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How Variability, Predictability, and Harshness Shape Cognitive Flexibility

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Introduction

Flexible problem-solving has long been revered as a hallmark of human ingenuity. Our global expansion and the sheer diversity of contemporaneous human cultures is a testament to our ability to flexibly adapt existing techniques and seek alternative strategies. Yet, humans' predilection for "sticking to what we know" is evident in a wide range of behaviors and biases. The question is not are humans flexible or rigid problem-solvers but rather when do the benefits of flexibly changing tack exceed the costs? The *constrained flexibility framework* (CFF) seeks to understand how variability, predictability, and harshness work in tandem to shape flexible versus inflexible strategy use. The CFF distinguishes between strategy switching that occurs in response to failure and strategy switching that involves searching for better alternatives, here referred to as responsive and elective flexibility, respectively. Efforts to understand human cognitive flexibility have almost exclusively focused on how well individuals switch when they have to, rather than when, and under what contexts, they choose to. Understanding the conditions in which changing strategies is most beneficial may help explain how our species strikes the balance between maintaining working strategies and finding or creating better ones.

Adaptive Flexibility

Francy Ntamboudila (2020) tells a Congolese fable of how the antelope, a weak but wily animal, became the king of the jungle. It had been decreed that whichever animal was strong enough to shoot an arrow through the trunk of the largest tree would win the throne. The elephant and the leopard, the strongest of the animals, practiced and practiced. But on the day of the competition, their arrows barely pierced its bark. They laughed when the antelope stepped up to take his turn. However, knowing that he would never be strong enough, the antelope had come up with a different strategy. Before the event, the antelope convinced his friend, the bee, to drill a hole through the tree in a place that only he would know. On the day of the competition, the antelope took aim and shot the arrow through the hole—thereby winning the throne. The leopard and the elephant failed because they relied solely on their might, whereas the antelope's flexible thinking was his true strength.

Flexible behavior is an adaptive response to dynamic environments. As challenges arise or opportunities shift, strategies must be updated in order to meet these changing demands. This chapter will focus on the cognitive mechanisms underlying flexible behavior, also known as cognitive flexibility. *Cognitive flexibility* is an individual's ability to adaptively select between known solutions and innovated or acquired novel solutions in response to relevant environmental changes (Laureiro-Martínez and Brusoni 2018; Pope 2018; Ueltzhöffer, Armbruster-Genç, and Fiebach 2015). In other words, cognitive flexibility is characterized by the contextually mediated optimal balance between repeating or returning to a familiar strategy and searching for or switching to an alternative, with suboptimal strategy-selection occurring as a result of either *inflexibility* (an inability to switch from one strategy to another) or *overflexibility* (an inability to maintain a working strategy).

Environments fluctuate predictably, with daily or seasonal cycles, as well as unpredictably, in response to stochastic events like earthquakes or cyclones. Moreover, an animal's lived environment is also a product of its local habitat, which may span multiple or even micro climates, and its ranging patterns, which might regularly extend into novel territory. Flexible behavior is especially important for long-lived, mobile species, like humans, who must cope with changing environments, both climatic and social, throughout their lifetimes (Dingemanse and Wolf 2010; Sol et al. 2016; van Schaik 2013; Vicente and Wang 1998). Indeed, humans exhibit an unprecedented degree of behavioral diversity (Fogarty, Creanza, and Feldman 2015; Hill, Barton, and Magdalena Hurtado 2009) that allows us, for better or for worse, to inhabit and modify over half of the Earth's landmass (Henrich and McElreath 2003; Vitousek et al. 1997), suggesting that, at least as a species, humans are quite capable of updating existing strategies to meet exogenous demands. However, on an individual level, humans' flexibility is not always evident.

Like the elephant and the leopard, humans are often blinded by familiar strategies or known solutions. In a classic example, children and adults who learned to solve a set of arithmetic "water jar" problems using a somewhat tedious four-step solution were later unable to replace this familiar strategy with a more efficient one-step alternative (Luchins 1942). Abraham Luchins tested thousands of Americans under various conditions and consistently found that people ignored the better alternative in favor of their learned strategy (Luchins 1942; Luchins and Luchins 1950). Termed *cognitive set*,¹ the propensity for familiar strategies to occlude other (even more efficient) alternatives has been demonstrated across a wide variety of contexts, including strategic reasoning (Bilalić, McLeod, and Gobet 2008), design and engineering (Chrysikou and Weisberg 2005; Jansson and Smith 1991), mathematics (Crooks and McNeil 2009; Lemaire and Leclère 2014; Wertheimer 1945), sequential problem-solving (Jacobson and Hopper 2019; Pope et al. 2015, 2019, 2020; Watzek, Pope, and Brosnan 2019), insight problem-solving (Hanus et al. 2011; Öllinger, Jones, and Knoblich 2008), and functional fixedness paradigms (Adamson 1952; Duncker and Lees 1945; German and Barrett 2005). This gives rise to a contradiction. On the one hand, humans are profoundly adaptive, the inventors and modifiers behind a technological revolution. On the other hand, we can be dismally conservative, either unwilling or unable to move beyond the tried and true. How is it that humans can be simultaneously flexible and inflexible? The answer lies in a different question altogether: *When do the benefits of being flexible exceed the costs?*

In this chapter, I begin by discussing the relative risks and benefits of repeating a current strategy versus switching to an alternative, while highlighting that the optimal balance

between the two is dependent on exogenous demands. Next, building on existing theories of human cognitive evolution, I propose the CFF for how variability, predictability, and harshness might work in concert with one another to shape cognitive flexibility.

Costs and Benefits of Staying, Switching, and Searching

Why Change Strategies?

Changing strategies is beneficial when an alternative strategy is better than the current strategy. Under *forced-switch conditions*, when a current strategy no longer works, a shift in goal or approach is clearly adaptive because the value of the current strategy has become zero. Switching that occurs in response to strategy failure, or even predicted failure, will be henceforth referred to as *responsive flexibility* (see also Tenpas, Schweinfurth, and Call, this volume, who describe individuals' *innovative* behavior and groups' *advancement*). Strategies can become temporarily or even permanently ineffective for a number of reasons. Capabilities, goals, and opportunities shift throughout development and in response to exogenous changes in the environment, like predation or other mortality risks, seasonal or spatial fluctuations in weather and resource availability, as well as downstream effects of climatic variability or anthropogenic disturbance. When a current strategy stops working, adaptive behavior might entail the discovery or innovation of a new technique or falling back on another known strategy. The majority of human cognitive flexibility research makes use of forced-switch metrics, wherein responsive flexibility, or rather inflexibility, is measured by the extent to which individuals persevere with an acquired strategy after it stops working (Doebel and Zelazo 2015; Meiran 2010; Monsell 2003; Sakai 2008; Zelazo 2004). Changing strategies under forced-switch conditions is considered an integral part of executive functioning, the suite of cognitive skills that regulate our thoughts and actions (Doebel and Zelazo 2015; Friedman et al. 2008; Miyake et al. 2000).

The other context in which flexible behavior can be beneficial is when a current strategy is or becomes less efficient than an alternative. Under *optional-switch conditions*, when a current strategy continues to work but alternatives are available, rather than avoiding failure, changing strategies can simply reduce inefficiency—but not always. Switching between known solutions or searching for new ones that occurs under optional-switch conditions will be henceforth referred to as *elective flexibility* (see also Tenpas, Schweinfurth, and Call, this volume, and their description of individuals' *creative* behavior and groups' *shifting*). Elective flexibility offers an important mechanism for understanding human ingenuity and cumulative culture, which necessarily builds on existing techniques. However, within psychology, flexibility under optional-switch conditions is rarely measured. Existing metrics include the water jar (described above) and other learned-sequence tasks (Luchins 1942; Luchins and Luchins 1950; Pope et al. 2020; Watzek, Pope, and Brosnan 2019) along with some task shifting (Ardiale and Lemaire 2012; Arrington and Logan 2004; Lemaire and Leclère 2014), token exchange (Hopper et al. 2011; van Leeuwen et al. 2013; van Leeuwen and Call 2017), and extractive foraging tasks (Davis et al. 2019; Jacobson and Hopper 2019; Price et al. 2009). However, the balance between exploiting useful strategies and exploring alternatives has been extensively studied within foraging (Charnov 1976; Cohen, McClure, and Yu 2007; Stephens and Krebs 1986) and decision-making research (Acuna and Schrater 2007;

Fischhoff and Broomell 2020; Gittins and Jones 1979; Payne, Bettman, and Johnson 1994; Peterson and Verstynen 2019), wherein it is measured using a range of reinforcement learning and sequential decision-making paradigms like patch-leaving and multiarmed bandit tasks (see Averbeck 2015 for a review). In optional-switch conditions, the benefit of selecting a better strategy is pitted against the computational and search efforts required to compare alternatives combined with the opportunity costs incurred by learning or switching delays.

Why Repeat a Strategy?

Failure to switch strategies occurs in many contexts and is not always maladaptive. In forced-switch conditions, *perseveration* is inflexibility arising from the continued use of a previously successful strategy, despite evidence that it no longer works (Floresco 2011; Schillemans 2011). Perseveration can be adaptive if the failure is transient or the causal mechanisms are unclear (i.e., the failure might have been a fluke). In optional-switch conditions, *conservatism* is the disinclination to explore or adopt novel strategies when a productive one is already known (Brosnan and Hopper 2014; Hrubesch, Preuschoft, and van Schaik 2009). When a familiar strategy still works, changing to another is only valuable if it leads to better outcomes. In other words, it would be maladaptive to switch if the chosen alternative was not more efficient than the current strategy—or if the efficiency benefit of the chosen alternative failed to exceed the time invested in finding, selecting, and honing it. Another benefit of inflexibility is that it can help maintain or refine useful strategies, reallocating the effort that might be spent searching toward skill practice and eventually specialization (Dingemans and Wolf 2013). Additionally, learning and maintaining a new strategy is neurologically expensive (Laughlin and Sejnowski 2003). It seems likely that repeating a strategy is an adaptive default approach, but one that should be deviated from when the benefits of finding an alternative exceed the costs (Duckworth 2010).

Elective Flexibility under Ambiguity

When the outcomes of all possible strategies are known, optimal behavior is simply a matter of switching to or maintaining the best one. However, we do not occupy nor have we evolved within unambiguous environments. Under conditions of uncertainty, the relative risks and rewards of potential strategies are often unclear. One could search for all possible strategies and test their payouts, but the time and effort spent gathering these data may quickly outweigh the benefit of using the better alternative, at least in the short-term. Heuristics, such as “always choose the second-cheapest wine” (McFadden, Machina, and Baron 1999), are guiding principles that support people’s decision-making under uncertainty, often by systematically ignoring some of the available information (Gigerenzer, Hertwig, and Pachur 2011). The computational requirements of perfect decision-making are immense, and heuristics can be useful cognitive shortcuts, but they lead to predictable biases and errors (Kahneman et al. 1982; Tversky and Kahneman 1974), especially when cognitive capacity is limited (Cash-Padgett and Hayden 2019). Behavior guided by heuristics is not often optimal, but on average, it should reach an acceptable level of efficiency, at least within the environment in which it was formed (Fawcett, Hamblin, and Giraldeau 2013). Under conditions of ambiguity, elective flexibility (i.e., the decision to either repeat a strategy or find or switch to another) is guided by heuristics that are, ideally, tuned to optimize decision-making in that environment

(Todd and Gigerenzer 2007; Vicente and Wang 1998). Thus, to understand how humans balance rigidity versus flexibility, we must first consider how exogenous pressures, like variability, predictability, and harshness, shape both responsive and elective flexibility.

The Constrained Flexibility Framework

When considering how exogenous forces shape cognitive flexibility, we can make use of existing hypotheses aimed at understanding the evolutionary origins of adaptive cognition (see box 9.1). The specific catalysts that gave rise to human cognition is a topic of considerable debate, but the most prominent hypotheses posit that our perhaps uniquely adaptive cognition was heavily influenced by environmental *variability*, the extent to which the environment changes over time or space; *predictability*, the temporal regularity of changes or the degree to which they are correlated; and *harshness*, which refers to exposure to factors that increase morbidity and mortality or the level of consequence elicited by strategy failure (Riotte-Lambert and Matthiopoulos 2020; Young, Frankenhuis, and Ellis 2020). The hypotheses described in box 9.1 offer important perspectives; however, they either conflate variability, predictability and harshness or consider their influence in isolation. Here, I propose that recognizing how variability, predictability, and harshness work in concert with one another to regulate responsive and elective flexibility is integral to predicting when strategies should be rigidly maintained or when they should be flexibly adjusted.

The CFF unifies existing hypotheses regarding the impacts of exogenous variability, predictability, and harshness on adaptive behavior, taking into account their unique and combined effects in order to predict the circumstances under which elective and responsive flexibility are most beneficial. Recall that responsive flexibility consists of switching as a result of strategy failure, and elective flexibility is switching that occurs despite already having a working strategy. Elective flexibility is risky, but here I argue that under certain circumstances, the adaptive benefit of potentially finding or innovating a better solution is enough to offset the costs. The CFF posits that (1) responsive flexibility is adaptive whenever failure is reliably detected or predicted, regardless of environmental variability or harshness, and (2) elective flexibility is suppressed in harsh, stable, or predictably variable environments but may be a valuable tool in unpredictable environments, so long as harshness is low.

Specifically, in stable environments, the usefulness of a strategy does not change over time, so responsive flexibility is not needed and elective flexibility is not pragmatic. Once an optimal strategy is found, there is little benefit derived from maintaining, using, or seeking alternatives. Thus, under stable conditions, both responsive and elective flexibility are maladaptive—and should be suppressed—so long as a good strategy can be maintained.

In variable environments, the usefulness of a strategy can either change regularly, as in predictably variable environments, or irregularly, as in unpredictably variable environments. In variable environments, regardless of harshness, responsive flexibility is critical for handling situations when a previously effective strategy stops (or will soon stop) working. However, the conditions that predict elective flexibility are more complex. In predictably variable environments, such as those governed by reliable seasonal changes, elective flexibility is not useful because even though optimal strategies rotate over time, the set of useful strategies is unchanged. Thus, cognitive resources should be devoted to detecting or predicting

when changes occur and to maintaining and honing one's repertoire of working strategies, rather than searching for alternatives. For example, to compensate for predictable traffic jams during rush hour, one might switch from a normal route to an alternate. This is an example of responsive flexibility between two known strategies.

In unpredictably variable environments, previous strategies may or may not work well or even at all. Here, increased elective flexibility might serve to minimize delays in updating to new optimal strategies or, in some cases, result in the discovery or innovation of a novel, more efficient technique. To elaborate on our driving example, if traffic patterns are unpredictable, perhaps because of frequent accidents, one may need to reroute at any

Box 9.1.

Hypotheses regarding Environmental Impacts on Adaptive Cognition

The idea that environmental challenges, such as variability, predictability, and harshness, act as major selection forces in shaping cognition is certainly not new. Many researchers have proposed a role of exogenous variation, or novelty, in cognitive evolution. For example, according to the *behavioral drive* hypothesis (Wyles, Kunkel, and Wilson 1983), expansion into novel habitats requires larger brains that are capable of handling the accompanying challenges, such as locating, identifying, and procuring unknown resources or avoiding risks that stem from novel climates, landscapes, and predators. And the *adaptive flexibility* hypothesis proposed that an initial period of high behavioral diversity is essential to adjusting to a novel habitat, with a subsequent decline as successful behavioral variants are honed (Wright et al. 2010).

Other hypotheses have focused on the role of encephalization in adaptive behavior. For instance, the *cognitive buffer* hypothesis (Allman, McLaughlin, and Hakeem 1993; Deaner, Barton, and van Schaik 2003) and the *brain size–environmental* hypothesis (Sol et al. 2005) suggest that increased cognitive capacity, supported by larger brains, acts as a buffer or as a means of handling changing environments. To support these claims, there is evidence that in primates, carnivorous mammals, and birds, neocortex size correlates with rates of innovative problem-solving (Benson-Amram et al. 2016; Lefebvre, Reader, and Sol 2004; Reader and Laland 2002; Reader and MacDonald 2003).

The role of harsh environments in promoting adaptive change (reviewed by van de Pol et al. 2017) is prominent in many well-known hypotheses aimed at understanding animal behavior and speciation, including *habitat theory* (Vrba 1992, 1995), the *savanna* hypothesis (Dart and Salmons 1925; deMenocal 1995), and *niche construction* (Odling-Smee 1988; also see Laland, Matthews, and Feldman 2016). For example, in the *necessity is the mother of invention* hypothesis (Laland and Reader 1999; Reader and Laland 2001), innovative adaptations are thought to only arise when needed. However, this stands in opposition to the *spare time* hypothesis, which suggests that innovation occurs in times of low stress because of the lower consequences of failure (Kummer and Goodall 1985).

Taking into account the role of environmental variation rather than just extremes, the *variability selection* hypothesis (Potts 1996) suggests that in response to fluctuations in temperature, aridity, and water abundance, early hominins developed a suite of cognitive traits that allowed them to not only move to more suitable environments but also develop flexible approaches to buffer local environmental instability (Grove 2011; see also Potts 2012; Boyd and Richerson 2005, 66–82; Richerson and Boyd 2013). And in support of this, through a combined analysis of paleoenvironmental and archaeological records of the last 5 million years, Richard Potts and J. Tyler Faith (2015) demonstrate considerable overlap between periods of high environmental variability and key behavioral adaptations and speciation events in the evolution of Hominins (see also Snell-Rood 2013).

point. Here, it is beneficial to have many alternative routes to select from. Elective flexibility, or trying alternatives before they are needed, serves to increase familiarity with available strategies. Thus, in unpredictably variable environments, elective flexibility minimizes search costs, allowing responsive flexibility to be more efficient.

Importantly, both predictably and unpredictably variable environments can exist partly or wholly in states of harshness, which places a penalty on elective flexibility commensurate with the severity of the consequences of failure. If you had an important meeting to get to, you should postpone trying an unknown route, which could result in significant delay, until conditions are more forgiving. By contrast, responsive flexibility is indifferent to harshness, as it only occurs when a previous strategy stops (or will soon stop) working, and thus no amount of harshness will outweigh the benefit of switching to or searching for an alternative. For example, if your normal route is suddenly impeded, it is better to use an alternative and risk delay than to not arrive at all.

The following sections will describe existing evidence supporting the CFF. See figure 9.1 for a graphic representation of these dynamics.

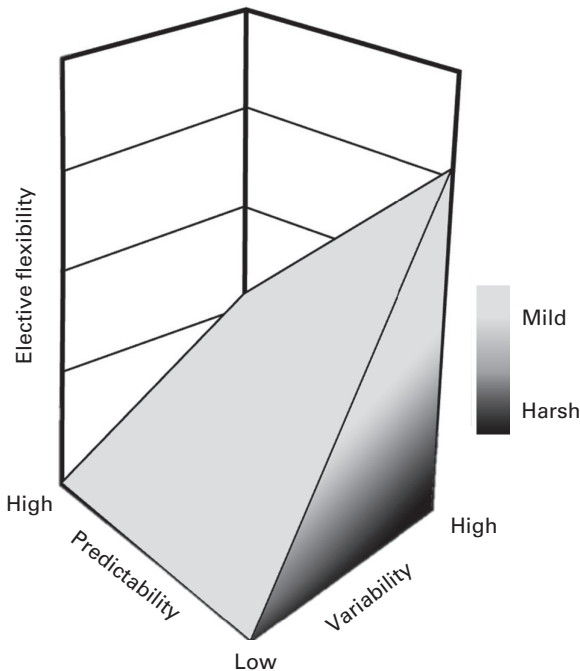


Figure 9.1

Putative impacts of variability, predictability, and harshness on elective flexibility as described by the CFF. The height of the object (z-axis) corresponds to the predicted likelihood of elective flexibility occurring. As variability increases (x-axis) from low to high or from stable to variable, elective flexibility also increases because the relative value of a current strategy is more likely to change. However, this effect is mediated by predictability (y-axis), such that unpredictable environments require more elective flexibility because the best strategy at any given point is unclear. In high-predictability environments, resources are better spent honing a repertoire of best strategies and recognizing when to switch between them. Harshness, which is indicated by gradient intensity, suppresses elective flexibility to limit the risk (and therefore the consequences) of failure at all levels of variability and predictability. *Source:* Provided by author.

The CFF and Cognitive Flexibility

In an uncertain and changing environment, where values of all potential options are unknown or the values of these options change over time, one must adapt by flexibly alternating between exploration and exploitation in order to maintain efficient performance over time and to keep track of the state of the environment (Addicott et al. 2017, 1932).

Predictable versus Unpredictable Environments

Both predictable and unpredictable variation are common in the natural world. Predictable variation can be seen in the many cycles that govern our climate on daily, monthly, and annual bases. Seasonal fluctuations, especially, might be drastic and require a range of behaviors throughout the year. However, seasonal transitions occur smoothly and predictably. Louise Riotte-Lambert and Jason Matthiopoulos (2020) suggest that when environmental predictability is high, learning and memory are advantageous because they allow existing strategies to be recalled and activated when needed, reducing the need for strategy search and its accompanying costs (also see Colwell 1974; Milton 1981). Indeed, several decision-making studies, which required participants to either exploit a current resource or explore alternatives, found increased exploratory behavior in response to unpredictable or stochastic, compared with stable, reward structures (Behrens et al. 2007; Meder et al. 2020; Navarro, Newell, and Schulze 2016; Speekenbrink and Konstantinidis 2015; Wu et al. 2021).

Even within mostly predictable environments, some volatility is inevitable. An analysis of the positional records of commercial fishing vessels showed that during a major disturbance, which resulted in the closure of the most-used fishing grounds, boats that had explored more waters during normal conditions outperformed their nonexploratory peers and were more likely to continue fishing despite the disturbance (O'Farrell et al. 2019). In other words, higher elective flexibility, or exploring alternatives before they were necessary, resulted in better responsive flexibility when the environment changed.

It seems likely that humans' susceptibility to cognitive set bias (as described briefly in this chapter's introduction section) might be the result of reduced elective flexibility that occurs when the context is—in these cases, inaccurately—considered to be fairly stable (Bilalić et al. 2008; Luchins 1942; Pope-Caldwell and Washburn 2022). In these studies, participants underexplored, and this seems to occur in humans' everyday lives as well. Following two days of public transportation strikes, an estimated 5 percent of London commuters, who had been forced to switch from their normal routes by station closures, did not return to their previous routes, which suggests that the need to search for an alternative strategy resulted in their finding a better one (Larcom, Rauch, and Willems 2017).

Inaccurate stability judgments may also help explain cross-cultural differences in humans' susceptibility to cognitive set. We (Pope et al. 2019) found that compared with their American study subjects, Namibian Himba participants were approximately four times more likely to use a more efficient “shortcut” strategy than Americans on a touch-screen task. It is possible that unfamiliarity with computer games led Himba participants to consider the game less predictable than their American counterparts. However, another intriguing possibility is that if decision-making heuristics are somewhat domain-general, unpredictability in other areas of the Himba participants' lives might have resulted in a lowered threshold for elective flex-

ibility. This possibility aligns with other research reporting that younger children exhibited increased exploration and elective flexibility compared with adolescents and adults (German and Defeyter 2000; Gopnik, Griffiths, and Lucas 2015; Pope et al. 2015). Indeed, young children may be more prone to trying alternatives as they are in a constant state of strategy acquisition, wherein predictive decision-making, based on reasoning and executive functioning, may still be out of reach (see Gopnik 2020; Ionescu 2017).

Harsh Environments

Elective flexibility is a valuable tool for handling environmental changes, especially those that are unpredictable, but it comes with a price. Searching for another strategy can take time and may result in failure. Even if a viable alternative is found, there are likely to be learning delays before it can be enacted, or else the attempts to learn it could fail. Finally, the net benefit of using the alternative strategy might be lower than the previous strategy, based on the time invested in finding, learning, and using it.

In harsh environments, the consequences of failure are high. This may be due to deficits in the quantity or quality of resources, increased risk of morbidity or mortality, decreased time or energy, or some combination of these factors. The CFF asserts that when the stakes are high, harshness places severe constraints on elective flexibility. For example, in a modified “water jar” paradigm, Sian L. Beilock and Maci S. Decaro (2007) found that participants with higher working memory were more likely to use the suboptimal four-step solution under conditions of high stress. Similarly, Wilson and colleagues (2014) found that humans decrease their information-seeking behavior when time horizons (the maximum number of choices or task duration) are short. Additionally, Bruno B. Averbeck (2015) reviews a number of decision-making tasks demonstrating that search is less beneficial when time horizons are short and the consequences of failure are high. Thus, only responsive flexibility should occur in harsh conditions and only when it is absolutely necessary.

It follows that strategy accumulation may be most beneficial in variable environments that are redundant exposed to harshness. Merideth A. Addicott and colleagues (2017) suggested that increased exploration and strategy accrual during periods of moderation, when the benefit of a possible alternative exceed the search costs, might result in useful backup strategies that could later be deployed during periods of harshness. They even expanded this idea to account for risky behavior during human adolescence, noting that it likely provides valuable information that can be used later in adulthood (Mata, Wilke, and Czienskowski 2013). For example, hunter-gatherer toolkits are significantly predicted by proxies for risk of resource failure, suggesting that the accumulation of more tools serves to buffer harshness (Collard, Kemery, and Banks 2005; Collard et al. 2011).

Thus, in alignment with the “necessity is the mother of invention” hypothesis (Laland and Reader 1999; Reader and Laland 2001), the CFF predicts that when no other options are available, responsive flexibility should kick in, even in harsh environments. However, consistent with the “spare time” hypothesis (Kummer and Goodall 1985), it notes that elective flexibility during periods of relative calm can also provide fitness benefits, even at later times. Elective flexibility is a powerful but costly tool. Next, we look at the ways in which the price of finding and flexibly adopting an alternative strategy can be mitigated.

Mitigating Costs of Flexibility

Optimizing Search Tactics

Flexibility, whether responsive or elective, often requires searching through potential alternatives. The hunt for a good alternative strategy can be guided by previous experience or the lack thereof, or it can be an unguided, random sampling. Generalizing from previous experiences decreases the risk of failure and, ideally, concentrates search efforts into most likely avenues; whereas directed exploration prioritizes the gathering of missing information with the aim of uncovering options that would be otherwise overlooked. Both generalization and directed exploration are computationally complex, requiring one to keep track of what is known and what is not known and to make step-by-step decisions about how to update and use this information each time a new path is sampled. Random exploration bypasses calculation costs but also misses the benefits of searching among alternatives that are more likely to be advantageous.

Humans' use of random versus directed exploration is strongly tied to age and context. Young children exhibit high rates of both random and directed exploration (Meder et al. 2020). Although random exploration declines sharply with age, children's directed exploration remains higher than adults' until at least 11 years of age (Schulz et al. 2019). In other words, children try to fill in missing pieces of information rather than explore options similar to their previously successful strategies. By adulthood, exploration is reduced, and generalization becomes a primary search tactic (Wu et al. 2018). One explanation for this trajectory is that random exploration is most useful when cognitive capacities are limited, such as in early childhood, but it is quickly replaced by more complex search tactics as the required calculations become cognitively feasible (Gopnik 2020; Gopnik et al. 2017). Search tactics are also tuned to context. For example, Robert C. Wilson and colleagues (2014) found that adults used directed exploration more than random exploration when they were given fewer decision opportunities, suggesting that when each decision carries more weight, adults capitalized on the less risky directed approach. Thus, selectively applying generalization and directed and random exploration to meet both endogenous and exogenous constraints can be a valuable tool for mitigating the costs of both responsive and elective flexibility.

Socially Acquired Strategies

In humans, perhaps the most prevalent means of reducing flexibility costs is by copying successful strategies from other individuals. Indeed, our ability to extract useful skills and information from social partners is thought to have shaped human life history, which seems tuned to benefit from cultural traditions (Kaplan et al. 2000; Richerson and Boyd 2020). Social learning is especially valuable when the costs of individual search are high. For example, studies find that learning from others is advantageous when the to-be-acquired technique is complex (Caldwell, Renner, and Atkinson 2017; Derex, Godelle, and Raymond 2013), and copying fidelity increases when actions are mechanistically or conceptually unclear, as is common when behaviors are guided by contextual or conventional constraints (Clegg and Legare 2016; Froese and Leavens 2014). Another consideration is the quality of the information that can be gleaned from others.

Socially acquired strategies are most beneficial when social partners' strategies are reliably successful. In other words, learning from others is only helpful when they have useful strategies to share (see Boyd and Richerson 2005, pt. 1, for an extended discussion). For example, children prefer to copy older, presumably more experienced, demonstrators when learning a novel technique (see Wood, Kendal, and Flynn 2013b whom do a review). Additionally, a recent interactive foraging study found that adults observed each other's foraging choices more when rewards were clumped and therefore predictive of other rewards in the area, rather than when they were randomly dispersed (Wu et al. 2021).

Humans often prioritize social information over individual learning, likely because the costs and benefits of individual exploration are often unknown and are therefore eclipsed by the low cost and known benefit of a socially acquired strategy. Yet, relying too heavily on social learning can be costly if the environment in which a strategy was originally formed has now changed (Boyd, Richerson, and Henrich 2011; Lehmann, Feldman, and Kaeuffer 2010) or if the learned strategy is itself suboptimal. Research on humans' proclivity for "over-imitation" finds that both children and adults incorporate even clearly irrelevant actions when copying a demonstrated technique, leading to marked inefficiencies (Haun, Rekers, and Tomasello 2014; Hoehl et al. 2019; Horner and Whiten 2005; McGuigan, Makinson, and Whiten 2011). Furthermore, Elizabeth Bonawitz and colleagues (2011) found that children who were explicitly taught how to play with a novel toy were far less likely to explore and discover untaught functions of the toy than naive peers. Thus, social learning can be an effective way to mitigate the costs of flexibility, but it is most adaptive when used in concert with individual learning (Acerbi and Parisi 2006; Boyd, Richerson, and Henrich 2011; Boyd and Richerson 1995; Legare and Nielsen 2015; Muthukrishna 2015; Muthukrishna et al. 2018; Wood et al. 2013a).

The value of social learning is also inextricable from one's social context more generally. Cultural factors and norms affect the extent to which social information is sought (Glowacki and Molleman 2017; Stengelin, Hepach, and Haun 2019, 2020; van Leeuwen et al. 2018) and how it is transmitted (Boyette and Hewlett 2017; Clegg et al. 2020; Kline 2017; Lew-Levy, Crittenden, et al. 2019; Lew-Levy, Kissler, et al. 2019). Conventions might also dictate the "best" strategy in a given circumstance, regardless of actual effectiveness (Keupp et al. 2015; Nielsen, Cucchiaro, and Mohamedally 2012). Switching strategies to match a group can result in positive social outcomes (Over and Carpenter 2013), whereas defecting from a common practice might have negative consequences for relationships or status (Watson-Jones et al. 2014). Thus, acquiring strategies through social learning comes with its own motivations and complications (see Tenpas, Schweinfurth, and Call, this volume, for a discussion on how the social environment biases cultural traits).

The CFF and Mitigating Costs of Flexibility

The CFF predicts that elective flexibility should be reduced when the consequences of failure are high. However, as described above, the costs of switching can be reduced under certain circumstances, sparking the question of whether the degree of harshness (and not just variability and predictability) in an environment predicts reliance on specific search tactics and socially acquired information. In a modeling study, Jesse Fenneman and Willem E. Frankenhuys (2020) found that higher impulsivity—choosing an action without

incurring the costs (or benefits) of sampling it beforehand—was most adaptive when resource quality was low and high but not moderate. One explanation is that when harshness is high, computationally difficult search tactics are too costly and therefore suppressed; and when harshness is low, the price of sampling alternatives does not outweigh, at least in their experimental design, the now-marginal benefits. But what about when sampling costs are eradicated? Social learning solves many of the problems of being flexible under harsh conditions. The risks of failure are low because a strategy's effectiveness is easily ascertained. In humans, teaching facilitates learning by reducing the time and energy required to pick up a new skill or technique (Caldwell, Renner, and Atkinson 2017; Csibra and Gergely 2011; Kline 2017). In effect, social learning may be the golden ticket to flexibly upgrading strategies, even in harsh environments—so long as the strategy itself is still useful (Nakahashi 2007; Richerson and Boyd 2020). Future research is needed to determine how and to what extent mitigating the costs of switching strategies supports the use of elective flexibility in harsh conditions.

Concluding Remarks

In reality, environments exist along a continuum—from stable to variable, predictable to unpredictable, mild to harsh. Humans occupy a range of ecological and cultural environments simultaneously, and the concepts of variability, predictability, and harshness depend on the domain and timescale being considered. This chapter has focused on cognitive flexibility as it occurs within an individual's lifetime. However, the CFF may also be useful in deciphering how the accumulation and modification of strategies and techniques evolve within populations in response to environmental pressures. Furthermore, exposure to environmental pressures is confounded by our behaviors, such as movement patterns or our ability to buffer variability—for example, niche construction (see Chevin and Hoffmann 2017 for a discussion). By differentiating between responsive flexibility (strategy changes that occur in response to failure) and elective flexibility (strategy changes that occur proactively), the CFF provides a theoretical basis for understanding how our species balances the need to rigidly maintain techniques that work with the potential risks and benefits of flexibly sampling alternatives.

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Note

1. Luchins (1942) referred to cognitive set as “*einstellung*.” Another common term is conservatism, which is the continued use of a strategy without consideration for alternatives (Brosnan and Hopper 2014; Davis et al. 2019; Hrubesch, Preuschhof, and van Schaik 2009).

References

- Acerbi, A., and D. Parisi. 2006. "Cultural Transmission between and within Generations." *Journal of Artificial Societies and Social Simulation* 9 (1): 1–16.
- Acuna, D., and P. Schrater. 2008. "Bayesian Modeling of Human Sequential Decision-Making on the Multi-Armed Bandit Problem." In Proceedings of the 30th annual conference of the cognitive science society (Vol. 100, pp. 200–300). Washington, DC: Cognitive Science Society.
- Adamson, R. E. 1952. "Functional Fixedness as Related to Problem Solving: A Repetition of Three Experiments." *Journal of Experimental Psychology* 44 (4): 288–291.
- Addicott, M. A., J. M. Pearson, M. M. Sweitzer, D. L. Barack, and M. L. Platt. 2017. "A Primer on Foraging and the Explore/Exploit Trade-Off for Psychiatry Research." *Neuropsychopharmacology* 42 (10): 1931–1939.
- Allman, J., T. McLaughlin, and A. Hakeem. 1993. "Brain Weight and Life-Span in Primate Species." *Proceedings of the National Academy of Sciences* 90 (1): 118–122.
- Ardiale, E., and P. Lemaire. 2012. "Within-Item Strategy Switching: An Age of Comparative Study in Adults." *Psychology and Aging* 27 (4): 1138–1151.
- Arrington, C. M., and G. D. Logan. 2004. "The Cost of Voluntary Task Switch." *Psychological Science* 15 (9): 610–615.
- Averbeck, B. B. 2015. "Theory of Choice in Bandit, Information Sampling and Foraging Tasks." *PLOS Computational Biology* 11 (3): 1–28.
- Behrens, T. E. J., M. W. Woolrich, M. E. Walton, and M. F. S. Rushworth. 2007. "Learning the Value of Information in an Uncertain World." *Nature Neuroscience* 10 (9): 1214–1221.
- Beilock, S. L., and M. S. DeCaro. 2007. "From Poor Performance to Success under Stress: Working Memory, Strategy Selection, and Mathematical Problem Solving under Pressure." *Journal of Experimental Psychology: Learning, Memory, and Cognition* 33 (6): 983–998.
- Benson-Amram, S., B. Dantzer, G. Stricker, E. M. Swanson, and K. E. Holekamp. 2016. "Brain Size Predicts Problem-Solving Ability in Mammalian Carnivores." *Proceedings of the National Academy of Sciences* 113 (9): 2532–2537.
- Bilalić, M., P. McLeod, and F. Gobet. 2008. "Why Good Thoughts Block Better Ones: The Mechanism of the Pernicious Einstellung (Set) Effect." *Cognition* 108 (3): 652–661.
- Bonawitz, E., P. Shafto, H. Gweon, N. D. Goodman, E. Spelke, and L. Schulz. 2011. "The Double-Edged Sword of Pedagogy: Instruction Limits Spontaneous Exploration and Discovery." *Cognition* 120 (3): 322–330.
- Boyd, R., and P. J. Richerson. 1995. "Why Does Culture Increase Human Adaptability?" *Ethology and Sociobiology* 16:125–143
- Boyd, R., and P. J. Richerson. 2005. *The Origin and Evolution of Cultures*. Oxford: Oxford University Press.
- Boyd, R., P. J. Richerson, and J. Henrich. 2011. "The Cultural Niche: Why Social Learning Is Essential for Human Adaptation." *Proceedings of the National Academy of Sciences* 108 (S2): 10918–10925.
- Boyette, A. H., and B. S. Hewlett. 2017. "Autonomy, Equality, and Teaching among Aka Foragers and Ngandu Farmers of the Congo Basin." *Human Nature* 28 (3): 289–322.
- Brosnan, S. F., and L. M. Hopper. 2014. "Psychological Limits on Animal Innovation." *Animal Behaviour* 92:325–332.
- Caldwell, C. A., E. Renner, and M. Atkinson. 2017. "Human Teaching and Cumulative Cultural Evolution." *Review of Philosophy and Psychology* 9:751–770.
- Cash-Padgett, T., and B. Hayden. 2019. "Overstaying in Patchy Foraging Can Be Explained by Behavioral Variability." *bioRxiv* (December): 868596.
- Charnov, E. L. 1976. "Optimal Foraging, the Marginal Value Theorem." *Theoretical Population Biology* 9 (2): 129–136.
- Chevin, L.-M., and A. A. Hoffmann. 2017. "Evolution of Phenotypic Plasticity in Extreme Environments." *Philosophical Transactions of the Royal Society B: Biological Sciences* 372 (1723): 20160138.
- Chrysiou, E. G., and R. W. Weisberg. 2005. "Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task." *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31 (5): 1134–1148.
- Clegg, J. M., and C. H. Legare. 2016. "Instrumental and Conventional Interpretations of Behavior Are Associated with Distinct Outcomes in Early Childhood." *Child Development* 87 (2): 527–542.
- Clegg, J. M., N. J. Wen, P. H. DeBaylo, A. Alcott, E. C. Keltner, and C. H. Legare. 2020. "Teaching through Collaboration: Flexibility and Diversity in Caregiver–Child Interaction across Cultures." *Child Development* 92 (1): e56–e75.

- Cohen, J. D., S. M. McClure, and A. J. Yu. 2007. "Should I Stay or Should I Go? How the Human Brain Manages the Trade-off between Exploitation and Exploration." *Philosophical Transactions of the Royal Society B: Biological Sciences* 362 (1481): 933–942.
- Collard, M., B. Buchanan, A. Ruttle, and M. J. O'Brien. 2011. "Niche Construction and the Toolkits of Hunter-Gatherers and Food Producers." *Biological Theory* 6 (3): 251–259.
- Collard, M., M. Kemery, and S. Banks. 2005. "Causes of Toolkit Variation among Hunter-Gatherers: A Test of Four Competing Hypotheses." *Canadian Journal of Archaeology* 29 (1): 1–19.
- Colwell, R. K. 1974. "Predictability, Constancy, and Contingency of Periodic Phenomena." *Ecology* 55 (5): 1148–1153.
- Crooks, N. M., and N. M. McNeil. 2009. "Increased Practice with 'Set' Problems Hinders Performance on the Water Jar Task." *Proceedings of the 31st Annual Conference of the Cognitive Science Society* 31:643–648.
- Csibra, G., and G. Gergely. 2011. "Natural Pedagogy as Evolutionary Adaptation." *Philosophical Transactions of the Royal Society B: Biological Sciences* 366 (1567): 1149–1157.
- Dart, R. 1925. "Australopithecus Africanus: The Man-Ape of South Africa." *Nature* 115: 195–199.
- Davis, S. J., S. J. Schapiro, S. P. Lambeth, L. A. Wood, and A. Whiten. 2019. "Behavioral Conservatism Is Linked to Complexity of Behavior in Chimpanzees (*Pan troglodytes*): Implications for Cognition and Cumulative Culture." *Journal of Comparative Psychology* 133 (1): 20.
- Deaner, R. O., R. A. Barton, and C. van Schaik. 2003. "Primate Brains and Life Histories: Renewing the Connection." In *Primates Life Histories and Socioecology*, edited by P. M. Kappeler and M. E. Pereira, 233–265. Chicago: University of Chicago Press.
- deMenocal, P. B. 1995. "Plio-Pleistocene African Climate." *Science* 270 (5233): 53–59.
- Dere, M., B. Godelle, and M. Raymond. 2013. "Social Learners Require Process Information to Outperform Individual Learners." *Evolution* 67 (3): 688–697.
- Dingemanse, N. J., and M. Wolf. 2010. "Recent Models for Adaptive Personality Differences: A Review." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365 (1560): 3947–3958.
- Dingemanse, N. J., and M. Wolf. 2013. "Between-Individual Differences in Behavioural Plasticity within Populations: Causes and Consequences." *Animal Behaviour* 85 (5): 1031–1039.
- Doebel, S., and P. D. Zelazo. 2015. "A Meta-Analysis of the Dimensional Change Card Sort: Implications for Developmental Theories and the Measurement of Executive Function in Children." *Developmental Review* 38: 241–268.
- Duckworth, R. A. 2010. "Evolution of Personality: Developmental Constraints on Behavioral Flexibility." *The Auk* 127 (4): 752–758.
- Duncker, K., and L. S. Lees. 1945. "On Problem-Solving." *Psychological Monographs* 58 (5): i–113.
- Fawcett, T. W., S. Hamblin, and L.-A. Giraldeau. 2013. "Exposing the Behavioral Gambit: The Evolution of Learning and Decision Rules." *Behavioral Ecology* 24 (1): 2–11.
- Fenneman, J., and W. E. Frankenhuis. 2020. "Is Impulsive Behavior Adaptive in Harsh and Unpredictable Environments? A Formal Model." *Evolution and Human Behavior* 41 (4): 261–273.
- Fischhoff, B., and S. B. Broomell. 2020. "Judgment and Decision Making." *Annual Review of Psychology* 71 (1): 331–355.
- Floresco, S. B. 2011. "Neural Circuits Underlying Behavioral Flexibility: Multiple Brain Regions Work Together to Adapt Behavior to a Changing Environment." Science brief, *Psychological Science Agenda* 25 (4): 1–8.
- Fogarty, L., N. Creanza, and M. W. Feldman. 2015. "Cultural Evolutionary Perspectives on Creativity and Human Innovation." *Trends in Ecology & Evolution* 30 (12): 736–754.
- Friedman, N. P., A. Miyake, S. E. Young, J. C. Defries, R. P. Corley, and J. K. Hewitt. 2008. "Individual Differences in Executive Functions Are Almost Entirely Genetic in Origin." *Journal of Experimental Psychology: General* 137 (2): 201–225.
- Froese, T., and D. A. Leavens. 2014. "The Direct Perception Hypothesis: Perceiving the Intention of Another's Action Hinders Its Precise Imitation." *Frontiers in Psychology* 5: 1–15.
- German, T. P., and H. C. Barrett. 2005. "Functional Fixedness in a Technologically Sparse Culture." *American Psychological Society* 16 (1): 1–4.
- German, T. P., and M. A. Defeyter. 2000. "Immunity to Functional Fixedness in Young Children." *Psychonomic Bulletin & Review* 7 (4): 707–712.
- Gigerenzer, G., R. Hertwig, and T. Pachur. 2011. *Heuristics: The Foundations of Adaptive Behavior*. Oxford: Oxford University Press.
- Gittins, J. C., and D. M. Jones. 1979. "A Dynamic Allocation Index for the Discounted Multiarmed Bandit Problem." *Biometrika* 66 (3): 561–565.

- Glowacki, L., and L. Molleman. 2017. "Subsistence Styles Shape Human Social Learning Strategies." *Nature Human Behaviour* 1 (5): 1–5.
- Gopnik, A. 2020. "Childhood as a Solution to Explore–Exploit Tensions." *Philosophical Transactions of the Royal Society B: Biological Sciences* 375 (1803): 20190502.
- Gopnik, A., S. O'Grady, C. G. Lucas, T. L. Griffiths, A. Wente, S. Bridgers, R. Aboody, et al. 2017. "Changes in Cognitive Flexibility and Hypothesis Search across Human Life History from Childhood to Adolescence to Adulthood." *Proceedings of the National Academy of Sciences* 114 (30): 7892–7899.
- Gopnik, A., T. L. Griffiths, and C. G. Lucas. 2015. "When Younger Learners Can Be Better (or at Least More Open-Minded) than Older Ones." *Current Directions in Psychological Science* 24 (2): 87–92.
- Grove, M. 2011. "Speciation, Diversity, and Mode 1 Technologies: The Impact of Variability Selection." *Journal of Human Evolution* 61 (3): 306–319.
- Hanus, D., N. Mendes, C. Tennie, and J. Call. 2011. "Comparing the Performances of Apes (*Gorilla gorilla*, *Pan troglodytes*, *Pongo pygmaeus*) and Human Children (*Homo sapiens*) in the Floating Peanut Task." *PLOS One* 6 (6): e19555–e19555.
- Haun, D. B. M., Y. Rekers, and M. Tomasello. 2014. "Children Conform to the Behavior of Peers; Other Great Apes Stick with What They Know." *Psychological Science* 25 (12): 2160–2167.
- Henrich, J., and R. McElreath. 2003. "The Evolution of Cultural Evolution." *Evolutionary Anthropology* 12 (3): 123–135.
- Hill, K., M. Barton, and A. Magdalena Hurtado. 2009. "The Emergence of Human Uniqueness: Characters Underlying Behavioral Modernity." *Evolutionary Anthropology* 18 (5): 187–200.
- Hoehl, S., S. Keupp, H. Schleihauf, N. McGuigan, D. Buttelmann, and A. Whiten. 2019. "'Over-Imitation': A Review and Appraisal of a Decade of Research." *Developmental Review* 51:90–108.
- Hopper, L. M., S. J. Schapiro, S. P. Lambeth, and S. F. Brosnan. 2011. "Chimpanzees Socially Maintained Food Preferences Indicate Both Conservatism and Conformity." *Animal Behaviour* 81 (6): 1195–1202.
- Horner, V., and A. Whiten. 2005. "Causal Knowledge and Imitation/Emulation Switching in Chimpanzees (*Pan troglodytes*) and Children (*Homo sapiens*)." *Animal Cognition* 8 (3): 164–181.
- Hrubesch, C., S. Preuschoft, and C. van Schaik. 2009. "Skill Mastery Inhibits Adoption of Observed Alternative Solutions among Chimpanzees (*Pan troglodytes*)." *Animal Cognition* 12 (2): 209–216.
- Ionescu, T. 2017. "The Variability-Stability-Flexibility Pattern: A Possible Key to Understanding the Flexibility of the Human Mind." *Review of General Psychology* 21 (2): 123–131.
- Jacobson, S. L., and L. M. Hopper. 2019. "Hardly Habitual: Chimpanzees and Gorillas Show Flexibility in Their Motor Responses When Presented with a Causally-Clear Task." *PeerJ* 7:e6195–e6195.
- Jansson, D. G., and S. M. Smith. 1991. "Design Fixation." *Design Studies* 12 (1): 3–11.
- Kahneman, D., S. P. Slovic, P. Slovic, and A. Tversky. 1982. *Judgment under Uncertainty: Heuristics and Biases*. Cambridge: Cambridge University Press.
- Kaplan, H., K. Hill, J. Lancaster, and A. Magdalena Hurtado. 2000. "A Theory of Human Life History Evolution: Diet, Intelligence, and Longevity." *Evolutionary Anthropology* 9 (4): 156–185.
- Keupp, S., T. Behne, J. Zachow, A. Kasbohm, and H. Rakoczy. 2015. "Over-Imitation Is Not Automatic: Context Sensitivity in Children's Overimitation and Action Interpretation of Causally Irrelevant Actions." *Journal of Experimental Child Psychology* 130:163–175.
- Kline, M. A. 2017. "Teach: An Ethogram-Based Method to Observe and Record Teaching Behavior." *Field Methods* 29 (3): 205–220.
- Kummer, H., and J. Goodall. 1985. "Conditions of Innovative Behavior in Primates." *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 308 (1135): 203–214.
- Laland, K., B. Matthews, and M. W. Feldman. 2016. "An Introduction to Niche Construction Theory." *Evolutionary Ecology* 30: 191–202.
- Laland, K. N., and S. M. Reader. 1999. "Foraging Innovation in the Guppy." *Animal Behaviour* 57:331–340.
- Larcom, S., F. Rauch, and T. Willems. 2017. "The Benefits of Forced Experimentation: Striking Evidence from the London Underground Network." *Quarterly Journal of Economics* 132 (4): 2019–2055.
- Laughlin, S. B., and T. J. Sejnowski. 2003. "Communication in Neuronal Networks." *Science* 301 (5641): 1870–1874.
- Laureiro-Martinez, D., and S. Brusoni. 2018. "Cognitive Flexibility and Adaptive Decision-Making: Evidence from a Laboratory Study of Expert Decision Makers." *Strategic Management Journal* 39 (4): 1031–1058.
- Lefebvre, L., S. M. Reader, and D. Sol. 2004. "Brains, Innovations and Evolution in Birds and Primates." *Brain, Behavior and Evolution* 63 (4): 233–246.

- Legare, C. H., and M. Nielsen. 2015. "Imitation and Innovation: The Dual Engines of Cultural Learning." *Trends in Cognitive Sciences* 19 (11): 688–699.
- Lehmann, L., M. W. Feldman, and R. Kaeuffer. 2010. "Cumulative Cultural Dynamics and the Coevolution of Cultural Innovation and Transmission: An ESS Model for Panmictic and Structured Populations: Evolution of Cumulative Culture." *Journal of Evolutionary Biology* 23 (11): 2356–2369.
- Lemaire, P., and M. Leclère. 2014. "Strategy Repetition in Young and Older Adults: A Study in Arithmetic." *Developmental Psychology* 50 (2): 460–468.
- Lew-Levy, S., A. N. Crittenden, A. H. Boyette, I. A. Mabulla, B. S. Hewlett, and M. E. Lamb. 2019. "Inter- and Intra-Cultural Variation in Learning-through-Participation among Hadza and BaYaka Forager Children and Adolescents from Tanzania and the Republic of Congo." *Journal of Psychology in Africa* 29 (4): 309–318.
- Lew-Levy, S., S. M. Kissler, A. H. Boyette, A. N. Crittenden, I. A. Mabulla, and B. S. Hewlett. 2019. "Who Teaches Children to Forage? Exploring the Primacy of Child-to-Child Teaching among Hadza and BaYaka Hunter-Gatherers of Tanzania and Congo." *Evolution and Human Behavior* 41 (1): 12–22.
- Luchins, A. S. 1942. "Mechanization of Problem Solving: The Effect of Einstellung." *Psychological Monographs* 54 (6): 1–95.
- Luchins, A. S., and E. H. Luchins. 1950. "New Experimental Attempts at Preventing Mechanization in Problem Solving." *Journal of General Psychology* 42:279–297.
- Mata, R., A. Wilke, and U. Czienskowski. 2013. "Foraging across the Life Span: Is There a Reduction in Exploration with Aging?" *Frontiers in Neuroscience* 7:1–7.
- McFadden, D., M. J. Machina, and J. Baron. 1999. "Rationality for Economists?" In *Elicitation of Preferences*, edited by B. Fischhoff and C. F. R. Manski, 73–110. Dordrecht: Springer.
- McGuigan, N., J. Makinson, and A. Whiten. 2011. "From Over-Imitation to Super-Copying: Adults Imitate Causally Irrelevant Aspects of Tool Use with Higher Fidelity than Young Children." *British Journal of Psychology* 102 (1): 1–18.
- Meder, B., C. M. Wu, E. Schulz, and A. Ruggeri. 2020. "Development of Directed and Random Exploration in Children." *Developmental Science* 24 (4): e13095.
- Meiran, N. 2010. "Task Switching: Mechanisms Underlying Rigid vs. Flexible Self-Control." In *Self Control in Society, Mind, and Brain*, edited by R. Hassin, K. Ochsner, and Y. Trope, 202–220. Oxford: Oxford University Press.
- Milton, K. 1981. "Distribution Patterns of Tropical Plant Foods as an Evolutionary Stimulus to Primate Mental Development." *American Anthropologist* 83 (3): 534–548.
- Miyake, A., N. P. Friedman, M. J. Emerson, A. H. Witzki, A. Howerter, and T. D. Wager. 2000. "The Unity and Diversity of Executive Functions and Their Contributions to Complex 'Frontal Lobe' Tasks: A Latent Variable Analysis." *Cognitive Psychology* 41 (1): 49–100.
- Monsell, S. 2003. "Task Switching." *Trends in Cognitive Sciences* 7 (3): 134–140.
- Muthukrishna, M. 2015. "The Cultural Brain Hypothesis and the Transmission and Evolution of Culture." PhD diss., University of British Columbia.
- Muthukrishna, M., M. Doebeli, M. Chudek, and J. Henrich. 2018. "The Cultural Brain Hypothesis: How Culture Drives Brain Expansion, Sociality, and Life History." *PLOS Computational Biology* 14 (11): 1–37.
- Nakahashi, W. 2007. "The Evolution of Conformist Transmission in Social Learning When the Environment Changes Periodically." *Theoretical Population Biology* 72 (1): 52–56.
- Navarro, D. J., B. R. Newell, and C. Schulze. 2016. "Learning and Choosing in an Uncertain World: An Investigation of the Explore–Exploit Dilemma in Static and Dynamic Environments." *Cognitive Psychology* 85 (March): 43–77.
- Nielsen, M., J. Cucchiari, and J. Mohamedally. 2012. "When the Transmission of Culture Is Child's Play." *PLOS One* 7 (3): e34066, 1–6.
- Ntamboudila, F. K. 2020. *The King of the Jungle*. Brazzaville, Republic of the Congo.
- Odling-Smee, F. J. 1988. "Niche Constructing Phenotypes." In *The Role of Behavior in Evolution*, edited by H. C. Plotkin, 73–132. Cambridge, MA: MIT Press.
- O'Farrell, S., J. N. Sanchirico, O. Spiegel, M. Depalle, A. C. Haynie, S. A. Murawski, L. Perruso, and A. Strelcheck. 2019. "Disturbance Modifies Payoffs in the Explore–Exploit Trade-Off." *Nature Communications* 10 (1): 3363.
- Öllinger, M., G. Jones, and G. Knoblich. 2008. "Investigating the Effect of Mental Set on Insight Problem Solving." *Experimental Psychology* 55 (4): 269–282.
- Over, H., and M. Carpenter. 2013. "The Social Side of Imitation." *Child Development Perspectives* 7 (1): 6–11.
- Payne, J. W., J. R. Bettman, and E. J. Johnson. 1993. *The Adaptive Decision Maker*. Cambridge University Press.

- Peterson, E., and T. Verstynen. 2019. "A Way around the Exploration-Exploitation Dilemma." *bioRxiv* (November): 671362.
- Pope, S. M. 2018. "Differences in Cognitive Flexibility within the Primate Lineage and across Human Cultures: When Learned Strategies Block Better Alternatives." PhD diss., Georgia State University.
- Pope, S. M., J. Fagot, A. Meguerditchian, D. A. Washburn, and W. D. Hopkins. 2019. "Enhanced Cognitive Flexibility in the Seminomadic Himba." *Journal of Cross-Cultural Psychology* 50 (1): 47–62.
- Pope, S. M., J. Fagot, A. Meguerditchian, J. Watzek, S. Lew-Levy, M. M. Autrey, and W. D. Hopkins. 2020. "Optional-Switch Cognitive Flexibility in Primates: Chimpanzees' (*Pan troglodytes*) Intermediate Susceptibility to Cognitive Set." *Journal of Comparative Psychology* 134 (1): 98–109.
- Pope, S. M., A. Meguerditchian, W. D. Hopkins, and J. Fagot. 2015. "Baboons (*Papio papio*), but Not Humans, Break Cognitive Set in a Visuomotor Task." *Animal Cognition* 18 (6): 1339–1346.
- Pope-Caldwell, S. M., and D. A. Washburn. 2022. "Overcoming Cognitive Set Bias Requires More than Seeing an Alternative Strategy." *Scientific Reports* 12 (1): 2179.
- Potts, R. 1996. "Evolution and Climate Variability." *Science* 273 (5277): 922–923.
- Potts, R. 2012. "Environmental and Behavioral Evidence Pertaining to the Evolution of Early Homo." *Current Anthropology* 53 (S6): S299–S317.
- Potts, R., and J. T. Faith. 2015. "Alternating High and Low Climate Variability: The Context of Natural Selection and Speciation in Plio-Pleistocene Hominin Evolution." *Journal of Human Evolution* 87:5–20.
- Price, E. E., S. P. Lambeth, S. J. Schapiro, and A. Whiten. 2009. "A Potent Effect of Observational Learning on Chimpanzee Tool Construction." *Proceedings of the Royal Society B: Biological Sciences* 276 (1671): 3377–3383.
- Reader, S. M., and K. N. Laland. 2001. "Primate Innovation: Sex, Age and Social Rank Differences." *International Journal of Primatology* 22 (5): 787–805.
- Reader, S. M., and K. N. Laland. 2002. "Social Intelligence, Innovation, and Enhanced Brain Size in Primates." *Proceedings of the National Academy of Sciences of the United States of America* 99 (7): 4436–4441.
- Reader, S. M., and K. MacDonald. 2003. "Environmental Variability and Primate Behavioural Flexibility." In *Animal Innovation*, edited by S. M. Reader and K. N. Laland, 83–116. Oxford: Oxford University Press.
- Richerson, P. J., and R. Boyd. 2013. "Rethinking Paleoanthropology: A World Queerer than We Supposed." In *Evolution of Mind, Brain, and Culture*, edited by Gary Hatfield and Holly Pittman, 263–302. Philadelphia: University of Pennsylvania Press.
- Richerson, P. J., and R. Boyd. 2020. "The Human Life History Is Adapted to Exploit the Adaptive Advantages of Culture." *Philosophical Transactions of the Royal Society B: Biological Sciences* 375 (1803): 20190498.
- Riotte-Lambert, L., and J. Matthiopoulos. 2020. "Environmental Predictability as a Cause and Consequence of Animal Movement." *Trends in Ecology & Evolution* 35 (2): 163–174.
- Sakai, K. 2008. "Task Set and Prefrontal Cortex." *Annual Review of Neuroscience* 31:219–245.
- Schaik, C. P. van. 2013. "The Costs and Benefits of Flexibility as an Expression of Behavioural Plasticity: A Primate Perspective." *Philosophical Transactions of the Royal Society B: Biological Sciences* 368 (1618): 20120339.
- Schillemans, V. 2011. "The Perseveration Effect in Individuals' Strategy Choices." PhD diss., KU Leuven.
- Schulz, E., C. M. Wu, A. Ruggeri, and B. Meder. 2019. "Searching for Rewards Like a Child Means Less Generalization and More Directed Exploration." *Psychological Science* 30 (11): 1561–1572.
- Snell-Rood, E. C. 2013. "An Overview of the Evolutionary Causes and Consequences of Behavioural Plasticity." *Animal Behaviour* 85 (5): 1004–1011.
- Sol, D., R. P. Duncan, T. M. Blackburn, P. Cassey, and L. Lefebvre. 2005. "Big Brains, Enhanced Cognition, and Response of Birds to Novel Environments." *Proceedings of the National Academy of Sciences* 102 (15): 5460–5465.
- Sol, D., F. Sayol, S. Ducatez, and L. Lefebvre. 2016. "The Life-History Basis of Behavioural Innovations." *Philosophical Transactions of the Royal Society B: Biological Sciences* 371 (1690): 20150187, 1–8.
- Speekenbrink, M., and E. Konstantinidis. 2015. "Uncertainty and Exploration in a Restless Bandit Problem." *Topics in Cognitive Science* 7 (2): 351–367.
- Stengelin, R., R. Hepach, and D. B. M. Haun. 2019. "Being Observed Increases Overimitation in Three Diverse Cultures." *Developmental Psychology* 55 (12): 2630–2636.
- Stengelin, R., R. Hepach, and D. B. M. Haun. 2020. "Cross-Cultural Variation in How Much, but Not Whether, Children Overimitate." *Journal of Experimental Child Psychology* 193:104796.
- Stephens, D. W., and J. R. Krebs. 1986. *Foraging Theory*. Princeton, NJ: Princeton University Press.

- Todd, P. M., and G. Gigerenzer. 2007. "Environments That Make Us Smart: Ecological Rationality." *Current Directions in Psychological Science* 16 (3): 167–171.
- Tversky, A., and D. Kahneman. 1974. "Judgment under Uncertainty: Heuristics and Biases." *Science* 185 (4157): 1124–1131.
- Ueltzhöffer, K., D. J. N. Armbruster-Genç, and C. J. Fiebach. 2015. "Stochastic Dynamics Underlying Cognitive Stability and Flexibility." *PLOS Computational Biology* 11 (6): e1004331.
- van de Pol, M., S. Jenouvrier, J. H. C. Cornelissen, and M. E. Visser. 2017. "Behavioural, Ecological and Evolutionary Responses to Extreme Climatic Events: Challenges and Directions." *Philosophical Transactions of the Royal Society B: Biological Sciences* 372 (1723): 20160134
- van Leeuwen, E. J. C., and J. Call. 2017. "Conservatism and 'Copy-If-Better' in Chimpanzees (*Pan troglodytes*)." *Animal Cognition* 20 (3): 575–579.
- van Leeuwen, E. J. C., E. Cohen, E. Collier-Baker, C. J. Rapold, M. Schäfer, S. Schütte, and D. B. M. Haun. 2018. "The Development of Human Social Learning across Seven Societies." *Nature Communications* 9 (1): 1–7.
- van Leeuwen, E. J. C., K. A. Cronin, S. Schütte, J. Call, and D. B. M. Haun. 2013. "Chimpanzees (*Pan troglodytes*) Flexibly Adjust Their Behaviour in Order to Maximize Payoffs, Not to Conform to Majorities." *PLOS One* 8 (11): 1–10.
- Vicente, K. J., and J. H. Wang. 1998. "An Ecological Theory of Expertise Effects in Memory Recall." *Psychological Review* 105 (1): 33–57.
- Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. "Human Domination of Earth's Ecosystems." *Science* 277 (5325): 494–499.
- Virba, E. S. 1992. "Mammals as a Key to Evolutionary Theory." *Journal of Mammalogy* 73 (1): 1–28.
- Virba, E. S. 1995. *Paleoclimate and Evolution, with Emphasis on Human Origins*. New Haven, CT: Yale University Press.
- Watson-Jones, R. E., C. H. Legare, H. Whitehouse, and J. M. Clegg. 2014. "Task-Specific Effects of Ostracism on Imitative Fidelity in Early Childhood." *Evolution and Human Behavior* 35 (3): 204–210.
- Watzek, J., S. M. Pope, and S. F. Brosnan. 2019. "Capuchin and Rhesus Monkeys but Not Humans Show Cognitive Flexibility in an Optional-Switch Task." *Scientific Reports* 9 (1): 1–10.
- Wertheimer, M. 1945. *Productive Thinking*. New York: Harper.
- Wilson, R. C., A. Geana, J. M. White, E. A. Ludvig, and J. D. Cohen. 2014. "Humans Use Directed and Random Exploration to Solve the Explore–Exploit Dilemma." *Journal of Experimental Psychology: General* 143 (6): 2074.
- Wilson, R. C., Y. K. Takahashi, G. Schoenbaum, and Y. Niv. 2014. "Orbitofrontal Cortex as a Cognitive Map of Task Space." *Neuron* 81 (2): 267–279.
- Wood, L. A., R. L. Kendal, and E. G. Flynn. 2013a. "Copy Me or Copy You? The Effect of Prior Experience on Social Learning." *Cognition* 127 (2): 203–213.
- Wood, L. A., R. L. Kendal, and E. G. Flynn. 2013b. "Whom Do Children Copy? Model-Based Biases in Social Learning." *Developmental Review* 33 (4): 341–356.
- Wright, T. F., J. R. Eberhard, E. A. Hobson, M. L. Avery, and M. A. Russello. 2010. "Behavioral Flexibility and Species Invasions: The Adaptive Flexibility Hypothesis." *Ethology Ecology & Evolution* 22 (4): 393–404.
- Wu, C. M., M. K. Ho, B. Kahl, C. Leuker, B. Meder, and R. H. J. M. Kurvers. 2021. "Specialization and Selective Social Attention Establishes the Balance between Individual and Social Learning." *bioRxiv* (2021): 2021–02.
- Wu, C. M., E. Schulz, M. Speekenbrink, J. D. Nelson, and B. Meder. 2018. "Generalization Guides Human Exploration in Vast Decision Spaces." *Nature Human Behaviour* 2 (12): 915–924.
- Wyles, J. S., J. G. Kunkel, and A. C. Wilson. 1983. "Birds, Behavior, and Anatomical Evolution." *Proceedings of the National Academy of Sciences* 80 (14): 4394–4397.
- Young, E. S., W. E. Frankenhuis, and B. J. Ellis. 2020. "Theory and Measurement of Environmental Unpredictability." *Evolution and Human Behavior* 41 (6): 550–556.
- Zelazo, P. D. 2004. "The Development of Conscious Control in Childhood." *Trends in Cognitive Sciences* 8 (1): 12–17.

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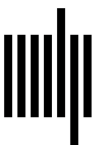
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