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Developmental origins of cognitive offloading

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Many animals manipulate their environments in ways that appear to augment cognitive processing. Adult humans show remarkable flexibility in this domain, typically relying on internal cognitive processing when adequate but turning to external support in situations of high internal demand. We use calendars, calculators, navigational aids and other external means to compensate for our natural cognitive shortcomings and achieve otherwise unattainable feats of intelligence. As yet, however, the developmental origins of this fundamental capacity for *cognitive offloading* remain largely unknown. In two studies, children aged 4–11 years ($n = 258$) were given an opportunity to manually rotate a turntable to eliminate the internal demands of mental rotation—to solve the problem in the world rather than in their heads. In study 1, even the youngest children showed a linear relationship between mental rotation demand and likelihood of using the external strategy, paralleling the classic relationship between angle of mental rotation and reaction time. In study 2, children were introduced to a version of the task where manually rotating inverted stimuli was sometimes beneficial to performance and other times redundant. With increasing age, children were significantly more likely to manually rotate the turntable only when it would benefit them. These results show how humans gradually calibrate their cognitive offloading strategies throughout childhood and thereby uncover the developmental origins of this central facet of intelligence.

1. Introduction

What is *cognition*? Although prominent theorists disagree on the answer to this question [1], most traditional formulations continue to include only mental processes occurring within the physical boundaries of the individual [2]. However, these conventional perspectives are being challenged by a growing number of philosophers, biologists and psychologists who advocate for definitions of cognition to incorporate interactions between the individual and the environment [3–7]. Most prominently, Clark & Chalmers' [8] *extended mind* thesis describes cognition as a cohesive system consisting of both internal processes and interactions with the external environment that facilitate performance on cognitive tasks. When relying on internal processes alone, humans often encounter hard limits—we have restricted memory storage [9], strong constraints on attention [10,11] and our perceptual abilities continually decline with age [12,13]. Making use of external manipulations or artefacts to intentionally reduce the internal demand of a task, or *cognitive offloading* [14], provides an avenue for bypassing or compensating for these limits, thereby enabling more efficient problem solving and the achievement of otherwise unattainable feats of intelligence.

Many non-human animals show behaviours that indicate sensitivity to cognitive task difficulty [15–17], and some even alter their environments in ways that appear to enhance cognitive processing [6,7]. Among invertebrates, for instance, orb-weaver spiders increase the tension of their webs when hungry, such that they are more likely than usual to perceive and respond to catches of small prey [18,19]; bumblebees deposit scent marks during foraging of flowers, and later use these marks (or those deposited by a conspecific) as indicators that a particular flower is unlikely to contain a reward [20,21]; and ants and other social insects create complex pheromone trails that store navigational information in the environment, often to the benefit of a broader colony [22]. Among mammals, it has recently been argued that territorial scent-marking may play a vital role in the formation and use of cognitive maps, thereby enhancing the efficiency of navigation [23,24]. Nonetheless, these behaviours are not necessarily underpinned by metacognitive awareness of cognitive difficulty [25] and may instead be attributed to instincts [26] or associative learning [15,27,28]. Adult humans, by contrast, can be acutely aware of their cognitive struggles and readily draw on this metacognitive awareness to offload cognitive demand into the environment [14,29,30]. Indeed, our evolved capacity to reflect on our internal cognitive limits may explain why only humans appear to create and interface with external 'thinking tools' [31] like maps, calculators and written text [32].

Consider how humans use cognitive offloading to enhance memory retrieval [33–39]. We frequently set reminders to help ourselves remember to perform tasks in the future, for example by creating alarms, writing lists, or leaving items in conspicuous locations. Critically, our use of external reminders increases when there is more information to be remembered [33] and when subjective confidence in unaided memory ability is lower [34]. Such patterns can be explained by the fact that reminder setting and other forms of offloading typically involve a cost of time and effort, which is weighed against the benefit gained by alleviating cognitive demand [14,30]. In other words, adults tend to be *selective* in their use of these behaviours, relying on internal processes in situations of relatively low cognitive demand but turning to external manipulations in situations of higher cognitive demand. This selectivity appears to be driven by metacognitive evaluations of one's own internal ability to solve a particular task, and decisions to use external manipulations when that internal ability is judged to be inadequate or inefficient [29,30,40]. Selective cognitive offloading can enhance performance in a wide variety of behavioural domains [14] without incurring the excessive costs of time and effort that would come with indiscriminate environmental manipulations independent of internal demand.

Despite being a central facet of complex human behaviour, the developmental origins of cognitive offloading remain largely unexamined. Previous studies have shown that young children can enhance internal cognitive performance with behaviours such as finger-counting [41] and by questioning knowledgeable adults in situations of uncertainty [42], and also that they can benefit from cognitive offloading cues provided by an experimenter [43–45]. Yet, the critical question of when and how humans begin to selectively modify their environment to overcome internal cognitive shortcomings remains unanswered [46]. Do young children, like adults, offload cognition more readily in situations of higher internal demand? To tackle this question, we examined children's offloading propensities in the domain of one of the most robust and well-replicated phenomena in all of cognitive science: *mental rotation* of visuospatial stimuli [47].

Decades of research have comprehensively charted the human capacity for mental rotation [48–50], with children as young as four [51–54] showing a linear increase in reaction time corresponding to linear increases in the degree of rotation [47,55,56]. Yet, in everyday life, humans often use mental rotation only as a last resort. When using a GPS device to navigate, for instance, we could either rotate the map mentally, or simply adjust the settings to ensure it automatically matches our orientation in space. Likewise, when handed an inverted restaurant menu, we could either mentally rotate the text to read it, or simply turn the menu around in our hands. Such behaviours alleviate cognitive demand via the process of *external normalization*, or by ensuring that our perception of the relevant stimulus corresponds with our internal representation of that stimulus stored in memory [57]. Studies have shown that adults often spontaneously tilt their heads to read rotated text presented on a computer screen [29,57], and that this behaviour is more likely to be used as the degree of rotation and number of words increase [29]. Adults are therefore selective in their external normalizations of rotated stimuli, offloading more frequently when mental rotation demand is higher [57].

Here, we report two studies in which children were provided with the opportunity to manually rotate a turntable to eliminate the internal demands of mental rotation. Studying children's cognitive offloading in this context has considerable advantages. First, because there is a linear relationship between the degree of mental rotation and the level of internal demand [47,51], it is possible to accurately assess whether children selectively deploy offloading behaviour as a function of this demand (as in study 1). Second, because there are some circumstances in which external normalizations of rotated stimuli do not alleviate cognitive demand [29], it is also possible to examine whether children have an overreliance on environmental manipulations when performing cognitive tasks (as in study 2).

2. Study 1

(a) Participants

In total, 126 children (71 males and 55 females) aged between 4.44 and 11.83 years (mean = 8.20, s.d. = 1.93) were included in analyses. Age was analysed as a continuous variable, with significant effects followed up by splitting participants into four pre-specified age groups: (i) 4- and 5-year olds, (ii) 6- and 7-year olds, (iii) 8- and 9-year olds, and (iv) 10- and 11-year olds. See the electronic supplementary material, table S1 for the breakdown of participants by age group and sex. The sample was mostly white and middle-class, and from a medium-sized Western and industrialized city.

(b) Materials and methods

In study 1, we presented children with an adaptation of Shepard and Metzler's [47] original mental rotation paradigm. As seen in figure 1, children were shown (i) an upright human figure and (ii) a rotated human figure. Each of the figures had either their right arm or left-arm facing upwards [51]. On each trial, children had to answer 'same' if the figures were identical, showing the same arm facing upwards, or 'different' if the figures were mirrored, showing different arms facing upwards. The angular disparity between the figures was varied (0 to 180 degrees at 20-degree increments), with all children completing one 'same' and one 'different' trial for each angle in a

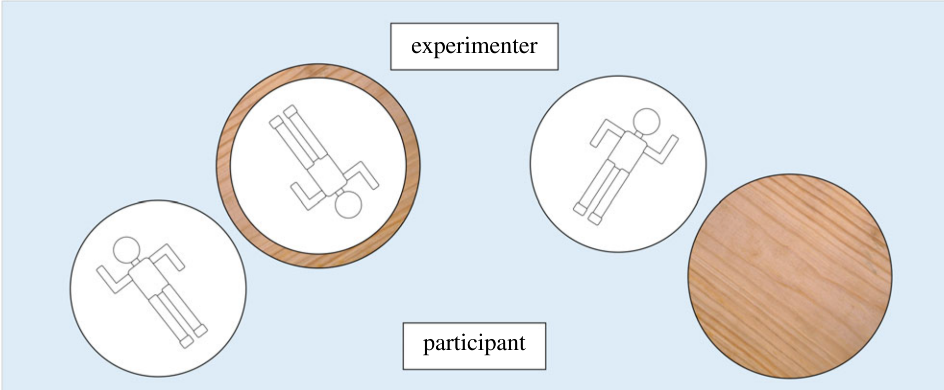

Figure 1. An illustration of the study 1 set-up. On each trial, a rotated figure was placed on a rotatable turntable next to an upright figure. Rotating the turntable so that the rotated figure matches the orientation of the upright figure makes it easier to compare whether the figures are identical or mirrored. To reduce experimenter error, two upright figures (one with the left-arm facing upwards, and the other with the right arm facing upwards) were placed on the ground on the left-hand side of two rotatable turntables. Rather than the experimenter changing the upright figure from 'left' to 'right' or vice versa on each trial, the child simply moved between the two setups on alternating trials. In the above example, the child would be asked to concentrate on the two stimuli on the left, with the option to rotate the turntable to reduce the angular disparity (currently 180°). (Online version in colour.)

counterbalanced order, resulting in a total of 20 trials per child. Critically, the rotated figure was always presented on a turntable, allowing children to solve the problem by simply rotating the turntable (i.e. external normalization) rather than an internal cognitive representation of the rotated figure (figure 1). To teach children that the turntable could rotate, each child first completed a preliminary rotation activity and was then told 'in this game, you can move these [turntables] whenever you like'. Rotation was operationalized as any time a child used the turntable to reduce the angular disparity between the upright and rotated figures, and this variable was measured at the moment the child provided their answer of 'same' or 'different'. During testing, the experimenter noticed that some children were tilting their heads rather than rotating the turntable, and so we decided to also score instances of head tilting that occurred after the experimenter placed a stimulus sheet onto the turntable (i.e. head tilting was not scored if the child simply had their head in a tilted position before the beginning of the trial). The coding of rotation and head tilting was completed using recorded footage of all participants.

A large body of findings indicates that mental rotation demand linearly increases with the degree of rotation [47,55,56]. Therefore, if children's likelihood of engaging in cognitive offloading is driven by the internal demand of the task, as in adults [14,33,57], then they should be more likely to manually rotate the turntable as the angular disparity between the upright and rotated figure increases. Given that cognitive offloading involves metacognitive judgements about one's own internal ability to solve a task [34,36,40], and given the well-established increases in children's metacognition throughout early childhood [58–60], we expected that such selective rotation would become more prevalent with age. To further explore children's metacognitive reflections on the task, we also included a crude, categorical measure of children's belief that task difficulty increased as the angular disparity between figures increased (both before and after the task). As basic metacognitive knowledge appears to emerge around the fourth year of life [58–60], we expected that even the youngest children in our sample would perceive such a relationship between angular disparity and task difficulty. Further methodological details are reproduced in the electronic supplementary material, Note S1.

(c) Results and discussion

Children's use of manual rotation across trials was analysed using generalized linear mixed models (GLMMs) with a binomial dependent variable (rotation versus no rotation) and a random intercept for participant. As shown in figure 2*a*, children across ages were significantly more likely to manually rotate the turntable as the angular disparity between figures increased, $\chi^2_{2391,n=126} = 304.30$, $p < 0.001$ ($w = 1.55$), paralleling the classic relationship between angle of mental rotation and reaction time [47,55,56]. However, contrary to predictions, this pattern of manual rotation did not vary linearly with age. There was no significant interaction between angular disparity and age, $\chi^2_{2390,n=126} = 2.30$, $p = 0.129$ ($w = 0.14$), consistent with the notion that children of all ages were similarly selective in their use of manual rotation (see the electronic supplementary material, table S2). However, this lack of an interaction does not tell the whole story. As also shown in figure 2*a*, 6- and 7-year olds appeared to be considerably more selective in their rotation than 4- and 5-year olds, with the use of rotation (selective or not) subsequently decreasing in the older age groups. This impression was confirmed by a post-hoc exploratory analysis, where we included only participants aged 4 to 7 and found a significant interaction between this limited age variable and angular disparity, $\chi^2_{983,n=52} = 9.70$, $p = 0.002$ ($w = 0.43$). In other words, among the younger half of our sample, children were significantly more likely to rotate as a function of angular disparity with increasing age. One interpretation is that children's *capacity* for selective rotation does indeed increase consistently throughout childhood, but that only some children in the older half of the sample *chose* to rotate the turntable accordingly as they did not find the mental rotation task particularly difficult.

Consistent with this interpretation, further analyses revealed that older children were significantly more likely to provide accurate answers than younger children, $\chi^2_{2390,n=126} = 24.26$, $p < 0.001$ ($w = 0.44$), despite their lower frequency of manual rotation. Children were also more likely to provide accurate answers at smaller

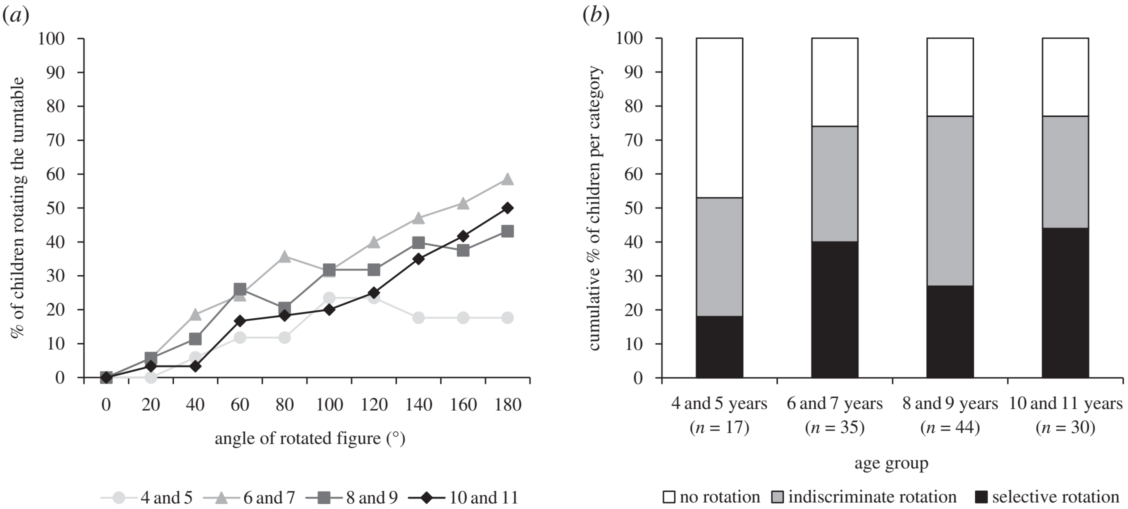

Figure 2. (*a*) The percentages of children who rotated the turntable at each angle (0–180 degrees) in study 1, displayed according to age group. Across ages, children were more likely to manually rotate the turntable as the angular disparity between figures increased. (*b*) The cumulative percentages of children per age group demonstrating selective rotation, indiscriminate rotation and no rotation.

degrees of angular disparity, $\chi^2_{2390,n=126} = 63.11$, $p < 0.001$ ($w = 0.71$), and if the upright figure had its left-arm facing upwards, $\chi^2_{2390,n=126} = 8.40$, $p = 0.004$ ($w = 0.26$; see the electronic supplementary material, table S3 for model details and note S2 for explanation of the unanticipated left-arm effect). Most importantly, children were significantly more accurate when they chose to rotate the turntable, $\chi^2_{2390,n=126} = 14.92$, $p < 0.001$ ($w = 0.34$), indicating that adopting the external strategy did indeed simplify the cognitive task. There was, however, no interaction between turntable rotation and angle, $\chi^2_{2389,n=126} = 3.34$, $p = 0.068$ ($w = 0.16$), inconsistent with expectations that rotation at higher angular disparity would improve performance more than rotation at lower angular disparity. This was probably owing to ceiling effects—even at higher angular disparity, children frequently provided accurate answers without manually rotating the turntable (see the electronic supplementary material, figure S1). Exploratory analyses revealed no sex differences in children's use of rotation, $\chi^2_{2391,n=126} = 0.19$, $p = 0.664$ ($w = 0.04$), or accuracy of answers, $\chi^2_{2391,n=126} = 0.05$, $p = 0.832$ ($w = 0.02$).

To further explore children's manual rotation behaviour, individual participants were sorted into three mutually exclusive categories. *Selective rotators* were significantly more likely to rotate the turntable as the angular disparity between figures increased, as indicated by a significant within-individual point-biserial correlation between manual rotation and angular disparity across 18 trials (zero-degree trials were removed as rotation on such trials was not possible). *Indiscriminate rotators* rotated the turntable at least once during the experimental task but did not meet the selective rotator criteria, and *non-rotators* did not rotate the turntable on any trial. Post-hoc point-biserial correlations were conducted to assess whether the likelihood of being categorized as a selective rotator increased with age. These correlations were performed twice—once including all participants, $r_{\text{pb}_{124}} = 0.05$, $p = 0.582$, and once excluding the non-rotators, $r_{\text{pb}_{89}} = 0.01$, $p = 0.922$—in order to account for the possibility that some non-rotators may have been capable of selective rotation but simply felt that they lacked permission to rotate the turntable. As is evident in figure 2*b*, the proportion of children engaging in selective manual rotation did not follow any clear age-related pattern. There was also no significant correlation between age and all forms of rotation (selective or indiscriminate), $r_{\text{pb}_{124}} = 0.10$, $p = 0.288$.

One interesting secondary finding was some children's spontaneous choice to rotate their heads towards the orientation of the rotated figure, rather than rotating the turntable. Thirty-six of the 126 participants (28.57%) tilted their heads at least once during the experimental task. This form of external normalization [57] did not significantly vary by age, $\chi^2_{2390,n=126} = 3.52$ $p = 0.061$ ($w = 0.17$), although none of the 4- and 5-year olds showed it (see the electronic supplementary material, figure S2). The prevalence of head tilting increased as the angular disparity between figures increased, $\chi^2_{2390,n=126} = 51.01$, $p < 0.001$ ($w = 0.64$), and this effect did not significantly interact with age, $\chi^2_{2389,n=126} = 0.03$, $p = 0.859$ ($w = 0.02$; see the electronic supplementary material, table S4). Yet, head tilting had no significant effect on accuracy, $\chi^2_{2389,n=126} = 0.48$, $p = 0.488$ ($w = 0.06$; see the electronic supplementary material, table S5). Notably, when children tilted their heads, the perceived angular difference between the two figures remained the same, and so it is perhaps unsurprising that this behaviour did not facilitate recognition of whether the figures were identical or mirrored. One possibility is that these children were attempting to match the rotated figure with a representation of the upright figure stored in working memory, (incorrectly) believing that this would benefit their performance.

Binomial tests revealed that children of all ages performed above chance on the prospective and retrospective metacognitive tasks (see the electronic supplementary material, table S6). Furthermore, the likelihood of children answering as expected did not significantly increase with age on either the prospective task, $r_{124} = 0.14$, $p = 0.122$, or the retrospective task, $r_{124} = 0.08$, $p = 0.372$. This indicates that, as intended by our design of the study, children of all ages perceived that task difficulty increased as the angular disparity between figures increased.

These results show that even from 4 and 5 years old, some children possess metacognitive awareness about mental rotation difficulty and are able to transform this awareness into selective manual rotation. Yet, many children did not appear to be selective at all—they did not rotate the turntable significantly more frequently as the angular disparity between figures increased. One possibility is that many children have an *overreliance* on external normalization [29], in that they tend to rotate stimuli to match what they usually see even

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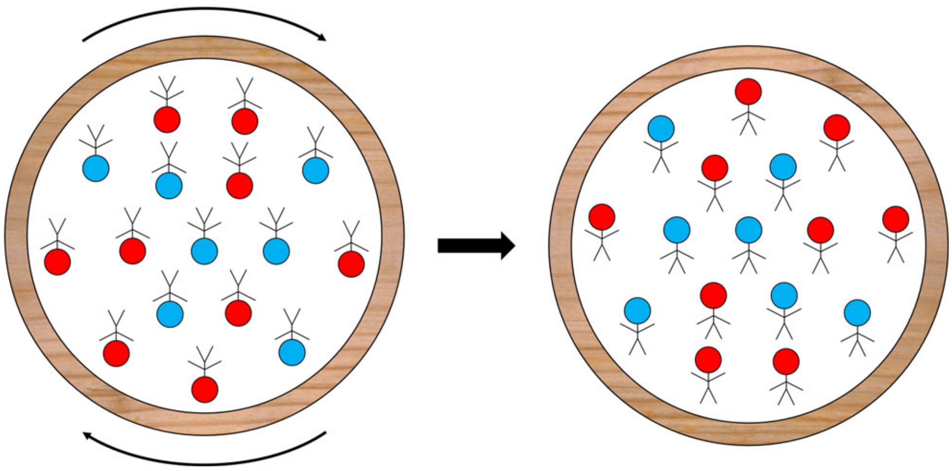

Figure 3. An illustration of the study 2 set-up. A single stimulus sheet was presented on a rotatable turntable (left panel). Rotating an inverted sheet so that the stick figures are upright (right panel) facilitates counting the number of figures with their arms pointing up but makes no difference to counting the number of figures with blue faces. (Online version in colour.)

when it is not particularly useful to do so (e.g. to render figures upright even at lower angles). Indeed, the fact that children often spontaneously tilted their heads rather than rotating the turntable, even when doing so did not facilitate performance, is consistent with the notion that children may not be particularly adept at identifying the usefulness of external manipulations in at least some cognitive tasks. An alternative possibility, however, is that the children who appeared to be indiscriminate in their manual rotation simply had a lower threshold for what they considered to be useful. In particular, some children may have decided that the minor benefit of manually rotating the turntable at lower angles was worth the few seconds of effort that it took to do so, even if the anticipated performance gain was not as great as at higher angles. The task we used in study 2 was able to differentiate between these explanations, as it included conditions where manual rotation was either useful or entirely redundant—independent of the angular orientation of the stimuli.

3. Study 2

(a) Participants

In total, 132 children (56 males and 76 females) aged between 4.03 and 11.99 years (mean = 7.72, s.d. = 2.02) were included in analyses. Age was analysed as a continuous variable, with significant effects followed up by splitting participants into the same four pre-specified age groups as in study 1. See the electronic supplementary material, table S7 for the breakdown of participants by age group and sex. The sample was mostly white and middle-class, and from the same medium-sized Western and industrialized city as study 1.

(b) Material and methods

In study 2, children were presented with a single stimulus sheet on a rotatable turntable, rather than two stimulus sheets as in the first study. Each sheet showed 16 stick figures that varied on two dimensions: (i) they either had a blue or red face, and (ii) they either had their arms pointed up or down (figure 3). Sheets were presented with the stick figures in an upright (0 degrees) or inverted (180 degrees) orientation, and on each of the 16 trials, children were asked to count either the number of blue figures or the number of figures with their arms pointed up (in a counterbalanced order). Although counting arms was more cognitively demanding when the figures were inverted than when they were upright (because inverted arms had to be mentally rotated), counting blue faces was equally easy in both orientations (as colours visually 'pop out' in perception [61]). This allowed us to clearly differentiate between selective rotation (i.e. rotation only when useful, in the critical inverted-arms condition) and indiscriminate rotation (i.e. rotation even when redundant, as in the inverted-colour condition). As in study 1, children first completed the preliminary rotation activity and were given permission to rotate the turntable during the main task. Measures of prospective and retrospective metacognition were included, in order to examine whether children perceived the inverted-arms condition to be the most difficult. Further methodological details are reproduced in the electronic supplementary material, note S3.

(c) Results and discussion

Children's use of manual rotation across trials was analysed using GLMMs with a binomial dependent variable (rotation versus no rotation) and a random intercept for participant. Children were more likely to manually rotate the turntable: (i) when counting arms compared to colour, $\chi^2_{1978,n=132} = 134.09$, $p < 0.001$ ($w = 1.01$), (ii) when the sheets were presented in the inverted compared to upright orientation, $\chi^2_{1978,n=132} = 131.46$, $p < 0.001$ ($w = 1.00$), and (iii) with increasing age, $\chi^2_{1978,n=132)} = 14.70$, $p < 0.001$ ($w = 0.33$). However, these effects were qualified by a significant three-way interaction between counting dimension, orientation and age, $\chi^2_{1974,n=132} = 10.23$, $p = 0.017$ (see the electronic supplementary material, table S8). This interaction, which had an approximately medium effect size ($w = 0.28$), indicated that children were more likely to selectively rotate the turntable as they became older. That is, with increasing age, children were increasingly more likely to manually rotate the turntable in the inverted-arms condition than in the inverted-colour condition, with no difference between the upright conditions (figure 4*a*).

This pattern was substantiated by planned follow-up analyses that compared the likelihood of rotation between the arms and colour trials for both the upright and inverted orientations in the four pre-specified age groups. As seen in table 1,

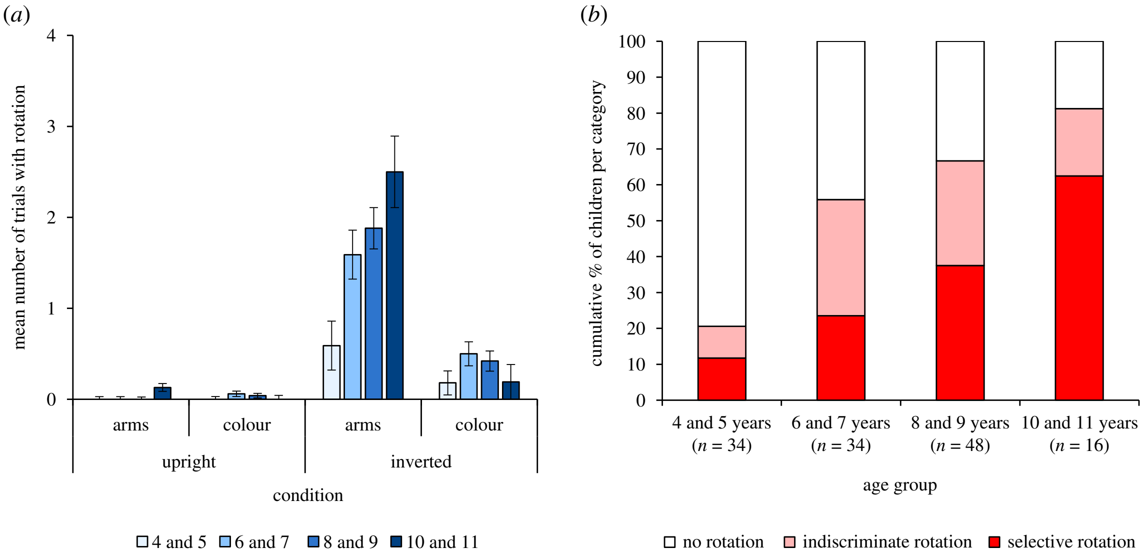

Figure 4. (*a*) The mean number of trials with manual rotation for each condition (range 0–4) in study 2, displayed according to age group. Error bars represent standard errors of the mean. (*b*) The cumulative percentages of children per age group demonstrating selective rotation, indiscriminate rotation and no rotation. (Online version in colour.)

Table 1. A comparison of rotation for arms and colour dimensions at each orientation for each age group in study 2. (Note: Positive *w* values indicate increased rotation in trials where children were counting the arms dimension relative to trials where children were counting the colour dimension.)

	upright orientation (arms versus colour)			inverted orientation (arms versus colour)		
effects	χ^2	*p*	*w*	χ^2	*p*	*w*
4–5 years	0.00	> 0.999	0.00	11.37	0.001	0.58
6–7 years	0.00	0.996	0.00	33.57	<0.001	0.99
8–9 years	0.00	0.996	0.00	68.03	<0.001	1.19
10–11 years	0.00	0.959	0.00	37.40	<0.001	1.53

children across all age groups were significantly more likely to rotate the turntable in the inverted-arms condition than the inverted-colour condition, with the size of this effect consistently large [62] but gradually increasing from the youngest group ($w = 0.58$, $p = 0.001$) to the oldest group ($w = 1.53$, $p < 0.001$). No age group differentially rotated in the upright conditions, with minimal rotation for both the arms and colour dimensions (across all participants, rotation occurred on only 0.40% of upright trials when counting arms and 0.75% of upright trials when counting colour). Additional analyses confirmed that counting arms was more difficult in the inverted orientation than in the upright orientation, with no such orientation effect for counting colour (see the electronic supplementary material, tables S9 and S10). Children of all ages also showed positive correlations between the correct number of figures and the counted number of figures in all conditions, indicating that they were genuinely attempting to count the stimuli rather than answering indiscriminately (see the electronic supplementary material, figure S3).

Again, children were sorted into three mutually exclusive categories: (i) *selective rotators*, who rotated the turntable on at least one inverted-arms trial but no other types of trials, (ii) *indiscriminate rotators*, who rotated the turntable on at least one trial but did not meet the selective rotator criteria, and (iii) *non-rotators*, who did not rotate the turntable on any trial. Post-hoc point-biserial correlations were then conducted to assess whether the likelihood of being categorized as a selective rotator increased with age. These correlations were performed twice—once including all participants, $r_{pb_{130}} = 0.40$, $p < 0.001$, and once excluding the non-rotators, $r_{pb_{69}} = 0.31$, $p = 0.008$—to again account for the possibility that some non-rotators may have been capable of selective rotation but simply felt that they lacked permission to rotate the turntable. Consistent with the planned trial-level analyses, these additional participant-level analyses demonstrated significant increases in selective rotation as children became older. Notably, it was not until 10 and 11 years old that the majority of children (62.5%) showed selective rotation, with the proportion of selective rotators increasing roughly linearly from 4- and 5-year olds (11.76%), to 6- and 7-year olds (23.53%), to 8- and 9-year olds (37.50%; figure 4*b*). In other words, when manual rotation was either beneficial or entirely redundant, older children were much more likely than younger children to be selective in their use of this behaviour.

For the metacognitive reflection questions, binomial tests revealed that the 4- and 5-year-old children performed no differently from chance level in both the prospective task ($p = 0.170$) and the retrospective task ($p = 0.531$). Children aged 6 and older, however, consistently performed above chance level on both tasks, all $ps < 0.001$. The proportion of children answering as expected increased significantly with age for both the prospective task, $r_{130} = 0.27$, $p = 0.002$, and the retrospective task, $r_{130} = 0.44$, $p < 0.001$ (see the electronic supplementary material, table S11, and accompanying note about the 4- and 5-year olds' performance).

4. General discussion

With technological innovation soaring exponentially, the line between human cognition and the external world is more blurred than ever before [5]. Proficiency with using environmental manipulations and artefacts to enhance thinking efficiency is therefore becoming increasingly central to modern notions of intelligence [63]. Across two studies, we have shown that even some 4- and 5-year-old children have the capacity to manually rotate external stimuli in order to alleviate the demands of internal mental rotation. This developmental trajectory parallels the initial emergence of mental rotation itself [51–54], suggesting that, at least in some domains, some children may become capable of externalizing cognitive operations as soon as (or not long after) they become capable of performing those operations internally.

Nevertheless, it is important to note that although we detected statistical indications of cognitive offloading in 4- and 5-year olds at the trial level, children of this age were less selective in their use of manual rotation than older children when there was a clear difference between beneficial and redundant rotation in study 2. In other words, younger children appeared to be less likely than older children to manipulate the environment in order to offload cognitive demand. One possibility is that, despite completing a preliminary rotation activity and receiving repeated verbal instructions to the contrary, some younger children may have been uncertain about whether they had permission to rotate the turntable during the main task. If so, then it could be that the majority of preschool-aged children do in fact possess a (latent) capacity for selective manual rotation in this context. Importantly, however, even when excluding the children who did not rotate the turntable at all in study 2, there was still a significant increase with age in children's likelihood of rotating the turntable selectively. In other words, even accounting for permission issues, older children were more likely than younger children to rotate the turntable only when useful.

One likely explanation is that the indiscriminate rotators incorrectly believed that manually rotating the turntable when counting inverted blue faces would benefit performance, just as many children in study 1 appeared to incorrectly believe that tilting their head would benefit performance. In other words, the indiscriminate rotators may have had the *intention* to offload internal cognitive demand when rotating in the inverted-colour condition, even if doing so did not offload internal demand at all. This metacognitive account of children's performance is consistent with findings from studies with adult participants, who deploy external manipulations not only as a function of the actual benefit of reducing internal demand, but also as a function of the *believed* benefit of reducing internal demand [14,31,34]. Just like the children in our study 2, for instance, adults sometimes deploy external normalizations of rotated stimuli in situations where doing so does not actually benefit performance [29]. Therefore, although our own pattern of results points to a gradual calibration of functional cognitive offloading throughout childhood, even adults display systematic biases in their use of environmental manipulations aimed at facilitating cognitive performance (see [30]).

This highlights an important avenue for future research: is it possible to train children (and adults) to become more selective in their uses of environmental artefacts and external manipulations aimed at alleviating cognitive demand [64]? In other words, is it possible to speed up and enhance the calibration of effective cognitive offloading strategies? Modern children increasingly have opportunities to use thinking tools [31], such as calculators and other computers, to solve problems that would have once been solved internally. Accordingly, it is becoming increasingly important that children know when to use external strategies and when not to. Paradigms allowing for a clear differentiation between true cognitive offloading and indiscriminate environmental manipulations, such as the task introduced in study 2, may in the future be used to explore factors that explain and perpetuate overreliance on such tools. In time, results could inform interventions aimed at improving selectivity and reducing the potentially deleterious effects of overreliance [39,65,66].

Another important avenue for future research will be to more directly examine relationships between children's ability to perform internal cognitive operations and their likelihood of externalizing these operations. Although our results clearly show that, at the group level, children selectively rotated stimuli as a function of internal demand, this conclusion would be strengthened by studies that correlate individual children's performance on: (i) a traditional timed mental rotation task [47,51], and (ii) a task where they have the option to manually rotate stimuli of variable angular disparity (as in our study 1). Our account would predict a positive correlation between reaction time as a function of angular disparity on task (i) and likelihood of manually rotating stimuli as a function of angular disparity on task (ii). Similarly, studies may wish to include fine-grained, continuous measures of school-aged children's metacognitive beliefs about task difficulty [46], and to correlate these measures with children's choices to use external manipulations. The crude, categorical metacognitive questions of the current study were designed only to provide a rough measure of children's beliefs about task difficulty, and were kept as simple as possible with the intention that even preschool-aged children could understand them.

Finally, future studies may wish to adapt our novel paradigm to examine the potential for cognitive offloading in non-human animals. As described in the Introduction, many animals appear to manipulate their environments with the effect of facilitating cognitive performance [6,7,15–21], but the mechanisms underlying these phenomena remain unclear. Notably, basic mental rotation effects have been observed in baboons [67,68], rhesus macaques [69] and sea lions [70], but not in pigeons [71]. If non-human primates and other mammals were given the opportunity to manually rotate stimuli on tasks such as ours (perhaps using a touchscreen [72]), then would they readily choose to do so as a function of internal cognitive demand?

In summary, the current studies introduced a minimalist paradigm to investigate developmental patterns of cognitive offloading and redundant external normalizations in the context of mental rotation. Although even the youngest children showed evidence of cognitive offloading, the ability to selectively use manual rotation increased linearly with age, with few 4- and 5-year olds but the majority of 10- and 11-year olds intelligently modifying their environment to alleviate mental rotation demands in study 2. Of course, these studies have targeted only one aspect of a remarkably broad capacity that cuts across many aspects of cognition. We therefore recommend much further exploration of cognitive offloading behaviours in children, adults and non-human animals. Such work will be crucial for expanding our knowledge of the nature, development, functions, dysfunctions and evolution of the extended mind.

Ethics. study 1 was approved by the University of Queensland's Faculty of Health and Behavioural Science's Ethics Committee (clearance ID: no. 2019000267). study 2 was approved by the University of Queensland's School of Psychology Ethics Committee (clearance ID: 18-PSYCH-4-03-AH).

Data accessibility. Datasets are available at https://osf.io/wbe7g/ and https://osf.io/nh32g/.

Authors' contributions. K.L.A. designed the studies, collected and analysed data, wrote the first draft and edited the manuscript. A.B. assisted with study design and editing. J.R. designed the studies, supervised the project and edited the manuscript.

Competing interests. The authors hereby declare no conflicts of interest.

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