windows points to the costs associated with plasticity, which cannot be indefinitely sustained. This is one reason why, after a certain age, learning new languages and solving amblyopia is so difficult, and why early experience is in many cases important for subsequent stages of life. Recent evidence in rodents suggests that the spontaneous plasticity of the nervous system is actively reduced by molecular 'brakes' that promote circuit stabilisation in mature brain function [13]. Declining plasticity is also ecologically adaptive: the realities of the perinatal period mean that the most relevant potential substrate for imprinting is the mother bird. If plasticity endured beyond the critical period, numerous erroneous substrates – any moving animal – would likewise trigger imprinting, thus reducing its adaptive valence. The constraint in time also serves to constrain candidate substrates appropriately. A similar effect may be observed in bird song, wherein young altricial songbirds learn their mating songs while still confined to the nest, which prevents the incorporation of irrelevant sounds experienced after fledging.

Considering the balance between priors, plasticity, and the observed brakes to plasticity, we argue that evidence from animal research suggests that (i) AI systems could benefit from being equipped with a rich but constrained set of priors and specialised learning mechanisms similar to those seen in precocial animal species, rather than being endowed only with general purpose, unifying mechanisms, (ii) plasticity without priors and critical periods of expression for these priors might be associated with costs that prevent effective learning and stable cognitive functions. The ability to shift between priors and thus direct plasticity may speed our way to strong AI, while pursuing less-structured AI may help to identify new and potentially unexpected useful priors.

Acknowledgments

G.V. was funded by a European Research Council (ERC) advanced grant (ERC-2011-ADG_20110406: project 461 295517, PREMESOR), Fondazione Cariitro Grant Biomarker DSA [40102839] and PRIN 2015 (Neural bases of animacy detection, and their relevance to the typical and atypical development of the brain). A.M. and A.K. were funded by a Leverhulme Foundation research grant (Relational Concept in Ducklings, RPG-2016-192).

[1]Queen Mary University of London, School of Biological and Chemical Sciences, Department of Biological and Experimental Psychology, Mile End Road, London E1 4NS, UK
[2]University of Oxford, Department of Zoology, New Radcliffe House, Oxford OX1 3PS, UK
[3]University of Trento, Center for Mind/Brain Sciences, Piazza Manifattura 1, Rovereto, Italy

*Correspondence:
e.versace@qmul.ac.uk (E. Versace) and
antone.martinho@zoo.ox.ac.uk (A. Martinho-Truswell).

https://doi.org/10.1016/j.tics.2018.07.005

References

1. Pinker, S. (2004) *The Blank Slate: The Modern Denial of Human Nature,* Viking
2. LeCun, Y. and Marcus, G. (2017) Does AI need more innate machinery? Debate at the NYU Center for Mind, Brain, and Consciousness, October 5, 2017. https://wp.nyu.edu/consciousness/innate-ai/
3. Marcus, G. (2018) Innateness, alphazero, and artificial intelligence. *arXiv*
4. Lake, B.M. (2017) Building machines that learn and think like people. *Behav. Brain Sci.* 40, e253
5. Vallortigara, G. (2012) Core knowledge of object, number, and geometry: a comparative and neural approach. *Cogn. Neuropsychol.* 29, 213–236
6. Wood, J.N. (2015) Characterizing the information content of a newly hatched chick's first visual object representation. *Dev. Sci.* 18, 194–205
7. Martinho, A. and Kacelnik, A. (2016) Ducklings imprint on the relational concept of 'same or different'. *Science* 353, 286–288
8. Versace, E. *et al.* (2017) Spontaneous generalization of abstract multimodal patterns in young domestic chicks. *Anim. Cogn.* 20, 521–529
9. Johnson, M.H. and Horn, G. (1988) Development of filial preferences in dark-reared chicks. *Anim. Behav.* 36, 675–683
10. Vallortigara, G. *et al.* (2005) Visually inexperienced chicks exhibit spontaneous preference for biological motion patterns. *PLoS Biol.* 3, e208
11. Bateson, P. (1978) Sexual imprinting and optimal outbreeding. *Nature* 273, 659–660
12. Johnson, M.H. *et al.* (2015) The two-process theory of face processing: modifications based on two decades of data from infants and adults. *Neurosci. Biobehav. Rev.* 50, 169–179
13. Hensch, T.K. and Quinlan, E.M. (2018) Critical periods in amblyopia. *Vis. Neurosci.* 35, E014
14. Di Giorgio, E. *et al.* (2017) Filial responses as predisposed and learned preferences: early attachment in chicks and babies. *Behav. Brain Res.* 325, 90–104

Forum

The Little Engine That Can: Infants' Persistence Matters

Kelsey Lucca[1,*] and Jessica A. Sommerville[1]

Persistence is central to outcomes across a range of domains: the harder you try, the further you get. Yet relatively little is known about the developmental origins of persistence. Here, we highlight key reasons for a surge of interest in persistence in infancy and early childhood.

Persistence, the ability and motivation to engage in sustained effort to overcome challenges and achieve goals (Figure 1), is a key predictor of educational attainment (i.e., graduation rates, grade point average), positive qualities (e.g., resiliency), and life outcomes (e.g., job maintenance, marital success) starting in middle childhood [1]. Yet, we know little about the developmental roots of persistence in infancy and early childhood. Here, we call for a new empirical interest in persistence that capitalizes on and expands upon recent discoveries in infants' knowledge, learning, and behavior. Specifically, we argue that (i) individual differences in persistence emerge during infancy and influence later development, (ii) persistence is a valuable measure of what infants understand and care about across domains, and (iii) persistence offers a window into metacognitive and decision-making processes. Below, we marshal the evidence to support each of these claims and point to important future directions on this topic.

Persistence in Infancy Has Implications for Long-Term Outcomes

Much of what is known about early persistence comes from research on a

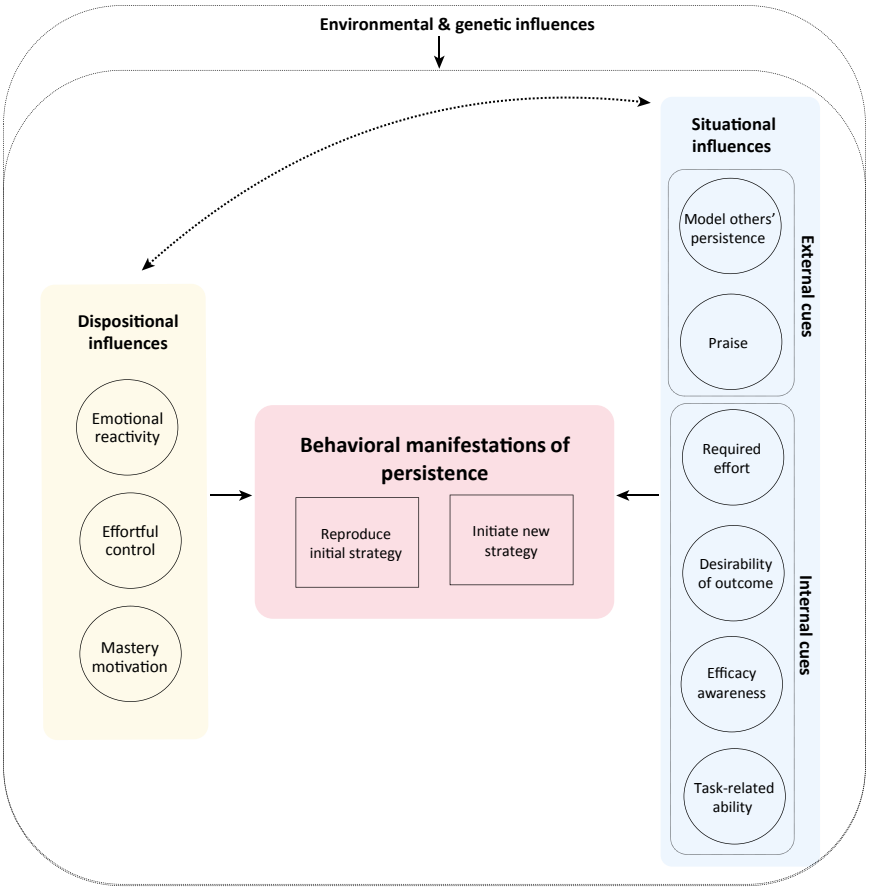


Figure 1. Conceptual Model of Persistence and Its Contributors. This conceptual model defines persistence as the ability and motivation to engage in sustained effort to overcome challenges and achieve goals and is designed to guide future research on early persistence. Persistence is a multifaceted, multidimensional construct that is both dispositionally and situationally derived. In any given context, young learners' persistence is influenced by the temperamental traits they approach the task with and factors that are task specific, both of which are shaped by genetic and environmental influences.

closely allied topic, mastery motivation (i.e., infants' interest in exploring and 'mastering' their environment). Individual differences in mastery motivation emerge by 6 months and predict problem-solving skills at 14 and 30 months of age that, in turn, predict academic achievement at age 5 years across domains (e.g., vocabulary knowledge, problem solving [2,3]). While much of the earlier literature conflated persistence and competence, making it difficult to determine their relative contributions, persistence now appears to be a unique and independent construct that is interesting in its own right [4].

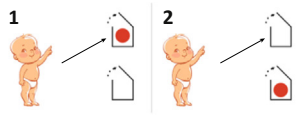
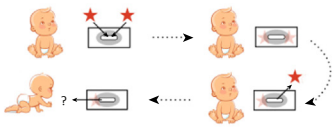
Individual variability in persistence is influenced by environmental and contextual factors. Caregivers with more sensitive and responsive teaching styles have infants who tend to persist more in their exploration of toys [2]; in turn, studies have shown that heightened exploration leads to advances in learning [5]. Recent work shows how concrete experiences enhance persistence. Demonstrations of persistent behavior cause infants as young as 13 months of age to act more persistently [4]. Moreover, parental praise of infants' effortful behaviors predicts academic motivation 7 years later [6]. Thus, research on persistence should target the first few years of life because that is when it is most malleable and open to environmental influence. This focus will help us understand, in detail, how to best design targeted interventions for enhancing persistence, when it matters most.

Persistence Demonstrates What Infants Know and Care About

Studying persistence is also a means to demonstrate what infants know about and value across a range of domains. For example, infants' persistence during manual search tasks uncovered that there are slow but significant developments in inhibitory control in the first 2 years of life [7]. More recently, researchers have shown that infants' persistence in manual search tasks following mathematically impossible events demonstrates that they not only track discrete quantities but also that their numeric representations are robust enough to drive behavior [8]. Infants' persistent use of communicative signals has challenged the long-held belief that infants' communicative behaviors lack creativity and are driven by egocentric motives. Instead, infants' persistence in their communicative attempts function to repair their original message and highlights that their requests are intentional and tailored to achieve an efficient transfer of information [13]. In the domain of prosocial behavior, infants' persistent engagement in high-effort helping behaviors has been used to specify the motivational drivers of infants' prosociality [9] (Figure 2).

Moving forward, persistence can be used to answer critical open questions in early development. For example, currently there is debate over exactly when infants and young children can represent false beliefs. Studies using infants' visual responses have yielded conflicting results, open to a range of alternative explanations, leading researchers to advocate for active measures to address this problem [10].

Using persistence to probe the nature of early representations, knowledge, and motivation across domains

Domain	Associated task	Contribution to the field	Refs
Executive functioning 	**A-not-B task:** objects are hidden in an initial location, infants are given the opportunity to search for it before watching it move to a new location. Researchers measure whether infants persistently search in the initial (incorrect) location or the new (correct) location.	There are slow but significant developments in inhibitory control across the first two years of life.	[7]
Numeric reasoning 	**Manual search task:** objects are hidden in a box. New objects are subsquently added or removed. Researchers measure infants' search persistence as a function of whether the number of objects in the box are consistent with the events witnessed. Adapted from Feigenson & Carey, 2003.	Infants are not only able to represent, keep track of, and perform basic mathematical computations on discrete sets of objects: these numeric representations are strong enough to drive behavior.	[8]
Language acquisition 	**Communicative interaction task:** infants deploy an initial communicative signal and are given a response from a communicative partner. Researchers use infants' subsequent communicative persistence as a signal that infants were not satisfied with the response, and are therefore negotiating the meaning of that message.	Long before infants produce their first words, they are already savvy negotiators of meaning and seekers of information. Their communicative signals are intentionally produced and tailored to ensure the efficient transfer of information.	[13]
Prosocial behavior 	**Helping task:** infants witness an individual in need of help. Researchers measure whether infants persist in their helping behaviors as a function of the physical effort required and amount of intrinsic reward associated with helping.	Infants' prosocial behaviors are governed by cost–benefit analysis: they are strategic in their helping endeavors, and are most likely to behave prosocially under contexts of high intrinsic rewards and low anticipated physical effort.	[9]

Trends in Cognitive Sciences

Figure 2. Persistence across Domains. Examples across domains of infants' and young children's persistence as a probe of the nature of underlying representations, knowledge, and motivation. Also see [7–9]. © Natalia Zelenina, Adobe Stock.

Investigating whether infants persistently attempt to correct a person's beliefs when they are false, but not when they are true, may provide insight into this debate.

Persistence Offers a Window into Metacognitive and Decision-Making Processes

Investigating early persistence is also informative because it serves as a way to gain insight into the processes that guide persistence itself. Adaptive persistence requires knowing when to act on a problem, when to switch strategies, and when to abandon a problem altogether. Given the inherently social nature of infants' world, persistence is guided by two processes: representing and integrating knowledge of the self and others (metacognition) and understanding and weighing the costs and benefits associated with acting (or not) in any given circumstance. While metacognition and decision-making are traditionally studied in older children and come from different historical lines and are therefore examined separately, as distinct constructs, persistence provides researchers with a means to study the intimate relationship between these processes.

Recent work suggests that the origins of metacognition, as well as the computational processes and principles underlying decision-making, can be traced back to infancy. Infants monitor their own knowledge states, keeping track of what they do and do not know, and strategically communicate this information to others to get gaps in their knowledge filled [11]. Similarly, infants engage cost–benefit analyses, a hallmark of decision making, by weighing the effortful costs of producing a prosocial action against the affiliative benefits when deciding to help another individual [9]. Moreover, these cost–benefit analyses

also guide infants' reasoning about other agents: as early as 10 months of age, infants and children use the costs an individual is willing to incur to obtain a goal to infer the value of that goal [12].

Studying infants' persistence can tell us about the integration of metacognitive and decision-making processes: costs are subjective, and therefore knowing what is costly and what is not requires an understanding of one's own abilities relative to the task at hand. Indeed, recent research on infants' persistent helping behavior indicates that infants harness their awareness of their own abilities to determine subjective physical costs. Under conditions of high-cost helping (i.e., when infants must carry a heavy block across a room to help another individual), experienced walkers (for whom carrying a heavier block is less effortful) are more likely to help an individual than inexperienced walkers [9]. Studying persistence in social contexts can tell us about infants' ability to compare and evaluate their own abilities to those of others and use this information to decide when and for how long to persist for, the range of costs that infants can compute (e.g., mental costs, opportunity costs, etc.), and infants' ability to detect when the rewards of persisting outweigh the costs.

Concluding Remarks

In this spotlight, we have argued for three reasons for studying persistence in infancy and early childhood. One reason is closely aligned to existing work with older children and adults: understanding early individual differences in persistence is important for predicting later outcomes, and identifying the factors that contribute to these early individual differences is critical for optimizing development. But we have also elucidated two additional reasons for studying persistence early in life. Critically, studying persistence can provide more graded measures of knowledge and motivation for a range of different domains, and better elucidate how these change in development. Finally, investigating early persistence can advance our understanding of the metacognitive and decision-making processes recently revealed to operate in infancy, and how these influence infants' trying behavior to ultimately drive their learning.

Acknowledgments

We thank the researchers of the Early Childhood Cognition Lab, particularly Rachel Horton and Lisa Chiang, and the Developmental Psychology Seminar Group at the University of Washington for helpful insights and feedback on earlier drafts of the paper. We also thank two anonymous reviewers for constructive feedback. This work was supported by a grant from NICHD (1R01HD076949-01).

[1]University of Washington, Department of Psychology and Center for Child and Family Well-being, Brooklyn Trail Building, 3903 Brooklyn Ave NE, Seattle, WA 98195, USA

*Correspondence: klucca@uw.edu (K. Lucca).

https://doi.org/10.1016/j.tics.2018.07.012

References

1. Duckworth, A. and Gross, J.J. (2014) Self-control and grit: related but separable determinants of success. *Curr. Dir. Psychol. Sci.* 23, 319–325
2. Banerjee, P.N. and Tamis-LeMonda, C.S. (2007) Infants' persistence and mothers' teaching as predictors of toddlers' cognitive development. *Infant Behav. Dev.* 30, 479–491
3. Martin, A. *et al.* (2013) Longitudinal associations among interest, persistence, supportive parenting, and achievement in early childhood. *Early Child Res. Q.* 28, 658–667
4. Leonard, J.A. *et al.* (2017) Infants make more attempts to achieve a goal when they see adults persist. *Science* 357, 1290–1294
5. Stahl, A.E. and Feigenson, L. (2015) Observing the unexpected enhances infants' learning and exploration. *Science* 348, 91–94
6. Gunderson, E.A. *et al.* (2018) Parent praise to toddlers predicts fourth grade academic achievement via children's incremental mindsets. *Dev. Psychol.* 54, 397–409
7. Diamond, A. (2013) Executive functions. *Annu. Rev. Psychol.* 64, 135–168
8. Feigenson, L. and Carey, S. (2003) Tracking individuals via object-files: evidence from infants' manual search. *Dev. Sci.* 6, 568–584
9. Sommerville, J. *et al.* (2018) Infants' prosocial behavior is governed by cost-benefit analyses. *Cognition* 177, 12–20
10. Poulin-Dubois, D. and Yott, J. (2018) Probing the depth of infants' theory of mind: disunity in performance across paradigms. *Dev. Sci.* 21, e12600
11. Goupil, L. *et al.* (2016) Infants ask for help when they know they don't know. *Proc. Natl. Acad. Sci. U. S. A.* 113, 3492–3496
12. Liu, S. *et al.* (2017) Ten-month-old infants infer the value of goals from the costs of actions. *Science* 358, 1038–1041
13. Lucca, K. and Wilbourn, M. (2018) The what and the how: information-seeking pointing gestures facilitate learning labels and functions. *J. Exp. Child Psychol.* (in press)