Review

Toddlers, Tools, and Tech: The Cognitive Ontogenesis of Innovation

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The development of tool innovation presents a paradox. How do humans have such diverse and complex technology, ranging from smartphones to aircraft, and yet young children find even simple tool innovation challenges, such as fashioning a hook to retrieve a basket from a tube, remarkably difficult? We propose that the solution to this paradox is the cognitive ontogenesis of tool innovation. Using a common measure of children's tool innovation, we describe how multiple cognitive mechanisms work in concert at each step of its process: recognizing the problem, generating appropriate solutions, and the social transmission of innovations. We discuss what the ontogeny of this skill tells us about cognitive and cultural evolution and provide recommendations for future research.

Highlights

Human culture is unparalleled in technological complexity, yet most children fail simple tool innovation challenges.

We explain how multiple cognitive mechanisms, including causal reasoning, problem solving, creativity, executive functions, and social learning work in concert to scaffold the development of tool innovation over childhood.

We describe the role these mechanisms play in three core steps of tool innovation; recognizing the problem, generating solutions, and the social transmission of innovations.

Using commonly used measures of children's tool innovation as examples, we detail the role each of these mechanisms plays in the development of tool innovation.

We show how understanding the cognitive ontogeny of innovation will help us understand cognitive and cultural evolution.

What Windmills Reveal about Cumulative Cultural Evolution

In 2002, in Masitala village, Malawi, 14-year-old William Kamkwamba[i] built an electricity-generating windmill from scrap materials to power his family's home. The windmill was created by modifying and combining a bicycle frame with plastic pipes to create a turbine. The turbine was attached to a wooden frame, such that when the wind blew a rubber belt turned, generating electricity via a dynamo. The electricity generated by the windmill powered the family radio and removed the need for kerosene, which provides more expensive, lower quality light. William had thus taken previous inventions and refined and adapted them to solve a problem. And he is not alone in his capacity for creating complex inventions for his age (Box 1). The 2019 winner of the Google Science Fair Introductory Meeting was Fionn Ferreira[ii], from Cork, Ireland, who, aged 18, invented a nonharmful method of extracting microplastics from water using vegetable oil and rust powder. The brilliance of these young people should not be overlooked. Most people could not build an electricity-generating windmill or a microplastic extractor, even if given ample materials and time.

This extraordinary capacity for **tool innovation** (see Glossary) is critical to human technological success. How do children acquire the ability to construct novel tools to solve problems? How does this skill develop over childhood? Our objective is to explain how the maturation of cognitive mechanisms operate in tandem with precocious social learning capacities to promote the development of tool **innovation**.

Tool Innovation and Cumulative Culture

Electric windmills and pollutant extractants are examples of **cumulative culture**: the accumulation of knowledge and skills in a way that increases the complexity and/or efficiency of technology over time [1–4]. Our capacity for cumulative culture has yielded complexity far beyond the capabilities of solitary brainpower and far more sophisticated and diverse than any other animal species. Innovation is a 'process that results in new or modified learned behavior and that introduces novel behavioral variants into a population's repertoire' [5]. Innovation thus has three components: (i) innovations should be something new, requiring at least some level of asocial learning; that is, individual learning which is largely devoid of direct social influence (although we

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Box 1. Coronavirus Disease 2019 (COVID-19): Topical Tool Innovation

The 2019 outbreak of the COVID-19 virus has had an unparalleled global impact. There have, however, been some remarkable and inspirational cases of tool innovation by young people in response to the pandemic that have benefited communities in ingenious ways. The examples here represent instances of young people inventing something novel, valuable, and widely adopted by others by building upon the products of previous technologies.

In Mukwa village, West Kenya, Stephen Wamukota[iii], aged 9, after learning that hand washing was crucial for stopping the virus spreading, designed a contactless hand washing device Stephen used wood, nails, and a bucket to create his hand washing device, with a pedal system. Two foot pedals allow members of his village to tip the bucket so water and soap flow on to their hands and thus avoid touching surfaces. Stephen created the device after learning construction techniques at school and several more such devices are being made for the village.

In Port-au-Prince, Haiti, Wens Dimanche[iv], aged 18, invented an electric-based contactless handwashing system for his local community using readily available objects from his neighborhood . Wens' device involves an electronic pedal linked to a bucket with a mechanical faucet, such that stepping on the pedal dispenses water through the faucet. The device is powered by a cell phone battery and the pedal can be removed for recharging. More devices are being constructed for the community.

In San Francisco, California, USA, Mizan Rupan-Tompkins[v], aged 12, developed a portable hook-shaped device named the 'Safe Touch Pro'. Made from germ-resistant, environmentally friendly plant-based plastic, the device can be 3D printed, be used to open doors, and touch, move, or pick up small objects, avoiding direct hand contact. At the time of writing, several hundred have been sold online.

In Herat, west Afghanistan, a team of adolescent women known as the 'Afghan Dreamers'[vi], aged 14–17, built a prototype mechanized ventilator using engine and battery parts from used cars and a motorcycle chain drive. Approved by researchers at MIT and Harvard University, the ventilators cost a fraction of the market price of commercially made ones and avoid the need for health workers to manually pump airbags. The Afghani government is supporting their mass-production.

note that for almost all innovations, individuals carry prior social information from their interactions with the world, which shapes our innovations [6,7]); (ii) innovations should be useful, they should solve new problems or increase the efficiency or complexity of current behaviors [6,8,9]; and (iii) innovations should be adopted and transmitted by others [8,9]. Innovations are thus the result of our collective knowledge, shaped by our sociality and capacity for faithful transmission [2,10].

Innovation can therefore be parsed into process (how) and product (why) based criteria (see also [5,6,11]), which, in unison, describe it in its entirety. Process-based criteria describe the process of acquiring and modifying knowledge from others, while product-based criteria describe the outcome or usefulness of an innovation to others. Thus, product-based criteria are indicators of the value of process-based ones.

Despite the accomplishments of the young inventors mentioned earlier, curiously, young children are markedly poor at solitary tool innovation. Over a dozen experiments have shown that when faced with comparatively simple tasks, such as needing to modify a pipe cleaner into a hook shape to retrieve a bucket from within a vertical tube, most children under 8 or 9 years will fail [12–14]. However, when shown how to succeed, even 4-year-old children show adult levels of success. How is it that humans can have such diverse and complex technology (smartphones, international travel, and biomedicine) and yet children find such simple innovation challenges so difficult? Understanding this requires understanding the cognitive foundations of tool innovation. Over childhood, children develop a remarkably sophisticated cognitive toolkit that allows them to navigate their complex physical and social environments (Box 2). This development is highly nuanced, as cognitive mechanisms mature at different trajectories and operate in concert to allow children to traverse the demands of our complex surroundings. And while this process is

Glossary

Attentional control: the capacity to control and sustain attention to goal-relevant stimuli and to ignore goal-irrelevant stimuli. Attentional control allows individuals to focus attention appropriately.

Causal reasoning: the capacity to logically infer cause and effect relationships. In the physical domain, causal reasoning allows children to understand spatial, temporal, and physical relationships between objects, including tools.

Cognitive flexibility: the capacity to flexibly adjust behavior in the face of environmental changes, by allowing individuals to switch between responses and strategies by disengaging from previously relevant information to attend to newly relevant information.

Creativity: the generation, but not implementation, of new ideas.

Cumulative culture: the accumulation of knowledge and skills in a way that increases the complexity, efficiency, and diversity of technology over time.

Executive functions (EFs): executive functions comprise attentional control, cognitive flexibility, inhibitory control, and working memory and allow us to achieve our goals by focusing attention, holding task aims in mind, switching between tasks, suppressing inappropriate behaviors, and planning.

Inhibition: the capacity to suppress a dominant or natural response or impulse to produce a more appropriate behavior.

Innovation: a process that results in new or modified learned behavior and that introduces novel behavioral variants into a population's repertoire.

Planning: the process of organizing a sequence of behaviors in a goal-directed manner and results from the coordination of executive functions. Planning involves sequencing future events and developing and carrying out plans.

Problem solving: generating solutions to problems in a goal-directed manner.

Social learning: learning resulting from the observation of, or interaction with, another individual or its products.

Social transmission: the transfer of behaviors or information between individuals.

Tool innovation: designing new tools, or using old tools in novel ways, to solve new problems.

unquestionably crucial to tool innovation, we still do not have an account of the cognitive ontogenesis of this skill.

Using the framework of cultural evolution, which aims to understand how culture changes over time [15], we detail the complex nature of the ontogeny of tool innovation; what is tool innovation and how it is measured? What is its developmental trajectory? Why is it such a difficult skill for children? We provide a theoretical account of how core cognitive mechanisms, including **executive functions (EFs)** (i.e., **working memory**, **attentional control**, **inhibition**, and **cognitive flexibility**), **planning**, **creativity**, **causal reasoning**, **problem solving**, and **social learning** work in concert during tool innovation. We discuss how the maturation of these mechanisms aids the development of tool innovation. We then consider what the ontogeny of tool innovation tells us about cognitive and cultural evolution and highlight future directions for research.

Working memory: a flexible memory system responsible for storing, organizing, and manipulating incoming information to facilitate goal-directed behaviors.

What Is Tool Innovation and How Is It Measured?

Tool innovation, a type of broader innovation, is designing new tools, or using old tools in novel ways, to solve problems [16] and is particularly crucial to cumulative technological progress. The pervasiveness of human tool use is unmatched in the animal kingdom [17] and our propensity for tool use means we are constantly altering our physical and social environments [18]. We have the most varied, complex, and intricate cultural technology on the planet: the smartphones we use, the airplanes that transport us around the globe, and the medicines that cure us of countless ailments are all products of innovations that have built upon previous iterations and which have been socially disseminated. Our capacity for tool innovation has set us along an evolutionary trajectory unique among other animals.

The process of tool innovation can be separated into three main steps. The first two steps, recognizing and solving a problem, are process-based criteria (how). The first step is to recognize the problem and goal. One must recognize and understand that they need to solve, and indeed

Box 2. Domain Specificity of Innovation?

Humans innovate in many domains: music, art, dance, play, folktales, and language. How similar is the ontogeny of innovation across domains? There are several important factors likely to shape the development of innovation in different contexts. Differences in expectations to conform to others, complexity, and learning opportunities are likely to impact children's expression of innovation across domains.

Different domains are associated with different expectations to conform. For instance, conformity to established rituals and religious practices is generally encouraged, reducing children's opportunities to innovate in these domains [85]. Acquiring social conventions requires faithful copying of group members because they lack overt causal information regarding bridging the goal and performed action. Rates of children's innovation for social conventions are lower than for instrumental (physical) tasks. Key to the latter is the functional end goal, rather than the precise way a behavior should be produced [1]. The difference in causal opacity between domains is an important predictor of children's propensity to innovate.

The amount of learning time required and the complexity of a domain can also impact the developmental trajectories of innovation. Children as young as 3 or 4 years can show impressive displays of creativity and innovation during free play [86], whereas innovation capacities in domains such as music, dance, or language develop comparatively later, often into adolescence [87]. The process of innovation often involves acquiring and modifying knowledge from others. These latter domains require a significant knowledge base before individuals understand the space sufficiently enough for innovation to occur. With increased experience, we are better equipped to innovate in complex domains.

An important next step is to systematically examine whether children's innovative capacities transfer across diverse domains. Are, for example, children who are particularly innovative in play also innovative with tools or music? Is the impact of socialization practices on the development of innovation similar across domains? Further research of this kind is key to our understanding of the cognitive ontogeny of innovation.

are capable of solving, a new problem. Second, one must develop an appropriate solution. Tool innovation requires using available materials and knowledge to construct effective tools. The third step is the **social transmission** of innovations. Successful transmission of an innovation to others, a product-based criterion (why), is an indicator of its value and is crucial to the diversification of cultural technology.

The past decade has seen a large upturn in studies examining the ontogeny of tool innovation. Individual problem-solving paradigms are typically used, whereby children are presented with novel tasks and materials, which require using and/or making tools to retrieve a reward. Examples include forming a loop from wool to retrieve a reward-baited platform [4] or requiring using cups of water to fill a tube to raise a floating toy within reach [19,20]. The most commonly used measure is the hook task (Figure 1), whereby children are presented with a narrow transparent tube containing a bucket that holds a reward. Alongside the tube are a straight pipe cleaner and a nonfunctional distractor item (typically a piece of string). Success is normally defined as manufacturing one end of the pipe cleaner into a hook shape to 'fish' the bucket from within the tube to obtain the reward [13,16,21,22].

What Is the Developmental Trajectory of Tool Innovation?

Given the unparalleled complexity and pervasiveness of human tools, one might expect that children would have precocious tool innovation capacities. From a very young age, children are proficient at highly complex behaviors, including imitating others, acquiring language, and learning through exploration [23,24]. Young children are strikingly poor at tool innovation, however. Less than 10% of children under 5 years and less than half of 7-year-olds are successful on the hook task [12–14,20,25,26]. It is not until around 8–9 years of age when over half of children can solve the hook task [1,13,27,28] and only at early adolescence do children begin to approach ceiling levels [13,25]. Importantly, these findings appear to be universal. Research with diverse populations has shown that young children consistently struggle on the hook task [14,25–28] (Box 3), as well as other tool innovation challenges involving different actions and tool types [28–30]. This suggests that population differences in exposure to premanufactured toys and tools or social norms alone cannot explain the trajectory of tool innovation abilities [14]. Tools are essential to the daily lives of all human cultures and even 2-year-olds are capable tool users [31] [32] and can select appropriate tools during independent problem solving [33]. And yet over 90% of 5-year-olds will fail to shape a pipe cleaner into a hook to retrieve a reward. These findings evoke critical and as yet unanswered questions about the ontogeny of tool innovation. Why is it that humans are so renowned for our tool use and innovative abilities, yet it is such an effortful and late-developing skill in children?

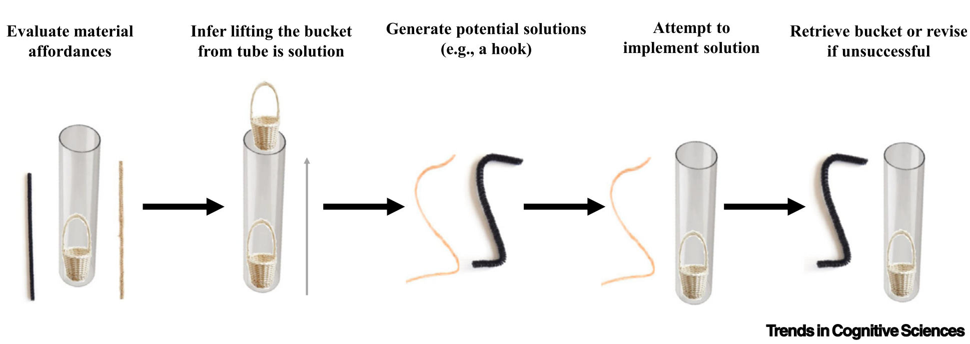

Figure 1. Example of the Hook Task.

Box 3. The Development of Tool Innovation Across Cultures

Research from a growing number of populations has shown that, universally, young children find tool innovation challenging. The hook task has been administered to children from diverse populations (including urban and rural locations) such as the USA, UK, France, Germany, Turkey, Serbia, South Africa, Vanuatu, Australia, and New Zealand, with broadly comparable findings; young children are similarly unsuccessful [13,25–27,35,44,88]. Yet, for most of these populations (outside of the UK and USA), the developmental trajectories of tool innovation beyond the age of 5 years are unknown. There are multiple reasons to believe that the trajectories of tool innovation may vary over childhood across different populations. These include (but are not exclusive to) cultural differences in attitudes to conformity, exposure to education, motivation, and developmental adversity.

Attitudes towards conformity differ substantially between populations. For instance, adults from the USA are less likely to describe children who conform as intelligent and well-behaved compared with adults from Vanuatu, a Melanesian archipelago relatively isolated from Western influence [72]. In general, individualism encourages independence and creativity, whereas collectivism encourages social conformity and cooperation [89], which may lead to cultural differences in the development of tool innovation.

Exposure to formal education may shape children's capacity for tool innovation. Children may learn practical skills useful for tool innovation in school (see Stephen Wamukota, Box 1). Moreover, a significant body of work has shown that cognitive mechanisms important to tool innovation, such as EFs, are positively impacted by schooling, to the extent that they improve more during school term time than during school vacations [90]. Cultural differences in educational focus on creativity and experimentation versus holistic thinking and rote learning are also likely to promote cultural differences in innovation [91].

Finally, differences in developmental adversity may also impact childhood innovative capacities. Limited resource access, higher mortality rates, and poverty may foster the ability to generate unconventional ideas [92]. In one pertinent example, Bolivian transient children displayed higher creativity than socioeconomic status-matched children living with their parents, possibly resulting from these children having more experiences in which they needed to generate novel ideas and solutions to solve problems and greater motivation to do so [93]. Exposure to childhood psychological adversity may thus shape cognitive development [94].

While research has analyzed the conceptual nature of tool innovation tasks [16,34], the methodological specifics [20,27,35], children's prior experience with materials [20,21], and the testing context [22], there has been very little investigation (empirical or theoretical) into how the development of core cognitive mechanisms promotes age-related improvements in tool innovation capacities. Studies that have, however, suggest the findings are inconclusive. Although small samples sizes prohibit firm conclusions, these studies provide a starting point for scientists to consider how the development of specific cognitive mechanisms shape tool innovation capacities over childhood [36].

Which Cognitive Mechanisms Support the Development of Tool Innovation?

The development of multiple cognitive mechanisms coincides with the age-related improvements in tool innovation, providing a useful point of departure for investigation. These include causal reasoning, planning, problem solving, creativity, EFs, and social learning. Each of these facilitate our ability to flexibly complete goal-directed behaviors and continue to develop into adolescence, when children can consistently master tool innovation challenges. We next describe three steps of tool innovation and the cognitive resources required for each (Figure 2). We use the hook task as a specific example because of its popularity in the assessment of children's tool innovation.

Recognize the Problem

For children to recognize and understand that they need to and can solve a new problem, they first must understand the value of the solution to themselves and potentially to others. Although innovation is not always motivated by an explicit desire to develop something valuable to others, those that are developed with others in mind tend to be transmitted and maintained [10]. William recognized that his family needed power (his father relied on radio weather forecasts

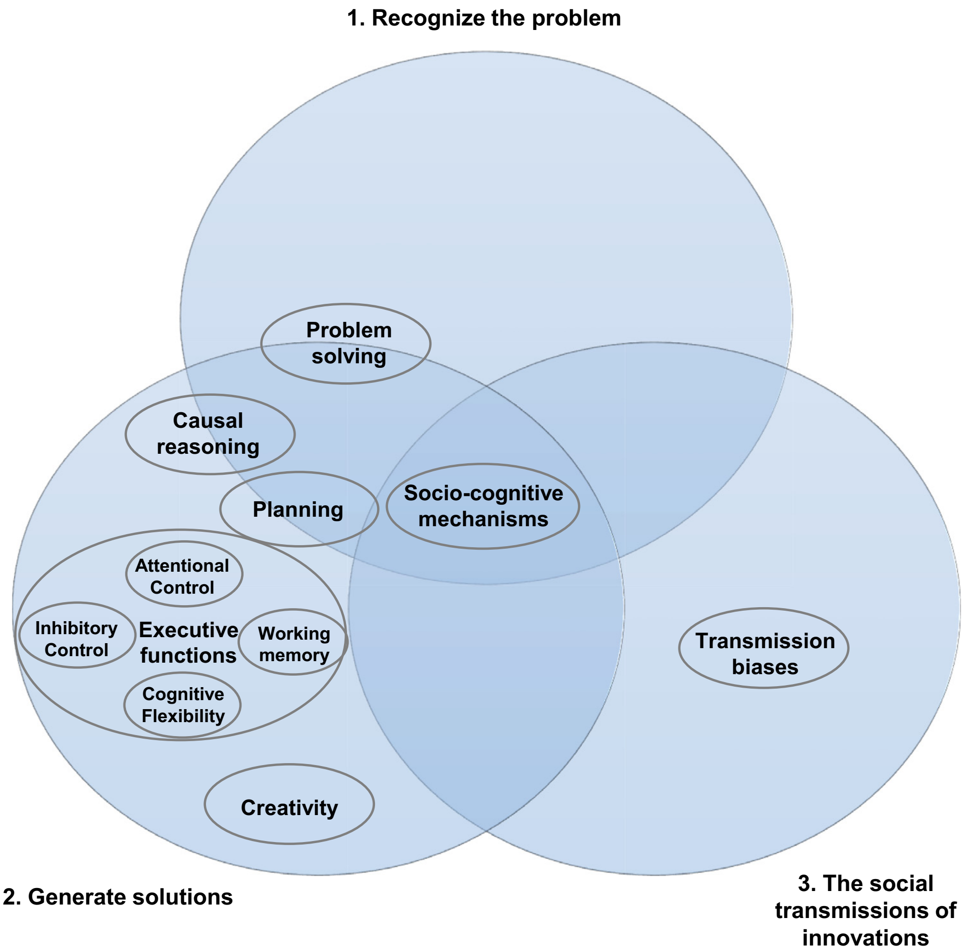

Figure 2. The Three Steps of Tool Innovation and Their Associated Cognitive Mechanisms. Mechanisms positioned over multiple steps indicates their overlapping contribution. Steps 1 and 2 reflect how innovations occur (process-based criteria) and steps 3 reflects why they occur (product-based criteria).

to harvest his crops) and that discarded materials in his village could be used to build a device. Children must next identify the task parameters and goals, the causal affordances of the materials, and the associations between them [34]. That is, based on materials present, children must understand the features and framework of the task. Using the hook task example, children must understand the intent of the experimenter (i.e., that they should solve the task). Next, they must identify that the bucket should be extracted, but it cannot be reached by hand.

These steps require causal reasoning and some conceptual understanding of problem solving. These mechanisms develop early; infants show surprise if expectations about causal events are violated [37] and preschool children can make predictions and explanations based on causal relations [38–40]. By 2 years, children can combine knowledge regarding required physical contact between tools in problem-solving tasks [33]. This early understanding of basic causal affordances and problem-solving contexts explains why children as young as 4 years can select a hooked pipe cleaner over a non-hooked one [13,21,27] and will easily solve the hook task after witnessing a demonstration [13].

Generate Solutions

Once children have understood the problem, they must derive the appropriate solution. Children must infer how the materials can be reconstructed into efficacious tools. William understood that if wind turned the blades, he could use a bicycle dynamo to harness the power the wind generated. This is likely to be the most cognitively demanding step in the tool innovation process: children find generating novel solutions remarkably different. Our brains have evolved to acquire information from our social environments and our cognitive prowess is in no small part dependent upon our capacity to learn from others [10,41]. Children are skilled at acquiring complex behaviors through social learning. When provisioned with a single demonstration of the hook task, 4-year-old children match the performance of adults [13]. Our psychological toolkit means children are well prepared to socially acquire behaviors.

When faced with innovation challenges, depending on the problem, success may mean creating a novel tool or using a familiar tool in a novel way, either of which may entail using familiar or unfamiliar materials. In the hook task, children must first infer that the solution is to lift the bucket out of the tube and that one or both of the materials (string and pipe cleaner) are appropriate for inserting into the tube for success. Children may have a direct causal understanding of the materials provided from prior experiences (i.e., that the pipe cleaner is malleable but sturdy enough to support the bucket, but the string is not sturdy enough), or may acquire this through exploration or trial and error. Exploration or trial and error can lead to perseveration errors (e.g., constantly using the string) and children are known to persevere with initial tool-use strategies even when they are ineffective [42]. If children initially use the string, they need to inhibit persevering with this method to switch strategies to use the pipe cleaner. Similarly, having prior experience with the materials may require overcoming functional fixedness (such as being unable to envisage using a pipe cleaner for a hook because it should be used for crafts [43]). If children can overcome these biases, they must derive the correct solution (a hook) and fish the reward out of the tube.

While children may have a working understanding of the causal basis of the task and materials, there are steps here that young children may not be cognitively equipped for. Generating novel tools and solutions such as a hook requires creativity and attentional control. Creativity facilitates the generation of new tool-use ideas and is linked to hook task performance [44], while attentional control optimizes the solution search space, which is important for optimal creativity [45]. Planning steps in advance may help mitigate becoming stuck on ineffective strategies by allowing children to envisage potential issues [46]. Each of these mechanisms, creativity, attentional control, and planning, continue to develop into late childhood: creativity improves linearly with age into adolescence [47], while it is not until 9–11 years that children are capable of selectively attending to appropriate stimuli (and filtering irrelevant stimuli) at mature levels [48]. Similarly, the vast majority of 4–5-year-old children fail on a three-step advanced planning task [49] and have difficulties planning strategies involving intermediate (indirect) steps [46]. By 9–10 years, however, children are capable of multistep, complex planning [49].

Throughout the problem-solving process, children must also hold in mind task rules and goals and ignore distractions, while simultaneously selecting, switching, or refining strategies based on online feedback. If an initial strategy is unsuccessful (i.e., using the string), children must inhibit the inclination to persevere on this strategy and instead must refine or switch their strategy until they arrive on a solution [12]. Developing solutions requires planning; switching strategies involves both inhibitory control and cognitive flexibility to relinquish a current behavior in favor of an alternative one [50,51]. Concurrently, working memory is needed to hold task rules and goals in mind whilst updating existing information based on online feedback [52].

These mechanisms, attentional control, inhibition, working memory, and cognitive flexibility, comprise EFs. The development of EFs is complex and protracted. EFs generally are not dissociable until mid-childhood [53,54] and young children perform poorly on individual EF measures. For instance, children under 4 or 5 years find switching from one rule to another difficult, even when instructed to do so [50,55], show poor inhibitory control, and limited working memory capacity [56]. By around 7 to 8 years, EFs become dissociable and performance markedly improves [50,54,56]. By late childhood and early adolescence, the structure of EFs is well established and they routinely work in concert collectively to hold task goals in mind, flexibly shift between strategies, inhibit and ignore irrelevant actions [56,57], and provide control to achieve specific goals [58]. EFs are inextricably linked with problem-solving skills, allowing individuals to execute plans, follow rules, and inhibit inappropriate responses [49,56], which closely match the skills required for tool innovation.

Thus, mechanisms such as creativity, planning, and EFs are required to work in concert to traverse the complex goal of deriving tool innovation solutions. As the capacity of these cognitive mechanisms enhances over childhood, so too does tool innovation performance.

The Social Transmission of Innovations

The third step of the innovation process is the social transmission of innovations, which is key to why (rather than how) innovations occur. The uptake of an innovation is an indicator of its value and its contribution to a population's existing technological repertoires. The transmission of innovations has important cultural and evolutionary implications [2,59]. Multiple windmills were soon developed in William's village based on his prototype, providing much of the power his village needed for lightbulbs, radios, and cellphones. Innovations solve critical problems, provide more efficient solutions, and in some cases, develop transformative technologies with major adaptive benefits. The global spread of medicine and smartphone technology has changed the way we live. In this way, the transmission of innovations is fundamental to cumulative cultural evolution.

Children are highly skilled at socially acquiring and transmitting cultural innovations [60]. Their associations with caregivers, family members, and peers promote the transmission of culture-specific skills and beliefs [41]. As noted, after a single observation of the hook task solution, young children reach adult success levels. Transmission chain studies, in which experimentally seeded behaviors are transmitted along chains of individuals, have shown that 2-year-olds will faithfully maintain puzzlebox solutions along multiple 'generations' [61,62]. Groups of 4- and 5-year-old children can establish shared innovations to solve simple tasks through social transmission, with some children then cumulatively building on these to generate more complex innovations for greater rewards [63]. Children's collective knowledge is fundamental to their cultural learning.

A suite of cognitive mechanisms supports cultural transmission. Imitation is fundamental to preserving innovations, but humans' unique capacities for prosociality, language, and teaching are also critical to the transmission of innovations [64,65]. Together, these mechanisms ensure that individuals are motivated to understand and solve others' problems and facilitate frequent and efficient transfer of information, both of which foster effective cultural transmission. Children have a range of cognitive biases that support cultural learning, including preferentially copying similar, older, experienced, and prestigious others and a propensity for conformity ('who' biases) and preferentially copying in certain contexts ('when' biases) [66]. These biases are adaptive, allowing children to rapidly learn relevant information from their social niches. Our 'collective brains' have evolved for cultural transmission and our shared cognitive resources support the cycle of the generation and transmission of innovations, thus repeatedly increasing our technological complexity and diversity beyond the capabilities of solitary brainpower [10].

What Does the Development of Tool Innovation Tell Us about Cognitive and Cultural Evolution?

What can we learn about the development of the human mind from the development of tool innovation? How did human tool use become so extraordinary among species? To answer this, we return to William. Aged 14, William adopted and modified others' innovations to create electricity. This may be a rarefied example, but it is this skill, the capacity to learn from others' products through our suite of social learning capacities and modify them to increase complexity or efficiency, that is uniquely human and the reason we have such advanced, diverse, and pervasive technology.

Studying the development of tool innovation informs us of the ontogeny of the unique qualities of human cultural evolution. From birth we are well equipped to learn from others. Children as young as 2 or 3 years can be multilingual and manage smartphones with ease. Four-year-old children need just one demonstration of the hook task solution before they can freely reproduce it, a behavior that some 11-year-olds would not innovate individually. As our tool innovation capacity develops, we combine this skill with our exceptional capacity for imitation. The result is instances such as William's invention of electricity-generating windmills.

Studying the ontogeny of tool innovation also reveals that we are deeply embedded in our social environments. Almost everything we interact with, from ideas to artifacts, are the product of others' minds [67]. Innovations are the result of our social surroundings; our ideas, beliefs, and customs are shaped by our social environment and human collaboration is fundamental to cultural evolution [10]. Our social worlds are central to the ontogeny of tool innovation [64]. Children are collaborative learners and peer learning is crucial for acquiring behaviors and skills more efficiently compared with individually, including tool use [62]. Dyadic interaction improves tool-based problem solving capacities beyond those of individual solving [68,69], including on the hook task [44].

Finally, the ontogeny of tool innovation also tells us what constraints the developing mind faces. The universal consistency of young children's difficulties with tool innovation across vastly different experiences with tools, norms, education, and physical environments shows that tool innovation is a uniquely difficult task requiring significant cognitive resources. Tool innovation also presents challenges. It can be time-consuming and risky [70] and in contexts of high risk, complexity, and uncertainty, children are less likely to rely on individual learning [66,71]. By contrast, young children in all cultures readily engage in high-fidelity copying [72–76], which allows them to rapidly acquire complex skills and to assimilate within their social environments [77]. The cognitive infrastructure supporting social learning is in place early, laying the foundation for the development of tool innovation over childhood. Tool innovation is a skill that requires the synchronized maturation of diverse cognitive mechanisms, as well as social learning, to foster. Given its importance to cumulative culture, perhaps it is not surprising that our brains need substantial time to build this skill.

Concluding Remarks

Humans stand alone in their technological complexity, which is the product of our ability to learn from, modify, and improve others' innovations. Yet we still do not understand why a 4-year-old year child can master multiple languages or an iPad but a nontrivial number of 10-year-olds cannot shape a pipe cleaner into a hook to retrieve a reward. We propose that a full

Outstanding Questions

Can we comprehensively measure how the development of cognitive mechanisms shapes the capacity for tool innovation over childhood? How do individual differences in performance on measures of cognitive mechanisms map onto individual differences in tool innovation performance?

Is tool innovation performance repeatable across time and contexts? Do children show generalizability of tool innovation across diverse measures of tool innovation?

Is there cultural variation in innovation? What experiences explain this variation?

To what extent can tool innovation be taught? How will the globalization of formal education impact tool innovation performance?

Does collaboration improve innovation? If so, what are the socio-cognitive mechanisms involved?

Are there different types of tool innovation? Are innovations unique to the individual separable from innovations unique to populations?

Is innovation domain specific or domain general?

understanding of the ontogeny of tool innovation requires a comprehensive and systematic examination, using convergence across tasks, of how the maturation of cognitive mechanisms scaffolds the development of tool innovation. Tool innovation is a multistep process and each step imparts different cognitive demands. Problem solving, planning, social cognition, and causal reasoning allow children to recognize and understand problems requiring tool innovation. The development of these mechanisms, and others such as EFs, creativity, and social learning, converge with age-related improvements in the ability to generate and implement appropriate solutions to tool innovation tasks. Social transmission of innovations is key to cumulative technological development and children exhibit a range of transmission biases facilitating effective and frequent dissemination of others' innovations.

Similar developmental trajectories alone are not sufficient to deduce a causal relationship, however. A complete understanding of the cognitive ontogeny of tool innovation requires at least seven questions (see Outstanding Questions) to be addressed. Administration of multitask batteries, longitudinally, is important for documenting developmental markers and individual differences in tool innovation. This involves variations on currently used measures of tool innovation to assess how differences in cognitive demands across tasks predict individual differences in innovative performance. It also includes assessing developmental differences in tool modification compared with tool innovation [78]. What, if anything, separates everyday tool innovation (such as reaching for objects) from exceptional innovation, such as electricity-generating windmills? Research can examine whether the mental processes behind P-creativity (an idea unique only to the individual) are different to H-creativity (an idea which has never been generated before by anyone [79]). At the individual level, motivation, personality, social network position, or an abundance of spare time also impact innovative propensity [80,81]. It is important to document whether, and how, these factors interact with the development of cognitive mechanisms to shape children's tool innovation.

To build on our cognitive model, research could examine how selective deficits in key cognitive processes impacts the development of tool innovation. For example, assessment of populations with selective deficits in mechanisms such as EFs, social learning, and combinations of both would be informative of how deficits in these specific mechanisms impact the development of the different stages of tool innovation. More research is needed to compare tool innovation in social and asocial contexts. Whereas asocial testing is crucial for isolating cognitive mechanisms underpinning tool innovation, collaborative tool innovation is arguably a more ecologically valid context in which children learn [44,82]. Cross-cultural research, driven by theoretically motivated questions, is critical to understanding the socio-cultural factors that facilitate tool innovation. For instance, the globalization of formal education presents an opportunity to examine whether exposure to schooling impacts the ontogeny tool innovation (Box 1) [28,83,84].

Tool innovation is fundamental to cumulative culture. Moving the field forward requires the integration of cognitive science, developmental psychology, and cultural evolution. Research of this kind will shed light on the cognitive drivers of tool innovation and will, in turn, improve our understanding of why humans have the most varied and complex cultural technology on the planet.

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Resources

[i]http://www.williamkamkwamba.com/about.html

[ii]https://www.forbes.com/sites/trevornace/2019/07/30/irish-teen-wins-2019-google-science-fair-for-removing-microplastics-from-water/

[iii]https://www.bbc.com/news/world-africa-52898797

[iv]https://www.voanews.com/covid-19-pandemic/finding-hope/haiti-teen-invents-hands-free-bucket-faucet

[v]https://www.nbcbayarea.com/news/coronavirus/san-mateo-county-honors-13-year-old-boy-for-invention-aimed-at-covid-19-safety/2324039/

[vi]https://www.npr.org/sections/goatsandsoda/2020/05/21/858087604/all-girl-robotics-team-in-afghanistan-works-on-low-cost-ventilator-with-car-part

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