Creation across culture: Children's tool innovation is influenced by cultural and developmental factors

Karri Neldner[1], Jonathan Redshaw[1], Sean Murphy[2], Keyan Tomaselli[3], Jacqueline Davis[4], Barnaby Dixson[1] & Mark Nielsen[1,3]

[1] The University of Queensland, Australia

[2] The University of Melbourne, Australia

[3] The University of Johannesburg, South Africa

[4] The University of Cambridge, England

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Abstract

Prior research suggests that human children lack an aptitude for tool innovation. However, children's tool making must be explored across a broader range of tasks and across diverse cultural contexts before we can conclude that they are genuinely poor tool innovators. To this end, we investigated children's ability to independently construct three new tools using distinct actions: adding, subtracting and reshaping. We tested 422 children across a broad age range from five geographic locations across South Africa (*N* = 126), Vanuatu (*N* = 190) and Australia (*N* = 106), which varied in their levels of exposure to Westernized culture. Children were shown a horizontal, transparent tube that had a sticker in its middle. Children were sequentially given each incomplete tool, which when accurately constructed could be used to push the sticker out of the tube. As predicted, older children were better at performing the innovation tasks than younger children across all cultures and innovation actions. We also found evidence for cultural variation: while all non-Western groups performed similarly, the Western group of children innovated at higher rates. However, children who did not innovate often adopted alternate methods when using the tools that also led to success. This suggests that children's innovation levels are influenced by the cultural environment, and highlights the flexibility inherent in human children's tool use.

Keywords: tool innovation, cross-cultural, innovation, tool manufacture, cognitive development, cumulative culture

Humans generate countless solutions to address the fundamental problems of survival, including storing food, retaining water and making shelter. These solutions, despite being functionally similar, often differ radically in structure and design across communities, highlighting the creativity and resourcefulness of human innovation. Yet the flexibility apparent in modern humans' technologies appears absent from the tool creation of young children. While children are adept tool users (employing an object in the environment to help achieve a goal; B. B. Beck, 1980; Brown, 1990; Casler & Kelemen, 2005; Chen, Siegler, & Daehler, 2000; Connolly & Dalgleish, 1989; McGuigan & Whiten, 2009; Reindl, Beck, Apperly, & Tennie, 2016) and skilled manufacturers (making tools after watching a demonstrator; S. R. Beck, Williams, Cutting, Apperly, & Chappell, 2016), they appear to lack the capacity for independent tool creation and design (S. R. Beck, Apperly, Chappell, Guthrie, & Cutting, 2011). Tool innovation, or the making of a novel tool without observing how to do so by another, is a comparatively late developing ability (Cutting, 2013). Children younger than 7 years of age struggle to create simple tools to achieve a goal if they are given no clues about how the tool could be created or what it might look like (S. R. Beck et al., 2011; Cutting, Apperly, & Beck, 2011; Neldner, Mushin, & Nielsen, 2017). Even when information is provided on one of these two dimensions, young children struggle to generalize their new knowledge to novel contexts, with only 14-22% of children doing so (S. R. Beck et al., 2014). Adults, by contrast, find these tasks relatively easy, performing close to ceiling (Beck et al., 2011).

While current evidence suggests low performance in young children, major limitations in the field of tool innovation development must be addressed before we can conclude that young children are poor tool innovators. For example, children should be provided with a variety of tasks in order to give them reasonable opportunity to display their innovative abilities. To date, most work has focused on tasks requiring the formation of hook-shaped tools, using the same material type (pipecleaners; S. R. Beck et al., 2011; S. R. Beck et al., 2014; Cutting et al., 2011; Neldner et al., 2017). Similarly, most tasks have required one type of manufacture action in order to create the successful tool: reshaping the material from one static shape into another (e.g. from a straight pipecleaner into one with a hook). However, multiple materials and methods might be employed to solve even a simple tool-use problem, as reflected by the diversity of toolkits present in human communities around the world. In order to examine tool creation in a more ecologically-representative manner, children's innovation must be examined across a range of tasks and contexts.

How does one create a simple tool? Although little investigation has examined the nature of children's tool-making, the types of actions employed by animals has been meticulously outlined. Beck (1980) collated a comprehensive list of tool manufacture behaviors observed in wild populations of nonhuman animals, categorizing them broadly into four modes of action (Kacelnik, Chappell, Weir, & Kenward, 2006). These comprised: 1) detachment: the removal of a tool from another object by the severing of a fixed attachment; 2) subtraction: the removal of unnecessary attachments away from a core object to make it a tool; 3) addition: the combination of more than one object to form a tool; and 4) reshaping: changing the overall structure of an object to create a tool (Shumaker, Walkup, & Beck, 2011). He noted that detachment was the most commonly observed action type, and plausibly the easiest. In wild populations of chimpanzees and orangutans, detachment of sticks and subtraction of leaves from branches occurs frequently (B. B. Beck, 1980; Boesch & Boesch, 1983; McGrew, 1974; Shumaker et al., 2011; van Schaik et al., 2009), and has been observed in capuchin monkeys (Costello, 1987; Westergaard & Fragaszy, 1987a, 1987b) and golden lion tamarins (Stoinski & Beck, 2001). In contrast, reshaping only occurs in some ape populations in the form of leaf sponging (scrunching multiple leaves down to make a sponge for soaking up water; Biro, Sousa, & Matsuzawa, 2006; Sanz & Morgan, 2007; Shumaker et al., 2011; van Schaik et al., 2003; van Schaik et al., 2009; Whiten et al., 1999, 2001) and the fashioning of sticks into sharp ends for hunting (Pruetz & Bertolani, 2007). Accounts of addition have only been observed in captive contexts, such as the chimpanzee Sultan combining two rods together to reach a suspended banana (Köhler, 1917, 1925; Lethmate, 1978), and experiments indicating that chimpanzees find subtraction easier than addition when manufacturing tools, but are capable of performing both (Bania, Harris, Kinsley, & Boysen, 2009). Arguably then, conceptualizing the restructuring of an object or its combination with another might require more cognitive resources than when simply taking elements away from it.

To date, only one investigation into children's tool innovation across a range of action types has been reported, wherein children aged 4-7 years old were required to extract a reward out of the middle of a transparent, horizontal tube (Cutting, 2013). The tool required to achieve the desired result was a long straight tool, which either needed to be extracted from a bundle of shorter sticks (detachment), constructed by removing two cross-pieces of wood from a longer dowel (subtraction), created by joining three small dowels together (addition), or made by unbending a V-shaped pipecleaner (reshaping). Children found detachment easy, but no differences existed amongst the other actions, where new tools were innovated at very low rates. Older children were nevertheless more adept at solving the subtract and reshape tasks than younger children, demonstrating that children's ability to innovate tools improves with age. Cutting thus concluded that there was little evidence for young children's proficiency in tool innovation, but that older children demonstrate greater skill. However, the presence of distractor items during testing may have increased the cognitive load on the children, thereby impeding performance. Similarly, innovation was only considered to have occurred if children constructed the tool correctly prior to its first insertion into the tube, meaning children who might have innovated their tool following a first attempt and necessary exploration on the task (Lancy, 2017) were considered unsuccessful. These limitations may have combined to obscure children's inherent tool innovation abilities. These were to be addressed using a bolstered methodology in the present study[1].

Current research on tool innovation in humans should also be viewed in light of a conspicuous caveat; that as with most published research in developmental psychology (Nielsen, Haun, Kartner, & Legare, 2017) study samples derive almost exclusively from Westernized, educated, industrialized,

[1] We chose to remove distractor items and only present the tool to be innovated upon. We also chose to code for innovations that occurred after inserting the tool into the tube as we recognize that innovative behavior often follows exploration of a task (Riede, Johannsen, Högberg, Nowell, & Lombard, 2018). Exploration allows for children to become familiar with materials, identify the affordances within tools, and gain an understanding of the causal relations involved in a certain task (Bjorklund & Gardiner, 2011). In this task children likely benefit from observing that the incomplete tool does not work in its current form, and this spurs on subsequent questions of how the tool needs to change in order for it to successfully fit in the tube.

rich and democratic (WEIRD) societies (Henrich, Heine, & Norenzayan, 2010, although see; Neldner et al., 2017; Nielsen, Tomaselli, Mushin, & Whiten, 2014). WEIRD children not only comprise a very small percentage of the world's children, but they differ distinctly from children of other cultures on a range of dimensions, and are frequently considered outliers on the scale of human performance (Henrich et al., 2010). For instance, their upbringing typically features more formal and individually directed teaching, and less observational and trial-and-error based learning than non-WEIRD cultures (Bakeman, Adamson, Konner, & Barr, 1990; Clegg & Legare, 2016; Hewlett, Fouts, Boyette, & Hewlett, 2011; Lancy, 2017; Little, Carver, & Legare, 2016). WEIRD societies also emphasize the self more than the group, and favor divergent thinking in young children, rather than conformity (Clegg, Wen, & Legare, 2017; Harkness et al., 2007; Mesoudi, Chang, Murray, & Lu, 2015; Suizzo, 2007; Tobin, Hsueh, & Karasawa, 2009; Wen, Clegg, & Legare, 2017), which might see their individual inventiveness improve. Tool using and tool making behaviors vary distinctly across human societies (Ambrose, 2001; Borgerhoff Mulder & Schacht, 2012; Foley & Lahr, 2003; Henrich & McElreath, 2003; Hodder & Hutson, 2003; Schlereth, 1985; Winterhalder & Kennett, 2006), with such differences reflecting variation in environmental pressures and cultural practices (Henrich et al., 2010). It is reasonable then to expect that sociocultural environments will also influence tool innovation outcomes. Before we are to understand how tool innovation emerges within human development, and the sociocultural factors that affect it, more investigation must occur across a diversity of cultures.

To this end, the current study takes a cross-cultural approach to track the emergence of tool innovation behaviors in children across five different cultural milieus, examining whether developmental patterns show concordance or variability across societies varying markedly in ecology (Kline, Shamsudheen, & Broesch, 2018). Our study sites comprised of communities in which the authors KT, MN and JD have established connections. The first study site was Vanuatu, a chain of over 80 islands in the South West Pacific with a population exceeding 240,000 living in a dozen main islands. Almost 80% of Ni-Vanuatu people practice subsistence horticulture, a small amount of animal husbandry, and fishing (Dixson et al., 2017). We collected data from children living on Tanna island (N = 190), one of the southern-most and remote populations in Vanuatu. Our second study sites were two small-scale communities of Kalahari Bushmen[2] from South Africa (N = 126) in Platfontein and the Kgalagadi. Bushmen people are historically hunter-gatherers, but present Platfontein populations live in townships outside of the capital city of the Northern Cape state in South Africa. Kgalagadi bushmen live in small communities of less developed townships in the North-Western corner of the Northern Cape. Finally, we collected data from Australian children from a large metropolitan city (N = 106), all of whom were educated and comparatively affluent.

In addition to ecological variation, our samples differed in their exposure to Westernized culture, access to education and exposure to novel artifacts. Our first Ni-Van sample came from the remote highland villages of Ikunala and Yakel, where education follows traditional *Kastom* practices and formal schooling is seldom attended; most children remain in the villages and help their families in

[2] We refrain from using the term *San* to refer to our Kalahari participants. *San* is a controversial, externally imposed term derived from a Nama word meaning "bandit." The people in the communities we visit call themselves Bushmen and, with respect, so do we. Where possible, we utilize the names of the communities.

farming practices. As a result, these children are most familiar with tools made from natural materials that are used for horticulture, such as wooden digging sticks and woven baskets. In contrast, our second sample of Ni-Vanuatu children was from the township of Lenakel, where people live in both traditional houses with small subsistence gardens and more modern dwellings. Here adults may work for salaries at the Ports, markets or in commercial agriculture. Children were recruited from the Catholic mission primary school, where they are exposed to some Western tools (i.e. blocks and pens) but limited educational curriculum, as well as with traditional and Western tools in the home (ie. axes and cooking pots). Participants from both our South African communities had greater access to schooling than our Ni-Vanuatu participants, although the systems available were rudimentary. The sample of Kgalagadi bushmen live in remote traditional communities with locally-run creches and schools. In contrast, Platfontein Bushmen live on the outskirts of a capital city. Here, schooling is more formalized than in the Kgalagadi sample and children are exposed to more Western artifacts in the classroom (e.g. animal figurines, blocks and dolls).

Variations across such factors may also lead to differences in children's propensity to innovate. Past cross-cultural research has found a delay in onset of theory of mind among Ni-Vanuatu children (Dixson et al., 2017) and a later onset in mental forecasting among South African bushmen children (Redshaw et al., 2018) between the ages of 3 to 6 years compared to preschool-educated Australian children. This may be because exposure to Western education at an early age equips children to better grasp the linguistic structures and concepts that might underpin Westernized experimental tasks (Dixson et al., 2017;

Redshaw et al., 2018), and provides greater confidence interacting with Western experimental apparatuses due to greater exposure to novel artifacts (Riede et al., 2018). In an attempt to capture such variation between our rural and more urbanized samples, we analyzed each cultural milieu separately.

We made no specific predictions regarding cultural differences between our samples. However, following previous research reporting that older children are more successful innovators than younger children (S. R. Beck et al., 2011; S. R. Beck, Chappell, Apperly, & Cutting, 2012; S. R. Beck et al., 2016; Chappell, Cutting, Apperly, & Beck, 2013; Cutting et al., 2011; Cutting, Apperly, Chappell, & Beck, 2014; Neldner et al., 2017), we did predict that tool innovation proclivity would increase with age across cultures.

Method

Participants

In total, 202 Ni-Van children from Vanuatu, 106 Western children from Australia and 126 Bushmen children from South Africa were included in this experiment, for a total of 434 children and 1, 244 observations made across culture for three tool types[3]. Participant demographics for each sample are summarized in Table 1. An additional 16 children were excluded due to excessive shyness (2 Bushmen; 2 Ni-Van), experimenter error (4 Bushmen; 2 Ni-Van; 2 Western), or not reaching the adequate age range (2 Bushmen; 2 Ni-Van). The lower limit of 3 years of age replicated previous tool innovation studies, and the upper limit of 9 years of age was determined to allow for analysis across a broad developmental trajectory, as Western samples have reported significant

[3] Using a simple correlation power analysis, a sample size of over 400 children provided close to 100% chance of detecting a medium age effect (r = .30).

improvements occurring on tool innovation tasks between 7-8 years of age[4]. All children who wished to be tested in the Vanuatu and South Africa field sites were given the opportunity to do so, which lead to variation in total cell sizes for each age group across samples[5]. Ethical approval[6] for all measures was obtained from the university and community and cultural boards in South Africa and Vanuatu before testing commenced. Community members fluent in the local language of each field site were recruited to translate task instructions during testing. Each translator back-translated the instructions to another community member to check for accuracy in translation prior to testing.

Western sample. The sample of Western children was recruited in the foyer of a science museum in Brisbane or through the parent database of the university laboratory. Brisbane is a large capital city with a population of 2.35 million. Young children attend preschool at age four, and curriculum-based schooling is compulsory until 15 years of age (Australian Bureau of Statistics, 2017). While specific demographic information was not collected for this sample, previous unpublished data collected at the science museum and laboratory indicates that the majority of participating families are from middle-class socioeconomic backgrounds and identify as Caucasian. Brisbane itself is a Westernized city, and children are typically exposed to TV, commercial toys and mainstream tools on a daily basis at school and in the home.

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[4] We did not record age in number of months for any of our samples, as this information is typically unavailable in Bushmen or Ni-Van communities.
[5] We had access to crèches and a primary school in Platfontein but no secondary schools were available for testing, so the upper age limit for this group was 6 years old.
[6] Ethical clearance number 2014001272 for project entitled 'Tool innovation abilities of young children: A question of prior experience and material type".

Ni-Van sample (villages). Ni-Van children from village communities were recruited from two communities on the island of Tanna. Roughly 300 people live in the highland villages of Ikunala and Yakel. These villages follow traditional *Kastom* practices and reject Western influence. They rely on subsistence farming for their livelihood -all housing and gardening implements are fashioned from natural materials such as bamboo, palms, vines and hardwoods from the surrounding forest. Very few children attend school; most children remain in the villages and help their families in farming practices, including planting, harvesting and caring for pigs and chickens.

Table 1. Participant demographics across the five community samples tested.

Participant group	Western city (*Australia*)	Ni-Van villages (*Vanuatu*)	Ni-Van township (*Vanuatu*)	Platfontein Bushmen community (*South Africa*)	Kgalagadi Bushmen community (*South Africa*)
3-year-olds (*m,f*)	17 (*10,7*)	2 (*0,2*)	4 (*2,2*)	14 (*10,4*)	13 (*9,4*)
4-year-olds (*m,f*)	13 (*8,5*)	32 (*19,13*)	4 (*1,3*)	8 (*5,3*)	12 (*6,6*)
5-year-olds (*m,f*)	15 (*7,8*)	22 (*18,4*)	8 (*7,1*)	10 (*6,4*)	8 (*5,3*)
6-year-olds (*m,f*)	28 (*11,17*)	16 (*11,5*)	22 (*16,6*)	9 (*4,5*)	19 (*8,11*)
7-year-olds (*m,f*)	14 (*11,3*)	8 (*5,3*)	21 (*9,12*)	-	18 (*4,14*)
8-year-olds (*m,f*)	10 (*5,5*)	10 (*4,6*)	12 (*5,7*)	-	3 (*0,3*)
9-year-olds (*m,f*)	9 (*5,4*)	22 (*14,8*)	7 (*3,4*)	-	12 (*8,4*)
Total (*m,f*)	106 (*57,49*)	112[a] (*71,41*)	78 (*43,35*)	41 (*25,16*)	85 (*40,45*)

[a] An additional 12 children were included in the overall analyses from the Ni-Van town sample, however these children's ages were unknown and are not reported here.

Ni-Van sample (township). Ni-Van children from townships were recruited at a Catholic mission primary school located in the coastal town of Lenakel on Tanna Island. This school provides some lessons to children from both *Kastom* village communities and Christian families living in Lenakel. Schools in Tanna loosely follow a British education system, and rely heavily on volunteer teachers with training overseas but also employ Melanesian teachers. Lessons are taught in Bislama, Vanuatu's national creole language. Children from Lenakel live in a mix of traditional thatched dwellings and basic concrete and corrugated iron buildings. While the majority of food is sourced from private gardens or markets, adults may work for income in the fishing, coffee or labor industries.

Platfontein Bushmen sample. Platfontein bushmen children were from the !Xun or Khwe communities, living in the settlement of Platfontein. Platfontein is situated on the outskirts of Kimberley, the capital city of the Northern Cape state in South Africa. These communities have endured a trying history of displacement and neglect. In 1990, the !Xun and Khwe people were relocated from their homelands in Namibia and Angola to South Africa following the end of the border war, where they had been employed as trackers by the South African Defence Force (Kleinbooi, 2007). At first, they were assigned to the tented camp of Schmidsdrift and endured difficult living conditions alongside each other. Following return of the lands of Schmidsdrift back to their traditional owners, the !Xun and Khwe people were relocated to Platfontein in 2003 by the South African Government, where they remain today. The township here consists of rudimentary concrete housing and self-built structures. Unemployment and poverty remain high. Only 6% of adults complete their senior high school certificate (Tomaselli & Ewing, 2012). Children here may attend Christian community crèches and government-funded schools, although regular attendance is low. Some houses have a TV and some adults own cellphones. Children use makeshift toys for play with their peers, including tyres and sticks to run races, and making footballs from paperbark and grass. However within schools they are also exposed to more commercial toys such as blocks and dolls.

Kgalagadi Bushmen sample. Kgalagadi bushmen children were recruited from two settlements within the region of Kgalagadi Transfrontier Park (KTP). The Khomani San community repossessed the land in this region in 1999 following a restitution land claim. The Khomani people have faced displacement, violence and the loss of many cultural practices through the reign of apartheid and colonialism in South Africa (Grant, 2011; Tomaselli, 2005). The Khomani San settlements consist of basic concrete buildings, self-built thatched huts and informal housing, although there is no running water, electricity or sanitation. There are government-funded crèches and schools within the community, which employ local teachers and assistants, however attendance is inconsistent. Children have exposure to Western toys in the crèches and schools, and often play football outside, but are relatively isolated from Western society (Tomaselli, 2005).

Materials

The apparatus consisted of three 30 cm x 3.5 cm diameter plexiglass tubes that were mounted horizontally on a platform. A 4 cm wide pompom was placed in the middle of the tube, with a sticker attached. Three tools were used. The Subtract tool was a 30 cm long x 1.5 cm wide plastic rod that had two 3 cm rods attached perpendicular to the main rod with strong magnets (refer Figure 1). Each could be pulled away from the main tool with a little force to leave one long, rigid tool. The Add tool consisted of three 10 cm length x 1.5 cm width plastic rods. Each rod had a hole containing a magnet at one end and a metal dowel at the other end, allowing the rods to be joined together. Each rod could be combined to create one long, rigid tool. The Reshape tool was a 30 cm long x 1 cm wide rubber curve with flexible wire in its interior. The Reshape tool was presented in an S-shape, but each end could be straightened out to become a long, straight tool. We removed the Detach tool from our battery, as it was found from previous research that young children found this action trivially easy, and solved it at ceiling (Cutting, 2013). We thus decided to focus on finding variation between the more complex tool-making actions.

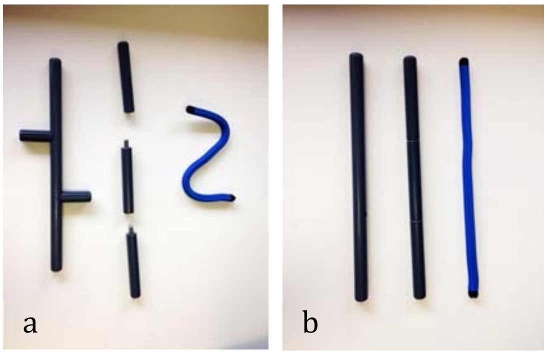

Figure 1. Subtract, Add and Reshape tools provided, in their a) presenting state and b) innovated form.

Procedure. Tools were presented in a counterbalanced randomized order in an A-B-C, B-C-A, or C-A-B pattern, such that each child participated in all tool conditions.

Innovation phase. Before testing commenced, the study was explained to parents, community leader or the chief of the village, and written consent or verbal consent obtained. All children were tested out of view of other children on a mat, seated across from the experimenter (and translator, for Ni-Van and Bushmen children; see Figure 2). Western children were tested within the foyer of a science museum or a university laboratory. Ni-Van children were tested in a thatched house in the villages and inside a relief tent in the township community. Bushmen children were either tested outside a crèche or school building. The experimenter pointed at the plexiglass tube to show the sticker inside. The child was told that if they could get the sticker out of the tube, they could keep it. The experimenter then presented the first tool in its unmodified form. The child was told that maybe they could use that item to get the sticker out. All children were given one minute to retrieve the toy doing whatever they liked. However, if children ceased to interact with the task or perseverated with the same action for a 20 second duration, the trial was terminated. If children succeeded in retrieving the sticker they were given it and moved on to the next innovation trial. However, if children failed to retrieve the sticker, they proceeded to a partial demonstration phase. Each child received all three tools across three trials.

Partial demonstration phase. In this phase, children were shown the action required on one end of the tool. The experimenter removed one dowel on the Subtract tool, added two pieces of the Add tool together, and straightened one of the two bends of the Reshape tool. This phase served to examine whether children could take the action they had observed and apply it to the entirety of the tool to create the ideal tool. This is considered tool modification, rather than tool innovation, because children have observed the experimenter perform the action previously. If children still did not succeed on the task, they proceeded to the full demonstration phase.

Full demonstration phase. In this phase, the experimenter completed the making of the ideal tool, by doing the final action on the other end of the tool (removing the final dowel on the Subtract tool, adding the final piece in the Add tool, and straightening the final part of the Reshape tool). This phase served to check that children were capable of recognizing the ideal tool as appropriate for the task and effectively using it to retrieve the sticker. All children were given a prize at the conclusion of testing: armbands for the Western children and t-shirts for the Ni-Van and Bushmen children.

Figure 2. The experimental setup in a) Brisbane science museum, b) Ni-Van village communities and c) Platfontein Bushmen communities. The persons depicted in these images have provided signed consent to have their likeness published in this article.

Coding. Dependent variables were coded for each of the three test phases as follows: a) whether the appropriate innovation[7] was made on the tool (yes/no) b) whether the innovation occurred before the first insertion of the tool into the tube (yes/no), c) whether the sticker was successfully retrieved (yes/no), and d) whether success occurred by innovation[8] (yes/no). Inter-rater

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[7] Note that tool innovation only occurred within the innovation phase – following the partial and full demonstrations, if children made an action on the tool it was considered a tool modification, as they had observed the action by the experimenter previously.

[8] This variable allowed us to distinguish between successful retrieval occurring by innovation, or by using an alternate strategy that did not require altering the tool's current form.

reliability coding occurred on 10% of videos for a strong agreement rating (Cohen's kappa = .945).

Results

Testing in the Western community revealed relatively high rates of tool innovation across the tasks, with the majority of children successfully innovating a tool to solve the target problem (see Figure 3). However, when the task was taken to Vanuatu and South Africa, roughly 40% of children utilized force or multi-tool use strategies to solve the reshape and add tasks respectively using the tools in their current state, rather than innovating on them. In the reshape task, children would repeatedly push the reshape tool against the inside of the tube with force until it straightened. In the add task, they would slide each dowel inside the tube one after the other in order to push the reward out, without combining the parts together to create one long tool. These actions were not classified as directed tool innovation. This meant that comparisons across the three tasks were not feasible, as no comparable alternate solution was possible for the Subtract task – it could only be solved through tool innovation. We therefore analyzed each action type separately.

Before conducting main analyses, children's performance in cultural milieus in Vanuatu and South Africa were compared to examine similarities or differences in responding. Some statistical differences in innovation performance were detected, and each sample was analyzed separately. This meant that 5 groups were used for the main analysis – the Western group, the Vanuatu village group, the Vanuatu township group, the Platfontein Bushmen group and the Kgalagadi Bushmen group. For a full breakdown of frequency data, refer to supplemental materials.

Main analysis.

Children's success and innovation responses were entered into a series of binomial logistic generalized linear models using the GLIMMIX procedure in SAS 9.4 (Stroup, 2012). The dependent variable (yes/no) was classified as binomial, and thus the models were tested against a binomial distribution with a logit link function. Each tool was analyzed separately, comparing models including all unique combinations of the fixed effects of age (3-9 years old), sex (boys or girls), and culture (5 groups) nested within the full factorial model, with order of presentation (RAS, SRA or ASR) entered as a random intercept. The results of the best fitting model for each task are presented here, with details of model selection and the results of other models available in the supplementary materials. All significant culture effects were followed up with pairwise comparisons of least squares means estimates between all cultures, utilizing Bonferroni corrections for multiple comparisons.

Innovation Rates.

Subtraction. The best fitting model for innovation rates on the subtraction task contained significant fixed effects of age and culture, but no effect of gender and no interactions. The age effect indicated that children were innovating more on the subtraction task at older ages than younger ages, F (1, 397) = 21.36, b = .34, se = .07, p = < .001, see Figure 3. The culture effect revealed that children from different groups varied in their innovation rates, F (4, 397) = 14.00, p = <.001. Follow up comparisons revealed that the Western group innovated significantly more on the subtraction tool than any other group (bs ranged from 1.37 to 3.09, all ps < .05, see supplementary materials). In addition, the Vanuatu township group was significantly poorer at innovating by subtraction than the Kgalagadi Bushmen group, b = -1.72, se = .47, p = .002.

Addition. The best fitting model for innovation rates on the addition task contained significant fixed effects of age, culture and gender, but no interactions. The main effect of age, F (1, 397) = 50.45, b = .62, se = .09, p = <.001 demonstrated that children across all cultures innovated by addition at higher rates as they aged (see Figure 3). The culture effect demonstrated that there was variation in the levels of innovation across the 5 groups, F (4, 397) = 20.96. p = <.001. Follow up tests revealed that the Western group innovated significantly more compared to all other groups (bs ranged from 2.76 to 3.75, all ps < .001), but that no other group significantly differed from each other on innovation rates (see supplementary materials for comparisons). A significant gender effect indicated that boys had higher rates of innovation by addition across all cultures than girls, F (1,397) = 11.67, b = .99, se = .29, p = .001.

Reshaping. The best fitting model included significant fixed effects of age and culture, but no gender effect and no interactions. The age main effect revealed that all children improved in their ability to innovate by reshaping as they got older, F (1, 404) = 34.76 , b = .47, se = .08, p < .001, refer Figure 3. The culture effect demonstrated variation in the rates of innovation across cultural group, F (4, 404) = 17.37, p < .001. Follow up comparisons found significant differences between Western groups compared to all groups (bs ranged from 1.90 to 3.75, all ps < .001) excepting the Platfontein Bushmen group (b = .74, se = .45, p = 1.000). Thus, there was no evidence that the Platfontein Bushmen differed from the Western children in their capacity to innovate on the reshape task. In addition, the Platfontein Bushmen group innovated at significantly higher rates than the Vanuatu township group (*b* = -2.11, *se* = .52, *p* = .001) and the Vanuatu village group (*b* = -2.41, *se* = .52, *p* < .001).

Innovation Rates on First Insertion

In general, the pattern of results for innovations occurring before inserting the tool into the tube reflected those for overall innovation rates (see supplemental materials for tables). Western children innovated significantly more on first insert than non-Western children (in 20-65% of instances for Western children across the three tasks and 0-21% for non-Western children; *b*s ranged from .33 to .66, all *ps* ≤ .002; except on the subtract task where there were no group differences), and older children more than younger children. Overall, a substantial number of children in all groups innovated before inserting the tool into the task, suggesting that haptic experience gained by applying the tool to the task may be necessary before many children recognize that the presenting tool is inadequate and go on to innovate its form.

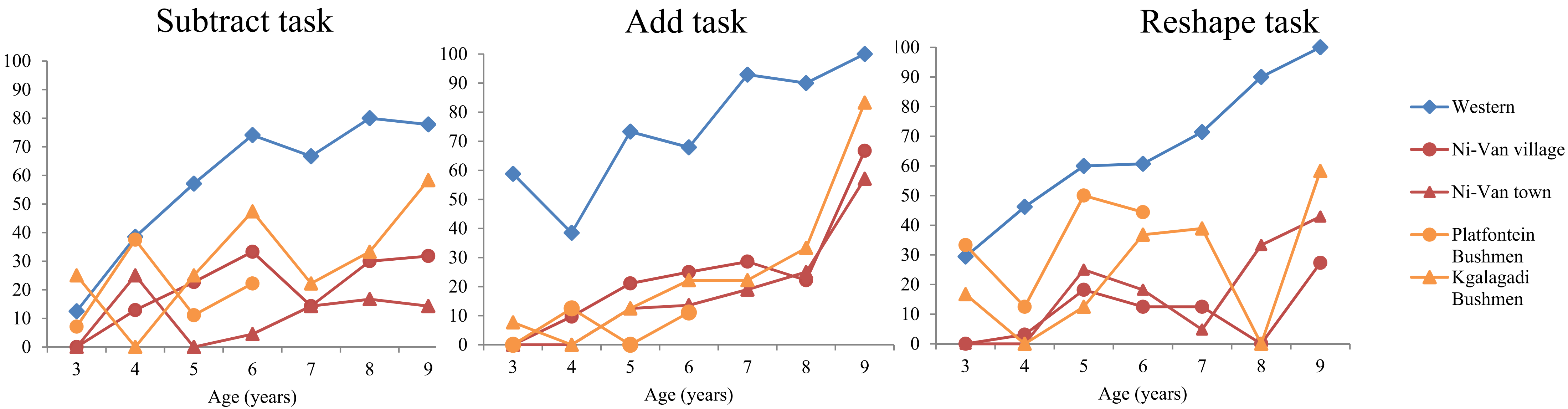

Figure 3. Percentage of children in each age group[9] across culture who innovated on the Subtract, Add and Reshape tasks.

[9] The twelve children from the Ni-van township who did not have known ages are excluded from these graphs.

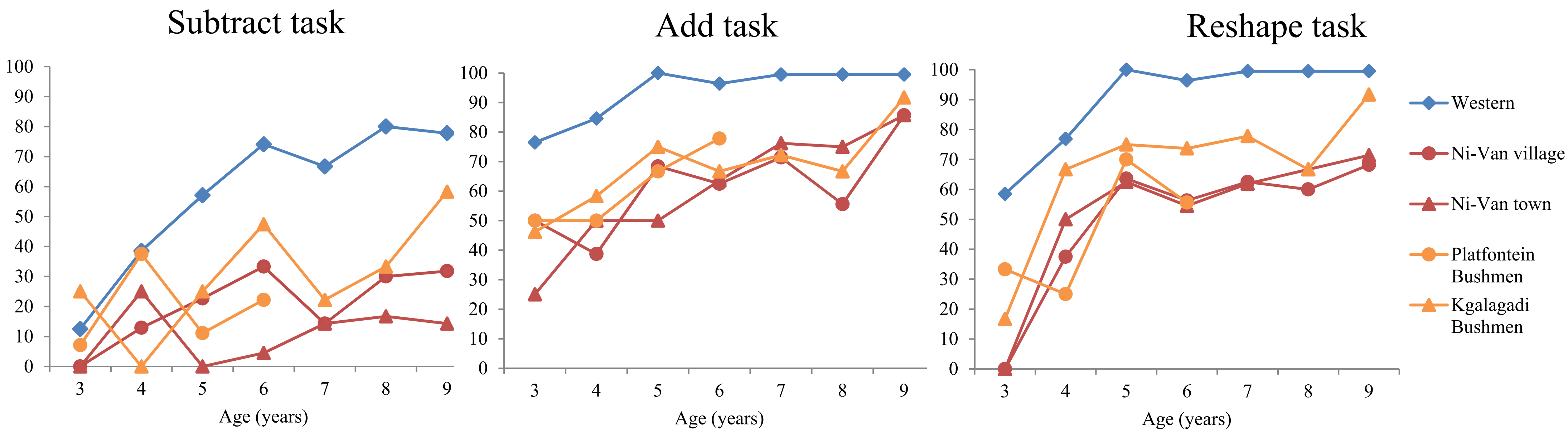

Figure 4. Percentage of children in each age group[10] across culture who successfully retrieved the sticker from the tube on the Subtract, Add and Reshape tasks.

[10] The twelve children from the Ni-van township who did not have known ages are excluded from these graphs.

Success Rates.

Subtraction. The best fitting model for success rates on the subtraction task using any strategy contained significant fixed effects of age and culture, but no effect of gender and no interactions. The age effect indicated that children were succeeding more on the subtraction task at older ages than younger ages, F (1, 397) = 19.45, b = .32, se = .07, p = < .001, see Figure 4. The culture effect revealed that children from different groups varied in their success rates, F (4, 397) = 13.97, p = <.001. Follow up comparisons revealed that the Western group succeeded significantly more often on the subtraction tool than any other group (bs ranged from 1.41 to 3.04, all ps < .01, see supplementary materials). In addition, the Vanuatu township group was significantly poorer at succeeding on the subtraction task than the Kgalagadi Bushmen group, b = -1.63, se = .46, p = .005.

Addition. The best fitting model for success rates using any strategy on the addition task contained significant fixed effects of age and culture, but no gender effect and no interactions. The main effect of age, F (1, 398) = 25.86, b = .39, se = .08, p = <.001, indicated that older children were more successful than younger children at solving the task across all cultures (refer Figure 4). The main effect of culture demonstrated that children varied in their success rates across the 5 groups, F (4, 398) = 7.72. p = <.001. Follow up comparisons revealed that Western children were significantly more successful on the task than all other groups (bs ranged from 1.89 to 2.46, all ps < .004,). However, there were no significant differences in the success rates of all other groups.

Reshaping. The best fitting model for success rates using any strategy on the reshape task contained significant fixed effects of age and culture, but no gender effect and no interactions. The age effect demonstrated that children were more successful on the reshape task as they aged, $F\ (1, 400) = 35.46$, $b = .45$, $se = .08$, $p = <.001$, see Figure 4. The culture effect again indicated variability in success rates amongst the five groups, $F\ (4, 400) = 9.42$, $p = <.001$. Follow up comparisons revealed significant differences between the Western group compared to every other group (b*s* ranged from 1.62 to 2.40, all $ps < .003$; see supplementary materials), with Western children being more successful on the task than all other children. There were no other significant group differences.

Alternate Strategy Rates.

A detailed description of children's alternate strategy rates is presented in the supplementary materials. Unlike for innovation, Western children did not employ an alternate strategy on the tasks significantly more than non-Western children. Rather, they used the alternative strategy at relatively similar rates to non-Western children on the reshape task, and significantly lower rates than non-Western children on the addition task. This suggests that the Western children's relative overall success compared to other groups was not due to higher adoptions of an alternate strategy, but due to higher employment of innovation techniques.

Demonstration phases.

Children who did not retrieve the sticker were presented with a Partial Demonstration and then if still failing, a Full Demonstration. Full results are presented in the Supplementary Material, but what these phases document is that the capacity[11] for making the target tools is within the motor action

[11] When referring to capacity, we mean that within each of our tested age groups, some children were capable of performing the target tool manufacture and succeeding on the

capabilities of the children we tested –that is, the tasks were not physically beyond our participants once they were shown the actions by the experimenter.

Discussion

Our sociocultural environment influences the methods by which we innovate, and the tools we create (Ambrose, 2001; Foley & Lahr, 2003; Henrich & McElreath, 2003; Nielsen, in press). Yet research exploring differences in tool design across multiple cultural contexts is limited (Kline et al., 2018). We measured variability in children's tool innovation across five different cultural milieus using a range of manipulation actions. We predicted that children would become more skilled innovators as they aged. Consistent with previous research, older children within each culture were significantly more adept than younger children at innovating a new tool using subtraction, addition and reshaping to solve a task (S. R. Beck et al., 2011; S. R. Beck et al., 2014; Cutting, 2013; Cutting et al., 2014). By 7-9 years of age, the average child (summed across cultures) innovated in 26-74% of occurrences compared to the lower rates of 12-22% in the average 3-year-old; rates within the range of previous studies (S. R. Beck et al., 2011; Cutting, 2013; Neldner et al., 2017). We found higher performance rates in Western children than those reported in previous tests of tool innovation (rates from 12-59% for 3 year olds and 57-93% for 7 year olds), suggesting that simplifying task demands can facilitate children's tool innovation performance.

task after a demonstration. This suggests that it is within the cognitive and motor abilities of the children to perform this task at these ages once shown the appropriate action.

By monitoring innovations occurring not only before first insertion but also after, we were also able to detect innovations in an additional 83% of children (averaged across cultures and tasks) that would not have been considered on previous tasks. This suggests that a majority of children only innovate following haptic experience and exploration of the task materials (Lancy, 2017). Future tasks should incorporate exploration time prior to testing in order to allow children opportunity to investigate the affordances of the task.

Our findings support the notion that young children, while being very skilled imitators and avid social learners (Legare & Nielsen, 2015), are less likely to innovate (S. R. Beck et al., 2012; Cutting, 2013). It may be more crucial to adopt normative uses of tools when young, to ensure social cohesion and a rapid transmission of skills. Only in the later years of childhood might children begin to solve problems independently and build on existing cultural knowledge (Locke & Bogin, 2006; Riede et al., 2018). The parallel developmental trajectories we observed across 5 distinct groups and 3 different manipulation actions suggest that children's innovation improvement across age may be a universal phenomenon.

We also found evidence for cultural variation in children's tool innovation proclivities on these tasks. While performance across the non-Westernized small-scale society groups was, in general, similar, the performance of children from a Westernized city was considerably higher (with one notable exception when comparing with Platfontein children in the Reshape condition, who demonstrated similar proficiency to Western children). Our findings highlight the importance of collecting measures from multiple cultural samples before inferring generalizability of a trait (Nielsen & Haun, 2016; Nielsen, Haun, Kärtner, & Legare, 2017). Had we examined our Western sample only, we might have made conclusions misrepresenting the breadth of variability in innovation performance in our extended sample. Instead, we found that children across our sample often utilized the tools in alternate ways (using force or multi-tool use) in order to retrieve the sticker. This suggests that different elements of the tool and task were salient to the children in each group, generating different behavioral approaches to solving it. Further, it highlights the flexibility inherent in children's tool use – several approaches may be used within even a simple task to achieve the same goal.

While the purpose of the current investigation was to track variability in innovation proclivity across culture, the cultural factors driving our observed differences, and their unique level of contribution, are still unclear. These children varied on numerous sociocultural variables, including their level of exposure to and interaction with family tools, familiarity with testing contexts and materials, access to schooling, and exposure to white people, none of which were directly measured. Any or all of these factors may play a role in shaping a child's understanding of tools and affect the way they interact with them on experimental tasks. What we can surmise, however, is that irrespective of the driving mechanisms or the specific combination of them, the social world in which a child develops has a direct influence on how they perceive a tool-related problem, and the strategies they devise to solve it. A valuable goal for future research then would be to isolate and quantify the role of such variables within these tasks.

For example, it is likely that differences in our samples' exposure to novel artifacts through formal education influenced their approaches to and successes in tool innovation. The way children play and explore objects is heavily influenced by prior experience and social exposure (Bakeman et al., 1990; Bjorklund & Gardiner, 2011; Lancy, 2017; Nagell, Olguin, & Tomasello, 1993; Tomasello, Savage-Rumbaugh, & Kruger, 1993; Williamson, Meltzoff, & Markman, 2008). Children that engage with a large diversity of tool artifacts, such as is typical in Western cultures, display more divergent thinking skills (Riede et al., 2018). Western children are much more likely to be familiar with toys designed for constructive purposes, such as Lego or blocks (Bjorklund & Gardiner, 2011), and receive more parental facilitation during object play than children from small-scale societies (Bakeman et al., 1990; although see Little et al., 2016 for differences seen in modality type but not overall facilitation). These factors might contribute to their relative aptitude in innovating tools on these particular tool innovation tasks and detecting affordances in the materials faster (ie. before inserting the tool into the tube). This pattern extends previous research implicating formal education as a contributing factor in the onset of theory of mind and mental forecasting in children (Dixson et al., 2017; Redshaw et al., 2018) to include tool innovation onset. However, despite variation in the level of formal schooling available between our Kalahari bushmen and Ni-Van groups, in general their innovation rates were similar, suggesting that education alone cannot fully account for our observed differences between cultural groups.

Unfortunately, we were unable to make direct comparisons on tool innovation performance between the tasks and therefore could not determine whether children displayed superior skill in one action domain over another. Research from nonhuman animals suggests a hierarchy of action complexity might exist, as detachment is observed far more commonly than addition or reshaping (B. B. Beck, 1980; Kacelnik et al., 2006; E. Visalberghi, Fragaszy, & Savagerumbaugh, 1995; Elisabetta Visalberghi & Trinca, 1989), and chimpanzees are better at subtraction than addition when constructing tools (Bania et al., 2009). However, the one reported account of action complexity in children failed to detect a hierarchy like this (Cutting, 2013). Alternatively, it is possible that children might develop aptitudes for certain actions in some cultures - the Platfontein Bushmen children demonstrated particular skill in reshaping techniques relative to other non-Western groups and other innovation actions, suggesting that their cultural environment enabled them to become particularly skilled within this domain. Further constraining our task to only allow innovation solutions, and comparing performance between each action to see if a hierarchy of complexity exists in children would be extremely valuable as a pursuit for future research. Further, it is possible that doing so might see children's innovation rates increase by making innovation necessary for success.

Our unexpected gender effects revealed that boys performed significantly more additive innovations than girls in each group, and that they innovated the correct tool before insertion more often than girls on both the add and subtract tasks. It is possible that boys receive more exposure to models using and combining tools from a young age than girls across cultures, although we know of no research to suggest this is the case. There is however, evidence that boys tend to build more structures than girls (Caldera et al., 1999), and will engage in more object-related play than girls in comparison to other forms of play in Western contexts (such as social play; Bjorklund & Gardiner, 2011). This suggests that boys might be more inclined to engage with physical tools from an early age (Bjorklund & Gardiner, 2011; Bornstein, Haynes, O'Reilly, & Painter, 1996; Gredlein & Bjorklund, 2005), which might allow them to learn to detect object-related affordances faster. Future investigations could examine the types of tool-using actions and amount of tools used by adults in the presence of girls and boys across multiple cultural ethnographies to further shed light on this question.

Finally, our findings raise an important issue regarding the ecological validity of the methodologies employed in cross-cultural research. Tasks developed in one cultural context may not easily or equally translate to another (Kline et al., 2018). For example, Ni-Van children routinely create tools and solve practical problems using palm leaves and vines rather than the plastic and rubber dowels used in our experiment. Their tool making consists of the weaving of baskets and grass skirts for girls or thatching of roofs for boys. Unlike in Western cultures, there is little pedagogy involved in the transfer of these new skills to children, instead younger siblings watch older siblings or adults performing these actions and imitate them (Clegg & Legare, 2016; Lancy, 2017). Further, in small-scale societies it is customary to defer to authority figures and to not voice opinions or divert from established social roles in their presence (Clegg et al., 2017; Wang, Devine, Wong, & Hughes, 2016). These variables in combination might have suppressed Ni-Van children's innovative action on these elected tasks. Had they been allowed to explore the task in front of a trained age-matched peer rather than an experimenter and translator, or if natural materials were instead provided, innovation rates and explorative action might have increased in Ni-Van groups. The implementation of Westernized tasks to other contexts must be done with caution and a preparedness to acknowledge potential confounding variables to ensure such investigations remain valuable

(Kline et al., 2018). Future studies would benefit from incorporating ethnographic information within the design process to ensure tasks are as comparable as possible across elected study sites.

Tool innovation certainly appears to be difficult for young children. However, the results of the current study demonstrate that, when mapping across distinct cultures and several action types, children's innovation skills reliably improve with age. This pattern of relatively late, but predictable development stands in stark contrast to another remarkable human capacity – imitation – which children universally acquire as toddlers and preschoolers (Legare & Nielsen, 2015; Tomasello, 2016). A primary payoff of an extended childhood in humans might then be that it allows children to transition from rampant copiers to resourceful innovators, and in doing so allows them to become active perpetuators in advancing cultural knowledge for their community.

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