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Generative cultural learning in children and adults: the role of compositionality and generativity in cultural evolution

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Are human cultures distinctively cumulative because they are uniquely compositional? We addressed this question using a summative learning paradigm where participants saw different models build different tower elements, consisting of discrete actions and objects: stacking cubes (tower base) and linking squares (tower apex). These elements could be combined to form a tower that was optimal in terms of height and structural soundness. In addition to measuring copying fidelity, we explored whether children and adults (i) extended the knowledge demonstrated to additional tower elements and (ii) productively combined them. Results showed that children and adults copied observed demonstrations and applied them to novel exemplars. However, only adults in the imitation condition combined the two newly derived base and apex, relative to adults in a control group. Nonetheless, there were remarkable similarities between children's and adults' performance across measures. Composite measures capturing errors and overall generativity in children's and adults' performance produced few population by condition interactions. Results suggest that early in development, humans possess a suite of cognitive skills—compositionality and generativity—that transforms phylogenetically widespread social learning competencies into something that may be unique to our species, cultural learning; allowing human cultures to evolve towards greater complexity.

1. Introduction

What cognitive processes drive our species' distinctive ability to aggregate cultural knowledge over time and across generations? There are various answers to this question, of course. Most empirical research has focused on social learning, specifically, imitation and teaching (for reviews, see [1–3]). Others have focused on prosocial and folk psychological skills, such as referential communication, sharing and theory of mind [4,5]. This suite of domain-specific, socio-cognitive skills has garnered significant empirical attention because it appears to be highly developed (if not entirely unique) in humans relative to other social animals [4,6–8]. Cognitive scientists have only recently begun to systematically explore how asocial, domain-general skills such as causal and analogical reasoning along with changes in executive functions allow individuals to introduce innovations into a population's cultural repertoire [9–13]. Regardless of exactly how social and asocial processes interact to produce cultural complexity, results from a majority of studies in the comparative [14,15], developmental [10] and computational [16] sciences have pointed to differences in fidelity [17] and breadth [18] of social learning competence between humans and other animals. According to these arguments, high-fidelity copying is necessary to generate, preserve and transmit adaptive cultural variants. By contrast, low-fidelity

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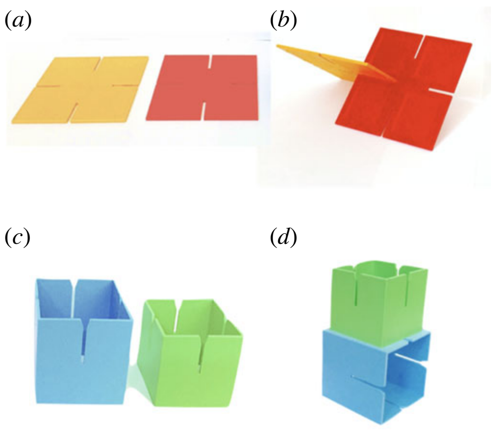

Figure 1. Tower Building Task. Tower pieces: (*a*) flat squares and element (*b*) linked squares, forming the tower's apex. Tower pieces: (*c*) hollow cubes and element (*d*) stacked cubes, forming the tower's base. During the demonstration (e.g. summative imitation), participants saw one model combining squares (*a*,*b*) and another stacking cubes (*c*,*d*) in counterbalanced order. In the original study [24], participants received the demonstrated tower pieces (unassembled) and were instructed to build the tallest tower possible. In the present study, during testing, participants received twice as many tower elements as was demonstrated (cf. figures 2 and 4).

copying has been shown to result in 'backward slippage' or cultural loss, as adaptive practices are forgotten or replaced with less adaptive variants [1–3,19].

However, some have challenged these broad claims about the uniqueness of cumulative cultural evolution (CCE) and the learning mechanisms that support it [20]. For instance, Gruber *et al.* [21] using Mesoudi & Thornton's [22] 'core' (or basic) criteria for CCE[1] have pointed to instances of cultural evolution towards greater efficiency or simplification in various animal species. Setting aside whether these changes are driven by 'cultural' or natural/environmental forces, the evidence provided by Gruber and colleagues says nothing about the divergent developmental and evolutionary trajectories of cultures observed in nature: simplification in the case of animals versus complexity in the case of humans.

The relative failure of animals to evidence CCE that leads to more complex rather than simpler cultural products begs for an explanation and a tractable empirical model. One possibility suggested by Lewis & Laland [16] is that cultural complexity is driven by a pair of component cognitive features, one social, the other asocial: faithful imitation and representational combination. Subiaul and co-workers [23,24] have operationalized this idea and referred to this pair of skills as summative social learning (SSL), encompassing summative imitation and emulation. Both have been shown to contribute to cumulative learning within [24] and between individuals [25].

To evaluate SSL, Subiaul & Stanton [24] used a novel Tower Building Task (figure 1) inspired by the spaghetti tower of Caldwell & Millan [26] and Price *et al.*'s [27] tool construction task. In the key manipulation (i.e. summative imitation condition), *different* models demonstrated *distinct* responses on *separate* objects that could be combined to produce an optimal tower. Results showed that relative to an independent invention group (Baseline), both children and adults copied the demonstrated responses (stacking cubes and linking squares) and then, spontaneously combined them, to produce an unobserved—novel—product. Bauer *et al.* [28,29] have independently devised a similar paradigm that involves the semantic integration of disparate facts provided by testimony. We have previously referred to these types of inferences that involve the spontaneous combination of different types of knowledge provided by others as 'intuitive invention' [24].

But imitation and combination might not fully explain the power and breadth of human cultural evolution. What is needed is compositionality; that is, the iterative combination of discrete representations (e.g. about actions, objects and/or functions) in a goal-directed manner[2] [30–33]. Compositionality is made possible, first, by how knowledge itself is *represented* and, second, by how that knowledge is *processed*. For instance, events can be encoded semantically in an abstract, generic format (*a* car) or episodically (*the* pink Cadillac) in a rich, detailed format that includes what (Cadillac), who (Elvis), where (Memphis, TN, USA) and when (*ca* 1950s) information [5,34]. These representations can be processed vis-a-vis other representations in a variety of ways. For example, combining existing object representations (e.g. spear = cutting flake + rod), embedding representations within each other in an 'action grammar' [35–37] (e.g. core preparation: detach a flake, to prepare to detach a flake, to prepare to detach a flake…) or by 'blending' different representations (e.g. spork = spoon + fork) [16,38].

Using this framework, the present study builds on the concept of cultural learning proposed by Tomasello and co-workers [19,39]. Here, we propose that cultural learning is a species of social learning characterized by compositionality and generativity (cf. electronic supplementary material, table S1). Using the Tower Building Task and SSL paradigm [24] involving different models [20], we evaluated the hypothesis that *human culture is uniquely cumulative because human social learning is distinctively compositional by default; appearing early in development prior to formal instruction* [35,40,41]. We contrast that hypothesis with one where *cumulative culture is driven by human-specific pedagogical practices (e.g. apprenticeships and schooling) that favour compositionality.* To assess whether human social learning is compositional and generative throughout development, two studies explored the following: Do children and adults (i) iteratively extend observed responses to different or additional exemplars and (ii) combine different iterative responses to produce a novel—unobserved—product? If participants represent observed responses discretely and generically, then they should be able to iteratively extend observed actions to new exemplars in the imitation condition (where participants can discretely represent objects and action) but not the emulation condition (where whole segments are provided without actions to help parse them). Moreover, if they are capable of compositionality, then they should be able to iteratively combine responses *within* and *between* objects to produce a novel product. Finally, if this suite of skills represents a default cognitive mode that is not explicitly taught, preschool children should perform similarly to college students across measures of generativity and compositionality.

We refer to the iterative combination and extension of responses as *generative cultural learning* or, simply, *cultural learning*, including generative imitation and emulation. The combination of different socially learned generative responses is referred to as *summative cultural learning*; an extension of the term 'summative imitation' introduced by Subiaul *et al.* [23] (see table 1). See electronic supplementary material, table S1, for definitions of terms.

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Table 1. Description of terms, processes/computations and rules used in the Generative Tower Building Task.

representations and computations	task features and cognitive components: cubes (to form BASE)	task features and cognitive components: squares (to form APEX)
object features	**cube size-colour: largest-red; second largest-orange; smallest-green; second smallest-blue**	**square colour: red; yellow**
goals	sub-goal: build base by stacking (all) cubes	sub-goal: build apex by linking (all) squares
	end-goal: build tallest possible tower by combing subgoals	
actions	Grab = take hold of object; Rotate = reorient object clock- or counter-clockwise; Balance = set on edge; Set = place object; Link = connect objects; Repeat = replicate action; End = stop	
dependencies	AGROUND = on floor, STACK = set on top of, RIDGES = by/in ridges; EDGES = by/on edges; FLAT (squares) = lay flat; WHEN = temporal-causal structure	
executive functions	*select and integrate: objects, features, goal, sub-goal, actions, dependencies*	

The pre-registration of this study can be found here: https://aspredicted.org/mb3vb.pdf. See electronic supplementary material for descriptions and justification for procedural deviations.

2. Experiment 1

(a) Methods

Participants. A total of 101 adults (females = 50) with a mean age of 23.27 years (s.d. = 7.63) were tested on three trials in three independent conditions: Independent Invention or Baseline ($n = 33$), Imitation ($n = 32$) and Emulation ($n = 36$) using a mixed between-/within-subject repeated design (see measures below). Participants were recruited and tested in the Estelle and Melvin Gelman Library on the Foggy Bottom Campus of the George Washington University in Washington, DC following GWU IRB-approved procedures. The participant pool was diverse (greater than 50% non-white). See electronic supplementary material for demographic details.

Experimental task. The Tower Building Task for adults (figure 1). See electronic supplementary material for details.

Learning phase. Adults were randomly assigned to one of three independent learning conditions. Two of these involved a video demonstration (30 s in length) before testing like the procedures described in Subiaul & Stanton [24]. See electronic supplementary material for details.

The two demonstration groups were as follows:

— *Summative imitation (imitation)*: This group saw two models. One model built the tower base by rotating and stacking two cubes atop each other. Another model built the tower's apex by combining two flat squares. However, participants never saw these two tower elements—base and apex—combined. See electronic supplementary material for more details. A sample video demonstration can be found here: https://www.youtube.com/watch?v=S0UWqwtujgo.

— *Summative emulation (emulation)*: Participants saw different models and demonstrations for the base and apex as was the case with the Summative Imitation group. However, the actions used to create each tower element by each model were removed. Consequently, participants saw the unassembled pieces for each tower element immediately followed by the completed tower element. The emulation conditions allowed us to evaluate whether generativity could be achieved by linking large segments or wholes, rather than discrete elements. See electronic supplementary material for more details. A sample video demonstration can be found here: https://www.youtube.com/watch?v=-w0cGOui8EI.

The third group served as an independent invention or baseline—control—group:

— *Independent invention* (baseline): This group received no social input. See electronic supplementary material for more details.

Testing phase. During testing all participants were given twice the number of tower pieces seen in the video: four squares and four cubes. They were then instructed to build the tallest possible tower, without collapsing, using *all* the pieces. There was no time limit. Upon completing, an experimenter measured the tower from base to apex. If participants did not build an optimal tower (cf. figure 2), towers were disassembled and participants were given additional trials (up to 3) to produce an optimal tower. No additional demonstrations were provided. See electronic supplementary material for more details.

(i) Measures and video coding procedures

Participants' responses were all coded by research assistants not involved in data collection. A coding template with 67 different responses was used to categorize each of the responses made by participants. We evaluated two continuous repeated measures, including tower height and duration of tower building across Trials 1–3 within-subjects as well as between-subjects (i.e. across learning conditions. We also measured various non-parametric (between-subjects) target responses described below. Inter-rater reliability was high for all measures (0.99). See electronic supplementary materials.

The non-parametric measures for cultural learning and summative cultural learning were coded as present (1) or absent (0).

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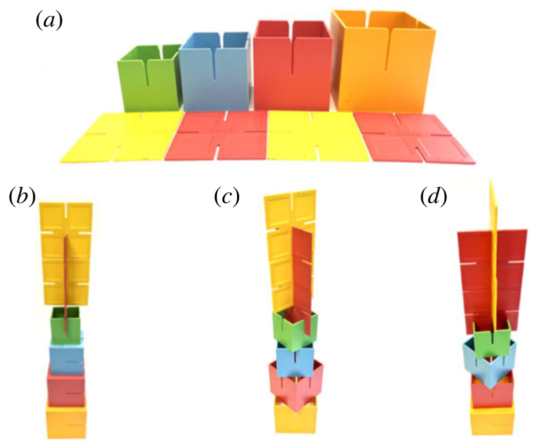

Figure 2. Adult Tower Building Task. (*a*) Tower pieces consisted of cubes and squares. Cubes could be stacked to form the tower base element. Squares could be linked together via ridges to form the tower apex element. The apex could then be affixed to the base via the cube's ridges resulting in optimally tall towers (*b*,*d*). However, towers varied in structural soundness: optimal stacking on a solid surface (*b*), sub-optimal stacking by balancing cubes on edges (*c*) or consisting of optimal and sub-optimal elements (*d*). Note that during demonstration, participants saw the green cube stacked atop the blue cube and a red square linked with the yellow square (cf. figure 1).

(ii) Cultural learning: generative action sequence (tower element)

Stacking (base)

— *Optimal*. Rotating and stacking a novel cube (red or orange) atop the solid surface of a rotating cube (e.g. figure 1*a*). Participants received a generative stacking score of 1 if they stacked three cubes (two demonstrated cubes, plus one of the undemonstrated cubes). They scored 2 if they stacked all four cubes. Scores ranged from 0 to 2. Scores of 2 were re-coded as 1, resulting in a binary score (1/0).

— *Sub-optimal*. Stacking cubes along their surface/edge (making them unstable and prone to collapse). Children received a generative stacking score of 1 if they stacked three cubes (two demonstrated cubes plus one of the undemonstrated cubes). They received a score of 2 if they stacked all four cubes. Scores ranged from 0 to 2. Scores of 2 were re-coded as 1, resulting in a binary score (1/0).

Linking (apex)

Linking two squares (e.g. figure 1*b*) with additional squares (undemonstrated). Again, scores ranged from 0 to 2. Scores of 2 were re-coded as 1, resulting in a binary score (1/0). Although some participants inefficiently linked squares, these instances of sub-optimal linking did not result in a functioning element (i.e. collapsed). For this reason, only optimal linking is reported.

(iii) Summative cultural learning: generative tower, including both tower elements and action sequences

Optimal (figure 2*b*). Rotating the four given cubes to their sides and stacking them on top of one another to form the tower's base. Alternatively, the top cube may be stacked with its ridges facing upward. Combining the four squares and connecting them to the top cube's ridges. Coded as 1 or 0.

Sub-optimal (figure 2*c*,*d*). Sub-optimally stacking the four cubes as the base (e.g. cubes balanced on edges with ridges facing up or down) and affixing the four linked squares to the top cube. Or a 'blended' tower that consisted of optimal and sub-optimal stacking methods that were blocked or interleaved with other tower elements (e.g. linked squares). Coded as 1 or 0.

Briefly, measures qualified by the term 'generative' represent iterative combinations (or a combination of iterative responses). For instance, linking squares involves a *single* combination of two squares. Whereas generative linking (of squares) involves the *iterative* combination of three or more squares. See electronic supplementary material, table S1.

The following measures were continuous:

Tower height (height): Changes in tower height across trials served as a proxy for cumulative cultural learning within-subjects. Towers were measured from base to apex in centimetres (cm). Only towers that stood by themselves were measured. Maximum tower height: 50 cm. To compare performance across conditions with minimal data loss, if participants produced an optimally tall tower (i.e. stacking optimally or sub-optimally) on Trial 1, tower height (along with all other measures) was copied for Trials 2 and 3.

(iv) Statistical analyses

Statistical analyses were conducted in R v.4.2 [42] using the *stats* package in Rstudio [43]. Non-parametric tests (chi-squares) were used on categorical learning measures. The Holm [44] and Bonferroni correction procedures were used to correct for multiple chi-squares and ANOVA *post hoc* tests using the *RVAideMemoire* package [43] and JASP [45]. All *p*-values were two-tailed. Unless stated otherwise, only first trial responses while building the tower (i.e. process) are reported. Additional exploratory analyses are available in electronic supplementary material. Preliminary analysis showed that neither age nor gender identity correlated with any of the dependent measures. So, unless otherwise stated, these variables were excluded from analysis.

Data files can be found in the OSF website: https://osf.io/pjfq2/.

(b) Results

(i) Did adults evidence cultural learning: producing generative stacking (base) and linking (apex) responses?

Generative stacking (base)—optimal: On Trial 1, there were significant differences between learning conditions—baseline, imitation, emulation—($\chi^2_{2,101} = 11.58$, $p < 0.01$). Only participants in the imitation condition made more generative stacking responses than participants in the independent invention—baseline—condition (Bonferroni: $p < 0.01$). No other contrast was statistically significant. *Sub-optimal:* Groups did not differ ($\chi^2_{2,101} = 0.32$, $p = 0.85$).

Generative linking (apex): On Trial 1, differences between learning conditions were as not statistically significant ($\chi^2_{2,101} = 4.20$, $p = 0.12$).

Results are summarized in figure 3*b*.

(ii) Did adults evidence summative cultural learning: combining generative stacking (base) and linking (apex) responses?

Generative tower—optimal: On Trial 1, differences between learning conditions were significant ($\chi^2_2 = 8.6$, $p = 0.01$).

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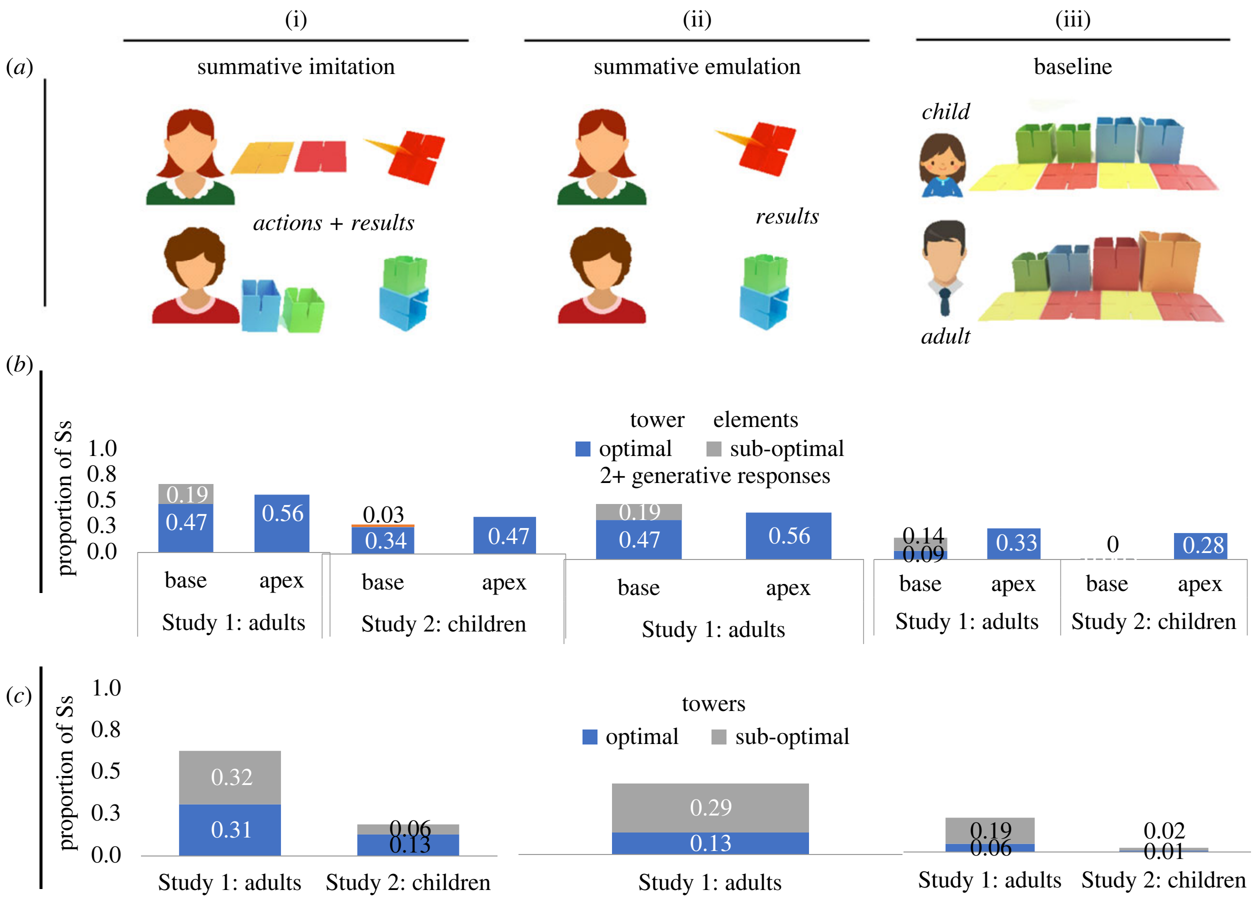

Figure 3. Results for Experiments 1 (adults) and 2 (children). Rows: (*a*) different learning conditions, (*b*) results for building individual tower elements (base, apex), (*c*) different towers. Columns: (i) summative imitation (imitation), (ii) summative emulation (emulation), (iii) independent invention (baseline). Note. *$p < 0.05$, + $p < 0.10$ represent differences from baseline. Errors are summarized in figure 5.

Specifically, more participants in the imitation condition produced an optimally tall tower consisting of generative stacking and linking elements than baseline participants (Bonferroni: $p < 0.05$). No other contrast was statistically significant (all $p > 0.10$). *Sub-optimal*: On Trial 1, differences between learning conditions were not statistically significant ($\chi^2_2 = 1.57$, $p = 0.46$).

Results are summarized in figure 3*c*.

To explore the role that age, sex and condition have in generative cultural learning, we examined predictors of our dependent variables using GLMs (generalized linear mixed models). We created GLMs that included condition (baseline, imitation, emulation) and age as our predictor variables. We did not include trial number as a factor because it significantly correlated with condition ($r = 0.31$, $p < 0.01$).

(iii) What factors predict generativity?

Generative stacking (base)—optimal. In addition to the intercept, there was a significant effect for the imitation condition (OR = 8.81, $p < 0.01$). The odds of optimally stacking cubes generatively in the imitation condition were 8.81 times greater than the odds in Baseline (i.e. 8.81 (imitation) × 1 (baseline)), or 881% more likely compared to baseline. There was also a marginally significant trend for emulation (OR = 3.84, $p = 0.06$) relative to Baseline; being in the emulation condition increased the odds of generatively stacking cubes (optimally) approximately 4 times, or 384% more likely compared to Baseline. No other predictor or interaction was significant. *Sub-optimal*: The model was not significant; no predictor or interaction was significant. Results are summarized in electronic supplementary material, tables S1 and S2.

Generative linking (apex): Imitation was marginally significant (OR = 2.64, $p = 0.06$), indicating that relative to Baseline, being in the imitation condition increased the odds of generative linking, on average, 2.64 times, or 264% more likely compared to Baseline. Results are summarized in electronic supplementary material, table S3.

(iv) What factors predict tower types?

Generative tower—optimal: The model produced a main effect for the imitation condition (OR = 8.34, $p = 0.012$). Specifically, the odds of participants producing the optimal tower in the imitation condition was 8.34 times greater than the odds in baseline, or 834% more likely compared to Baseline. No other predictor or interaction was statistically significant. *Sub-optimal:* Only the intercept was statistically significant. However, age by condition interaction approached significance (OR = 1.25, $p = 0.08$); the odds of producing the sub-optimal tower increased 1.25 times with each additional year in age in the imitation condition relative to the odds in Baseline, or 125% more likely compared to Baseline. No other predictor or interaction was significant. Results are summarized in electronic supplementary material, tables S4 and S5.

(v) Is there evidence of cumulative learning: tower height?

Tower height: To evaluate within-subject cumulative learning, we performed a repeated measures ANOVA that included

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Trial Height as the dependent variable with three levels corresponding to the three trials. Because the test of sphericity was not met (Mauchly test of sphericity: trial height, $W = 0.876$, approximate $\chi^2_2 = 12.96$, $p < 0.01$), we used the Greenhouse–Geisser correction procedure. There was an effect for trial number ($F_{1.78,174.22} = 41.71$, $p < 0.01$). Towers in T1 were significantly smaller than in T2 ($P_{\text{holm}} = 0.001$) that, in turn, were smaller than towers in T3 ($P_{\text{holm}} = 0.02$). There was also a main effect for each condition ($F_{2,98} = 5.17$, $p < 0.01$). Towers in Baseline were smaller than those in Imitation ($P_{\text{holm}} = 0.005$), but not Emulation ($P_{\text{holm}} = 0.15$). Tower height in the Emulation and Imitation conditions did not differ ($P_{\text{holm}} = 0.15$). The trial-by-condition interaction was not significant ($F_{3.56,174.22} = 0.83$, $p = 0.50$). Results are summarized in electronic supplementary material, figure S1 and table S6.

(c) Discussion

We found significant evidence of imitation (but not emulation) among adults, consistent with prior results [24]. Here, we also found evidence of generative cultural learning. Specifically, there was evidence of *generative* imitation. Participants in the imitation (but not emulation) condition produced more generative stacking and linking responses than participants in the independent invention (Baseline) group (cf. figure 3*b*), although these differences were only statistically significant for stacking responses. There was also evidence of *summative* cultural learning. When compared to Baseline, more adults in the imitation (but not emulation) condition combined generative stacking and linking responses to form an optimally tall tower (figure 3*c*). We also found evidence of cumulative learning within subjects. Across conditions, towers became taller with each additional trial. However, this effect was most pronounced in the imitation condition, relative to other conditions, including emulation (cf. electronic supplementary material, figure S1). Exploratory analysis using GLMs that included various predictors and their interactions rarely produced significant effects besides those for condition.

In an earlier study using this same task [24] we showed that adults overimitated stacking (base) and linking (apex) responses, consistent with episodic encoding. The results from the present study provide evidence that adults in the imitation condition represented demonstrations generically as well. That is, cubes, *in general*, can be stacked as demonstrated; squares, *in general*, can be linked and/or things with ridges can be combined (cf. table 1: goals, actions, dependencies). This conclusion is supported by adults' generative and summative responses across measures (i.e. figure 3*b*,*c*) and successively taller towers (electronic supplementary material, figure S1).

Performance in the emulation condition was relatively poor, replicating previous results [24]. These results confirm that end-state information alone lacks the relevant information necessary for producing discrete, generic—semantic—representations; or, at the very least, it appears very difficult to do so. Here, the end-state emulation condition favoured more episodic or holistic representations, as adults in this condition only saw tower elements, not the discrete actions that produced them (cf. table 1: actions, dependencies). Such holistic or episodic representations failed to produce significant generative responses (figure 3*c*). These results cast doubt on any strong claim that holistic representations play a significant role in cultural evolution.

Adults' generative as well as summative cultural learning skills in the imitation condition beg the following question: Do young, preschool age children with little to no formal schooling evidence similar levels of compositionality and generativity? Or are such skills themselves late-developing culturally learned products? Experiment 2 directly addressed these questions by testing preschoolers using the same task and analogous procedures.

3. Experiment 2

(a) Methods

Participants. A total of 66 children (females = 30) with a mean age of 5.09 years were tested in two independent conditions: Baseline ($n = 30$) and Imitation ($n = 32$) (s.d. = 0.86). This experimental design represented a deviation from the pre-registration plan, which included an emulation group. All participants were recruited and tested in the National Building Museum in Washington, DC following GWU IRB-approved procedures. Forty-one per cent of participants belonged to a minority group. See electronic supplementary material for demographic details.

Experimental task. The procedures used were identical to those of Experiment 1 with the following exception: during testing, children were given two green cubes (6 cm) and two blue cubes (7 cm). The maximum tower height was 44 cm (figure 4).

Learning phase. Children were randomly assigned to one of two independent learning groups: Summative Imitation and Baseline.

Demonstration phase. The same as Experiment 1, except that demonstrations during the summative imitation condition involved two live demonstrations by female research assistants showing children how to build the two tower elements, base and apex, using the same counterbalancing positions and script as in Experiment 1. And in contrast to adults in Experiment 1, children in the demonstration condition observed three live demonstrations (each approx. 1 min in length) before testing.

To summarize, the children's task differed from that of adults (described in Experiment 1) in the following ways. (i) Children saw live demonstrations (rather than a video recording), (ii) that were repeated three times prior to testing (rather than a single demonstration). (iii) During testing, children received two identical blue cubes and two identical green cubes (rather than four different cubes varying in size and colour) and (iv) only given only one response trial (instead of three).

(i) Measures and video coding procedures

Because children only had two different cubes (two blue and two green), a child-specific coding sheet was used. Otherwise, measures and coding procedures were identical to those described above for adults. Inter-rater reliability was high (0.99).

Testing phase. Same as Experiment 1, except that children were only given one trial to build the tallest possible tower. This represents another deviation from the pre-registered procedures. This procedural change was necessitated

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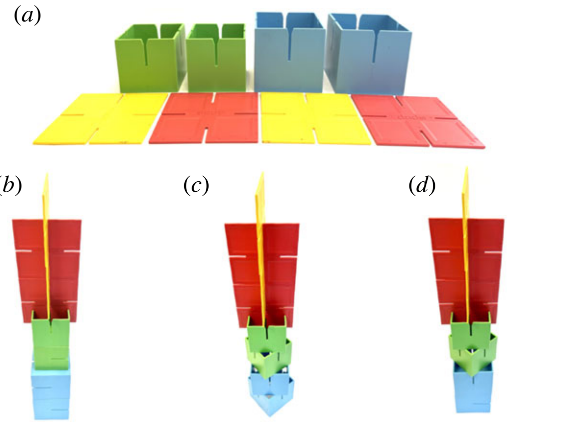

Figure 4. Child Tower Building Task. (*a*) Tower pieces consisted of cubes and squares. Cubes could be stacked to form the tower base element. Squares could be linked together via ridges to form the tower apex element. The apex could then be affixed to the base via the cube's ridges resulting in optimally tall towers (*b–d*). However, towers varied in structural soundness: optimal stacking on a solid surface (*b*), sub-optimal stacking by balancing cubes on edges (*c*) or consisting of optimal and sub-optimal elements (*d*). Note that during demonstration, participants saw the green cube stacked atop the blue cube and a red square linked with a yellow square (cf. figure 1).

by children's overall poor performance during testing and subsequent frustration with the task, precluding additional testing. See electronic supplementary material for additional details.

For children, target towers were any tower (with optimal or sub-optimal base) that measured at least 44 cm and could stand by itself. Seven participants' (three Baseline, four Imitation) tower height measures were imputed with the mean tower height of the respective condition.

(ii) Between-study measures

Error type. Type of error—Stacking, Nesting, Balance (figure 5)—on the first trial.

Error type count. A count measure of the total number of error types made (range 0–3) by participants.

Generative score. To estimate generative cultural learning, we produced a composite score of the total number of generative responses produced by adults (Experiment 1) and children (Experiment 2) while building tower components (base and apex). We defined generativity as the application of a demonstrated response to novel exemplars. For example, rotating and stacking (optimally or sub-optimally) the two new cubes (range of score: 0–2) and combining the third and fourth flat squares with the first and second that were demonstrated (range of score: 0–2). Total possible range of scores: 0–4.

(iii) Statistical analyses

Statistical analyses were the same as Experiment 1, except corrections were not used with chi-square tests since children only had two conditions, Baseline and Imitation. Because age and gender correlated with at least some of the dependent measures, we included them in all models.

Data files can be found in the OSF website: https://osf.io/pjfq2/.

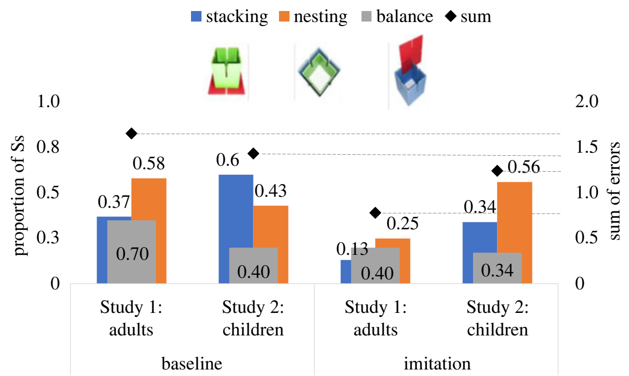

Figure 5. Different types of errors made by children and adults. Stacking errors: squares were placed flat atop or below cubes (or other squares). Nesting errors: smaller cubes nested inside larger cubes or squares nested inside larger cubes; both nesting and stacking errors failed to add to tower height (i.e. sub-optimal height). Balance errors: square balanced on edges of another cube or square or cube balanced on the edge of another cube (sub-optimal base). Balance errors increase tower height but at the expense of structural stability (i.e. sub-optimal structure). The graph shows the proportion of children and adults making each error type (left axis). Black diamonds correspond to the sums of those errors (right axis).

(b) Results

(i) Did children evidence cultural learning: producing generative stacking (base) and linking (apex) responses?

Generative stacking (base)—optimal: There were significant differences between the independent invention (baseline) and imitation learning conditions ($\chi^2_1 = 10.91$, $p < 0.01$). *Sub-optimal*: There were no significant differences between learning conditions ($\chi^2_1 = 0.002$, $p = 0.96$). *Generating linking (apex)*: Differences between learning conditions were significant ($\chi^2_1 = 40.34$, $p < 0.05$). Children in the imitation condition generatively linked squares more often than those in Baseline. Results are summarized in figure 3*b*.

(ii) Did children evidence summative cultural learning: combining generative stacking (base) and linking (apex) responses?

Generative tower—optimal: Differences between imitation and baseline were marginally significant ($\chi^2_1 = 2.68$, $p = 0.10$). Specifically, there was a statistically significant trend for more children in the imitation condition to produce an optimally tall tower consisting of generative stacking and linking elements than children in baseline. *Sub-optimal*: Differences between learning conditions were not statistically significant ($\chi^2_1 = 0.29$, $p = 0.59$). Results are summarized in figure 3*c*.

(iii) What factors predict generativity?

To explore the role of age and gender in generative cultural learning, we created GLMs for children that included age, gender and condition (baseline, imitation). Gender was included because preliminary data analysis showed it correlated with performance in some measures.

Generative stacking (base)—optimal: The imitation condition was significant (OR = 17.8, $p < 0.01$); when compared to the odds in Baseline, children's odds of generatively stacking cubes were 17.8 times greater in the imitation condition, or

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1780% more likely compared to Baseline. No other effect (e.g. age, gender) or interaction was significant. Results are summarized in electronic supplementary material, table S12. *Sub-optimal*: There were no significant predictors or interactions in the model. Results are summarized in electronic supplementary material, table S12.

Generative linking (apex): The intercept was significant, and there was a main effect for Condition (OR = 3.51, $p < 0.05$), where imitation > baseline. When compared to the odds in Baseline, the odds of children generatively linking squares were 3.5 times greater in the imitation condition, or 351% more likely compared to Baseline. None of the other predictors (e.g. age, gender) or interactions in the model were significant. Results are summarized in electronic supplementary material, table S13.

(iv) What factors predict tower types?

Optimal and sub-optimal: None of the predictors or interactions in the models were significant. Results are summarized in electronic supplementary material, tables S14 and S15.

(v) Is there evidence of cumulative learning: tower height?

Mean tower height in the imitation condition ($M = 29.20$, s.d. = 8.75) was greater those in the Baseline condition ($M = 25.70$, s.d. = 7.38; $t_{60} = -1.69$, $p < 0.05$). GLMs including age, gender and condition as factors showed that only the intercept was significant (Estimate = 15.37, $p < 0.05$). However, gender (Estimate = 3.73, $p = 0.07$) and the imitation condition were marginally significant (Estimate = 3.7, $p = 0.07$), indicating that male children built towers that were, on average, 3.7 cm taller than those built by females. Likewise, children in the imitation condition built towers that were 3.7 cm taller than those in baseline. There were no other significant predictors or interactions (cf. electronic supplementary material, table S16).

(vi) Did children and adults make similar errors when building the tower?

Given the similar procedures in Experiments 1 and 2, we were able to compare children's and adults' errors as well as their propensity for generativity.

To answer this question, we created GLMs with a binomial error distribution and logit link function that included one of three different types of errors, Balance, Nesting, Stacking (figure 5*a*), as the dependent measure and population (Child, Adult) and condition (Baseline, Imitation) as the predictors. All models included Population (children, adults), Condition (baseline, summative imitation) and the interaction of Population and Condition as predictors. Only baseline and summative imitation were analysed as they were the only two conditions shared by both populations across experiments.

Population stacking errors: The analysis of Stacking Errors showed a significant effect for condition (Imitation, OR = 0.25, $p < 0.05$). The odds of making a stacking error in Baseline were 4 times greater than the odds in imitation, or 400% more likely in Baseline compared to Imitation. Results are summarized in electronic supplementary material, table S18.

Population nesting errors: The GLM for Nesting Errors produced a significant condition by population interaction (figure 5: OR = 6.85, $p = 0.01$). For participants in the imitation condition, the odds of making a nesting error were almost 7 times greater for children than the odds for adults, or 685% more likely for children compared to adults. Results are summarized in electronic supplementary material, table S19.

Population balance errors: An analysis of Balance Errors showed a main effect for condition (OR = 0.30, $p = 0.02$), where the odds of making a balance error in Baseline was 3.33 times greater than the odds in Imitation, or 333% more likely in Baseline compared to Imitation. There was also a main effect for population (Children, OR = 0.29, $p = 0.02$), with the odds of adults making a balance error being approximately 3.5 times greater than the odds of children making that same error, or 350% more likely for adults compared to children. The population by condition interaction was not statistically significant. Results are summarized in figure 5*b* and electronic supplementary material, table S20.

To evaluate whether children and adults made the same number of errors, we used a GLM that included Error Type Count (counts of each error type) as the dependent variable and population (child, adult), condition (baseline, imitation) as well as their interaction as factors. A Poisson distribution was used because the sum of measures is a count measure and the identity link, as the results were above zero. Condition was a significant predictor of errors (Estimate = −0.203, $Z = -0.651$, $p < 0.01$). Specifically, participants (children and adults) in the imitation condition made −0.086 fewer scale errors than those in Baseline. Neither population nor the condition by population interaction were statistically significant, though this trend was more pronounced in adults than in children. Results are summarized in figure 5*b* and electronic supplementary material, table S21.

(vii) Did children and adults evidence equivalent levels of generativity?

Population generativity score: A linear model using the generativity score as the dependent variable and population (child, adult) and condition (baseline, imitation) as predictors showed a main effect for the imitation condition (Estimate = 1.25, $p = 0.001$), where participants in the imitation condition were 1.25 scale points higher on their generativity score than those in Baseline, on average. Neither population nor the population by condition interaction was statistically significant (cf. electronic supplementary material, table S22).

(d) Discussion

Like adults in Experiment 1, children evidenced generative cultural learning across measures, extending the stacking of cubes and linking of squares to additional cubes and squares (i.e. generative base and apex, respectively). However, unlike adults, most children struggled to combine these generative tower elements to form an optimal tower (cf. figure 3*c*) without making the tower collapse. These errors were more indicative of fine motor (i.e. action) and motor coordination (i.e. dependency) difficulties than representational difficulties (cf. table 1). Consider that in the present study, almost 20% of children (1 : 5) combined the generative tower elements (base, apex) and demonstrated summative cultural learning. But in a previous study [24], 42% of children

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(3 : 7) combined tower elements. But that earlier task included just four tower pieces. The present task included eight or twice as many. Nonetheless, children appear to have encoded what they witnessed generically as evidenced by their generative responses.

We do not have data that children—like adults—overimitate[3] on the Tower Building Task. However, many studies have found that children this age regularly overimitate across a variety of tasks [46]. That evidence, together with results from this study, suggests that children may also be capable of producing multiple representations during encoding, as appears to be the case with adults. These different representations would be available during retrieval to achieve a variety of goals. However, additional research is required to verify that suspicion.

Replicating earlier work with a more difficult version of the Tower Building Task [24], we found evidence that children and adults, despite the wide gulf of experience, performed similarly on composite measures (generative score, errors) collected in both studies (imitation, baseline). Those results are inconsistent with hypotheses that might argue that the compositional nature of human cultural learning is dependent on specific pedagogical practices (e.g. [47]). Instead, results indicate that performance in the generative version of the Tower Building Task was minimally affected by formal schooling. We cannot stress this last point enough. Formal schooling is a meta-cognitive gadget; a cognitive gadget that produces cognitive gadgets. Minimally, schooling should replace, modify and/or optimize early acquired gadgets. However, that was not the case. Perhaps the Tower Building Task primes folk physical (sensory and perceptual) biases known to be resistant to formal education [48]. While such biases may explain the continuity observed in errors made by children and adults (cf. figure 5), it is unclear whether they also explain the observed similarities in generative responses.

4. General discussion

For many, compositionality is what makes cognition, and all its products, generative, creative and seemingly boundless. In the archaeological record, evidence of what appears to be iterative combinations of spears with different blades affixed at varying orientations (presumably with unique functions) dates back to at least 70 000 years ago [49]. Other iterative—compositional—behaviours involving ochre-use applied to different objects (again, presumably, for different functions) date as far back as 300 000 years ago [50], a time associated with the first anatomically modern humans [51]. None of these behaviours are evident in the diverse and widespread cultures of great apes, for example [52,53]. Moreover, experimental studies summarized by Poti & Parenti [54] show that non-human apes, in contrast to young human children, rarely (if ever) show iterative exploratory play such as stacking objects to make a tower or linking objects in sequences. These are decidedly odd behaviours that are, nonetheless, common in the earliest play of human children at around 18 months [55], soon after two other uniquely human milestones, walking and talking.

Here, we sought to evaluate the hypothesis that *human culture is uniquely cumulative because human social learning is distinctively compositional by default; evident early in development prior to formal schooling* [35,40,41]. To test this hypothesis, two studies measured whether (i) participants iteratively extend observed actions to new exemplars and (ii) combined those iterative responses within and between objects to produce novel products. To evaluate whether these cultural learning skills are deployed by default, without formal or explicit instruction, we compared adults' performance to that of preschool age children.

Both Studies 1 and 2 replicated and extended prior results [24] by showing generative cultural learning in adults and children, respectively. Specifically, children and adults showed generative imitation across two different models operating on two distinct object sets (figure 1: cubes versus squares). Children, like adults, showed significant levels of generativity when building the tower's base and apex (figure 3*b*). However, unlike adults, this effect was only marginally statistically significant (figure 3*c*). Nonetheless, there were remarkable similarities between children's and adults' performance across learning measures. Composite measures capturing both populations' errors and generativity produced few condition by population interactions. These results, coupled with those showing overimitation [24,46], where individuals faithfully copy all demonstrated responses whether meaningful or not, suggest that adults and children might be encoding observed responses in multiple formats: (i) episodic encoding in end-state emulation (Studies 1 and 2 [24]), overimitation (adults, Study 1 [24]) and 'full' imitation learning conditions (Study 2 [24]) versus (ii) semantic/generic encoding in summative imitation conditions and response phase (present study). If true, access to multiple representations, along with the ability to judiciously select among them, may explain species differences in social learning.

Still, the results comparing children and adults should be interpreted cautiously given the differences in procedures used in Experiments 1 and 2. These procedural differences may have produced distinct representations and inferences in the two populations. However, in both cases, the additional pieces presented to children and adults were novel relative to what was demonstrated. For instance, children observed how to stack the smaller green cube atop the larger blue cube (figure 1) but received no information about how to stack two blue cubes (figure 4). Adults had a similar (but harder) problem. They saw how to stack the blue and red cubes but had to infer how to stack the two new cubes that differed in size and colour.

Another limitation of the study is that the motor demands inherent in the generative version of the Tower Building Task may have exceeded the capabilities of preschoolers. These task features may have limited their ability to combine the generative responses (stacking and linking) they produced. Admittedly, basic representational and executive functioning limitations [10] cannot be ruled out. However, the main challenges appeared to be difficulties selecting and coordinating motor responses necessary for fitting or combining objects [56–58]. These motor difficulties limit our ability to fully appreciate children's earliest generative and summative cultural learning competence. For these same reasons, other animals, including primates, might experience difficulties with this task. See electronic supplementary material for additional details.

We also do not want to overlook an important (and surprising) result: the poor performance of adults in the

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emulation condition, here and in prior studies [24]. Adults in the emulation learning condition struggled producing generative responses (figure 3*b*,*c*). Moreover, the towers they produced did not become progressively taller relative to those in Baseline (electronic supplementary material, figure S1). These results indicate that generative cultural learning is significantly facilitated by learning contexts that allow for discrete representations of objects, actions and their affordances as was the case in the imitation condition. By contrast, generativity is hampered when only object segments or 'chunks' can be represented without any opportunity for parcellation as was the case in the emulation condition. These results suggest that the generativity of human cultural learning is driven primarily by compositional rather than holistic processing. Although, we want to emphasize that these processes are unlikely to be mutually exclusive (e.g. [59,60]). Still, we hypothesize that in problem-solving social learning contexts, the more opportunities there are to form discrete representations, the greater the opportunity for generativity.

These results reframe the debate about the role of imitation and emulation in cultural evolution [14,25,61]. It is not just that non-human animals fail to faithfully copy others' responses. The main problem is that whatever is copied is not compositional, hence, not generative. That is, whatever is learned is not intuitively combined or integrated in the individual's cultural repertoire as is the case with human children and adults alike [24,28].

Surprisingly few studies have explored the types of representations and cognitive processes underlying performance in problem-solving and social learning tasks, including generative (recursive, iterative), analogical [62] and inferential/derivational [28] processes. Future studies may want to identify the types of representations and processes driving CCE [63]. Specifically, studies might want to understand the frequency of different iterative processes, the contexts in which they are most evident, their relative adaptiveness and/or functionality and whether the archaeological record provides reliable signals by which to identify and discriminate between them.

Finally, we do not want to overlook the fact that all our participants were from a western, educated, industrialized, rich and democratic (WEIRD) culture [64]. Accordingly, some might be tempted to argue that the Tower Building Task measures a non-functional, culture-specific skill. But creating tall, stable, structures requires folk physical concepts likely to be universal [48,65]. Similar physical concepts are inherent in dwellings like igloos and teepees, tools like ladders and stools, as well as activities like tree-climbing. Still, these are assumptions that require empirical validation.

5. Conclusion

Social learning and behavioural traditions are widespread in the animal kingdom. Yet, humanity's imitative skills and open-ended cumulative cultural learning abilities are unparalleled. Explaining such discontinuities is a major challenge in the cognitive sciences. To date, most cumulative cultural learning research has focused on individual and population characteristics, different social and informational contexts and copying fidelity. Few have considered the underlying cognitive representations [66] and necessary computations that turn social learning (or group-specific traditions) into cultural learning (or cumulative culture). That is, open-ended, generative responses that are compositional, accumulating within individuals during their lifetime and remaining in their population across generations [67,68].

Using a Tower Building Task in a summative learning paradigm, we showed that children and adults alike appear to encode demonstrated responses by different models generically (and perhaps, episodically, as well). During recall, participants appear to use these different representations to extend the limited knowledge they observed to novel exemplars. This compositional process resulted in generative responses that were both novel and more complex than what was witnessed.

Although laboratory animals may be trained to do one or more of these actions or even acquire some of these skills [69–71] humans engaged in these behaviours spontaneously, with little to no explicit training. Moreover, unlike other animals, humans do not use these skills in isolation or in restricted task domains. Instead, the compositionality of knowledge [30,31,72] appears to be humanity's default cognitive mode; a habit of thought that operates across domains in a seemingly open-ended manner; one that develops early in humans but not in other primates [54]. These suites of cognitive skills (i.e. representations of varying formats that are compositional) may explain why human cultures do not just evolve towards greater efficiency [21] but also towards increasing complexity [67] sometimes within a single generation. Greater empirical attention to how cultural knowledge is encoded and processed may be necessary to answer whether the observed similarities between human and animal cultures are superficial or brain deep.

Ethics. GWU IRB (Institutional Review Board) approved all procedures. GWU IRB no. 051134.

Data accessibility. Data files can be found in the OSF website: https://osf.io/pjfq2/ [73].

The data are provided in electronic supplementary material [74].

Authors' contributions. A.V.: data curation, formal analysis, methodology, writing—original draft; N.B.: data curation, investigation, writing—review and editing; F.S.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, supervision, writing—original draft.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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Endnotes

[1]See electronic supplementary material for additional details.

[2]Note that the goal may be focused but exploratory (e.g. guessing someone's password randomly).

[3]Subiaul and Stanton operationalized overimitation as copying subpar stacking (medium–large–small cube) or linking squares using an alternating colour rule (red–yellow–red square).

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