes future-oriented behaviors such as seeking information before acting (Fenneman & Frankenhuis, 2020). These distinct behaviors develop because the goal of the simulated learners is to maximize rewards; via trial-and-error interactions, they learn that the best way to maximize rewards in a volatile environment is to rapidly adjust expectations and to take rewards when they are available, and the best approach when outcomes are uncertain is to gather more information. This framework might predict that for children, residential mobility (volatility in environmental structure) would reduce delaying of gratification, while unpredictable child-caregiver interactions (action-outcomes) would increase the seeking of information before acting (e.g. hesitantly observing a caregiver's mood before approaching). This latter idea, that certain kinds of unpredictability should lead children to show greater future-oriented behaviors like information-seeking, might seem to conflict with findings and frameworks highlighting the opposite pattern, that unpredictability increases present-oriented behaviors. However, this contrast highlights the importance of also considering the multidimensionality of future-oriented behaviors, such as goal-directed actions (which might decrease in unpredictable environments) versus knowledge-directed choices (which might increase in unpredictable environments).

More generally, what is adaptive for a child in one environment may not be adaptive for a child in another environment (Nketia et al., 2021). Traditional views of "good" cognitive control and associated environmental factors have been developed within a tradition of psychology built on the perspective of White, Western, wealthy men (Ledgerwood et al., 2021; Roberts et al., 2020). This tradition has contributed to a decontextualized, deficit-based lens that is often applied to minoritized children and children from lower socioeconomic status homes; characterizations of such children's environments and early experiences may overlook the role of systemic factors, such as racism and income and wealth inequality, in shaping these environments and experiences (Miller-Cotto et al., 2022).

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We have purposefully avoided characterizing differences in cognitive control in terms of “better” or “worse” cognitive control. We focus instead on higher or lower levels of cognitive control, either of which could be adaptive for a given situation.

Many questions remain about the mechanisms driving effects of unpredictable environments. Are these outcomes shaped by unpredictability *per se*, as simulated in computational frameworks? Or is *perceived* unpredictability–the subjective experience of unpredictability–more important, as has been argued in the case of perceived versus objective experiences of childhood adversity (Baldwin & Degli Esposti, 2021)? Measurements of unpredictability vary across studies and fields (e.g., assessing aspects of the environment vs. perceptions of unpredictability, via questionnaires vs. behavioral coding, measured retrospectively vs. prospectively), and it is unclear how these measures relate to one another (Young et al., 2020) and how such relationships might vary across timescales or other dimensions of unpredictability. Unpredictability could potentially become predictable for some children (Ugarte & Hastings, in press), such that the same situation could be experienced as predictable or unpredictable by different children, depending on the schemas they have formed around unpredictability based on prior experiences (Cabeza de Baca et al., 2016).

Another question concerns whether outcomes associated with unpredictability are instead (or additionally) shaped by consequences of unpredictability or associated life experiences, such as increases in stress, decreases in feelings of trust, and other factors that influence cognitive control and development (Ellis et al., 2022; Munakata & Michaelson, 2021). While unpredictability correlates with behavior in adolescence to a greater extent than stressful negative life events (Marcynyszyn et al., 2008), unpredictability could nonetheless exert its impact via stress-related mechanisms. In rodent models, experimentally-induced increases in the predictability of maternal signals led to reduced neuroendocrine stress responses in pups and increased their resilience to subsequent stress-related outcomes (Baram et al., 2012). Moreover, in human studies, lower socioeconomic status is sometimes treated as a proxy for stress, and is correlated with household unpredictability (Evans et al., 2005). Children from lower socioeconomic status environments show accelerated rates of brain development (e.g., Tooley et al., 2021), which have been linked with shorter sensitive periods to environmental input and lower scores on cognitive assessments (Brant et al., 2013). Thus, unpredictability may impact development via some mechanisms (e.g., stress) that are shared with other sources of influence, such as lower socioeconomic status. Conversely, from an ethological perspective, experiences like play may provide opportunities for children to “train for the unexpected” in lower-stress situations (Spinka et al., 2001). That is, children are practicing to engage behavior adaptively for unpredictable situations through less stringent interactions involved in play. The context of unpredictability thus matters for the consequences.

More generally, considering multiple dimensions of predictability may highlight points of alignment and misalignment among different approaches, and promising areas for future work. For example, computational investigations have focused on predictability *per se*, while behavioral studies have also explored potential mediators such as stress. If unpredictable action-outcomes do not increase children’s future-oriented information seeking in certain situations, contrary to predictions from computational models, that may highlight the role of factors such as stress that could decrease information seeking. Aligning approaches to focus on similar aspects of predictability can provide an important test of their generalizability and points of connection.

Conclusion

While prediction can be difficult -- especially about the future (as captured in the opening aphorism) -- it is ubiquitous and easier in certain environments. These variations in the predictability of environments early in life matter for developmental outcomes across the lifespan. Future work should further address levels and dimensions of predictability (across time scales, locations, actions, people, and outcomes), their interactions, related processes, and changes with development. Exploring profiles of predictability across psychological, computational, neural, and ecological frameworks will advance the ability to understand, predict, and support developmental trajectories.

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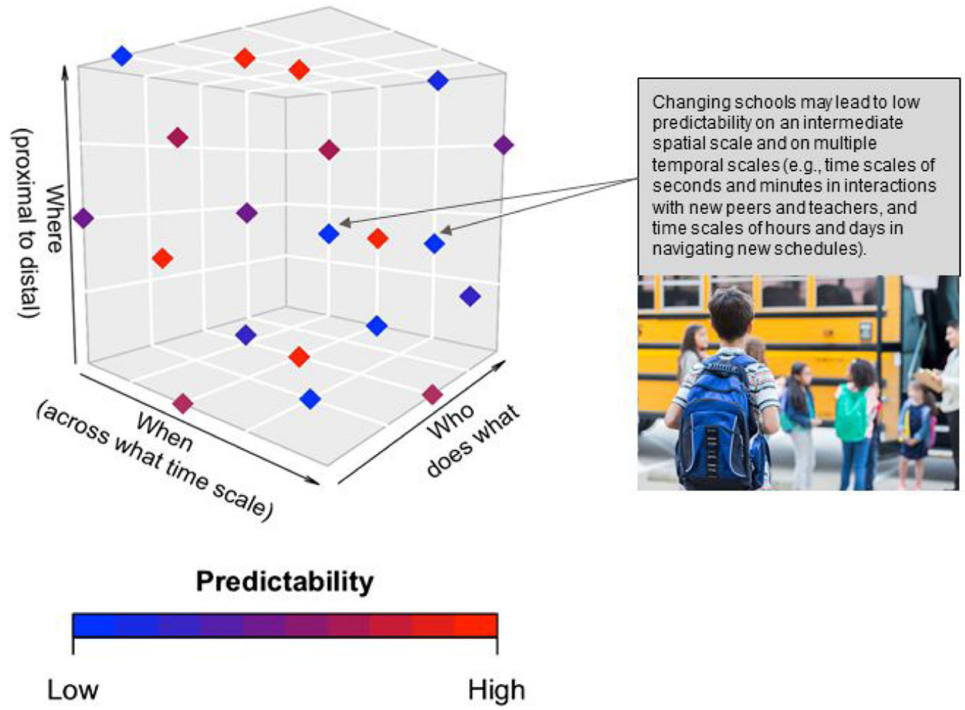

Figure 1.

Dimensions of predictability. A child may experience predictable or unpredictable environments across different time scales, spatial locations, and situations. Each child may have a unique profile of predictability across this multidimensional space (a landscape of multicolored points), which varies across development and shapes and explains outcomes. While predictable environments appear to promote cognitive development, consideration of these and other dimensions and their interactions can help to resolve seemingly conflicting findings and highlight promising directions for future work.