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Developmental change and the nature of learning in childhood

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How do children acquire humankind's remarkable cognitive skills? Why are the abilities children acquire readily, such as native-language fluency, harder for adults? Although attitudes to these questions span the continuum from nativism to learning theory, answers remain elusive. We relate a recent model of language acquisition in childhood to advances in the neuroscience of adult cognitive control, to propose a domain-general shift in the architecture of learning in childhood. The timing of this supports children's imitative, unsupervised learning of social and linguistic conventions before the maturation of cognitive control gives individuals greater self-direction, which causes learning to become less conventionalized and more idiosyncratic. These changes might represent an important adaptation supporting the development and learning of cultural and linguistic conventions.

Some people will never learn anything, for this reason, because they understand everything too soon.
Alexander Pope

Young children differ from adults in many ways. Notably, when it comes to cognitive abilities, adults are far more capable of self-monitoring (selecting between alternative responses or goals) and controlling their own thoughts than children. This raises a question: do these differences affect learning and, if so, how? It is likely that a learner's ability (or lack of ability) to control and construct their representations of events will affect what is learned. At the same time, the best learning strategies might not always be those consciously adopted by the learner. Here, we consider whether the increase in cognitive control during the transition from infancy to adulthood might benefit some aspects of learning and hinder others. We examine whether domain-general changes in control might be responsible for apparently domain-specific maturational effects, such as the relative ease with which children achieve native fluency in language as compared with adults. Specifically, we propose that the acquisition of response conflict processing, an aspect of cognitive control where researchers have recently made strides in understanding processing at numerous levels, affects learning strategies; this, in turn, affects convention learning. The changes underlying this are evident in several other cognitive domains, such as the acquisition of false belief.

The development of response selection in childhood

Recent findings suggest that in the fourth year of life, maturational changes in the frontal lobes result in a qualitative shift in the way children process information [1–3]. These changes enable children to monitor response-error and response-conflict information, and select context-appropriate responses in the face of competing alternatives. This is a key step in the development of the more agentive (and increasingly self-supervised) learning style that characterizes adulthood. The ability to discriminate and integrate subgoals, and to form and manipulate high-level relational representations, develops incrementally as the prefrontal cortex (PFC) matures [4,5].

Converging evidence from behavioral and patient studies, developmental neurobiology and cognitive neuroscience models supports the idea of a domain-general processing shift at age four. For example, 4-year-olds can:

(i) Spontaneously detect relational similarities between representations (as opposed to making feature-based matches [6]).
(ii) Change, in binary choice tasks, from maximization behavior to probability matching [7].
(iii) Switch between competing rules in dimensional change card sorting (DCCS) tasks [8].
(iv) Discriminate appearance and reality, and master false belief [9].

These changes share a notable common characteristic – they involve a shift from behavioral responses driven by a single (often prepotent) factor to those that integrate or select between multiple responses (or information sources involved in determining a response; see also Refs [5,10]). Explaining this change in terms of an increase in the ability of children to select between responses raises several questions: how does a child know which response to select? What changes in the child's mind to enable such selection? Which specific changes to the brain underlie this? How does processing after these changes differ from earlier, less controlled processing?

With regard to the first of these questions – giving a noncircular account of controlled and selective cognitive processing – models of cognitive control in adults have made progress. The problem can be illustrated as follows: when people undertaking the Stroop task are asked to name the color of the ink in which a color word is written, they have to concentrate when the printed word (e.g. red) does not match the ink color (e.g. black); they slow down and make errors they would not make if they were just reading the words. Reading is a well learned, prepotent skill and, therefore, explaining correct naming of the contrasting ink color

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requires accounting for its controlled selection. This raises the question: how can one thought be selected over another by thinking alone? One detailed answer is provided, and modeled in a functional circuit, by Cohen and colleagues [11–15]: the selection and updating of goals is a function of the midbrain dopamine system, which transmits signals prompting the development of goal and context representations in the lateral PFC (LPFC [16]). The LPFC is involved in the representation of these internal goals, along with the active maintenance of context information and the modulation of attention in response to conflict information that originates in the anterior cingulated cortex (ACC [11,12, 14,15]; in the model, error detection is a particular case of conflict detection and is also a function of the ACC [12]).

Von Economo neurons and the PFC

The qualitative changes in children's behavior at approximately age four might reflect important developmental changes to the circuit described above. The development of a morphologically distinct cell type, Von Economo neurons (VENs [17]), in the ACC and the frontal insular (FI) cortex, which seems essential in allowing these regions to communicate with other regions of the brain, provides neurobiological evidence for these behavioral changes. VENs only appear in apes and humans, and VEN volume is highly correlated with relative brain size [18]. Studies indicate that only 15% of VENs are present at birth in humans, suggesting that many aspects of ACC function are not available in the earliest stages of learning. Moreover, the development of adult numbers of VENs does not take place until approximately age four [1], which correlates with the changes we describe above. Further support for a developmental account of ACC function comes from the steady increase in metabolic activity in the area throughout childhood [19]. The delayed, nonlinear developmental trajectory of an event-related potential component associated with ACC activity in conflict monitoring [20] is consistent with a late maturation account of ACC function.

VENs in the ACC appear to have evolved in a manner to interact advantageously with the development of the anterior PFC, (aPFC [18]). Reviews of functional magnetic resonance imaging (fMRI) studies of the aPFC in humans suggest that it is best characterized as functioning to integrate the outcomes of two or more cognitive processes (or subgoals) [21–24]. If the move from processing unary to more complex relational representations in early childhood [25] is dependent on conflict monitoring, then the late development of the ACC (and related areas) might be an adaptation to facilitate such learning. Below, we review recent work that suggests these ideas can be used to shed light both on the characteristic patterns of acquisition in two high-level cognitive domains – language and false belief – and on the nature and development of the processes that allow the development of cultural and linguistic conventions.

Critical periods for language and the development of the ACC

How do children learn language? Why is learning a second language hard for adults? A common approach to these questions has been to argue that some component of language is specifically hard-wired in the brain, and that this is subject to (unspecified) maturational change. This approach is based on arguments about the learnability of aspects of language and changes in people's ability to learn as they mature. Taken with recent modeling work, the maturation of the response-conflict processing suggests a more domain-general explanation to several puzzles surrounding language learning.

The logical problem of language acquisition (LPLA) is a key objection to the idea that language acquisition can be explained solely in terms of learning. The objection begins with the limited amount of language children hear, and argues that, inevitability, children will make incorrect hypotheses about the language they are learning as a result of such limited exposure. The LPLA then notes that learners will need corrective feedback if they are to recover from some errors – for example, when two word-forms, such as mice or mouses, are both thought to be acceptable when only one is – but that children do not seem to get enough of this kind of feedback [26] and ignore it when they do [27]. Because children do make and recover from errors, such as mice versus mouses, and the LPLA suggests they cannot do this from experience, it is argued that their ability to do so is innate [27–29,59].

Counter to these arguments, Ramscar and Yarlett [30] describe a simple imitative, unsupervised, plural learning model that simulates children's patterns of morphosyntactic acquisition without any need for external feedback or internal monitoring. They found much evidence that children behave in accordance with the model's predictions.

In the model, nouns are represented in memory as exemplars comprising a semantic and a phonological component (the plural noun 'cars' is represented by a couplet encoding the association between the semantics of cars, including their plurality, and the phonological form/carz/). Items are stored when encountered, and learning, production and generalization are driven by activation of these items. In learning, activation strengthens the couplets as a negatively accelerated function of the current stage of learning [31]. Activation occurs both when a couplet is explicitly reinforced (e.g. some objects are labeled as cars) and when a learned couplet is activated [32,33] by priming of either its semantics [34] or phonology [35]. Thus, the association between a final sibilant and plural semantics common to regular plural nouns is frequently activated, and hence regulars are learned more rapidly than irregulars [36] (Figure 1).

Language production and learning

An important aspect of the model is the way competition affects the production of nouns. When a set of semantic cues is presented, two factors determine the model's (child's) response: the direct imitative memory response that reactivates the phonological form a child has previously learned to associate with the semantic cue (if prompted to make a production when presented with the semantics a child has learned to associate with a form, the child will attempt to produce that form); and supporting and competing responses activated by any subset of the presented cues [26,27]. Whether activation supports or competes with output of the correct learned response

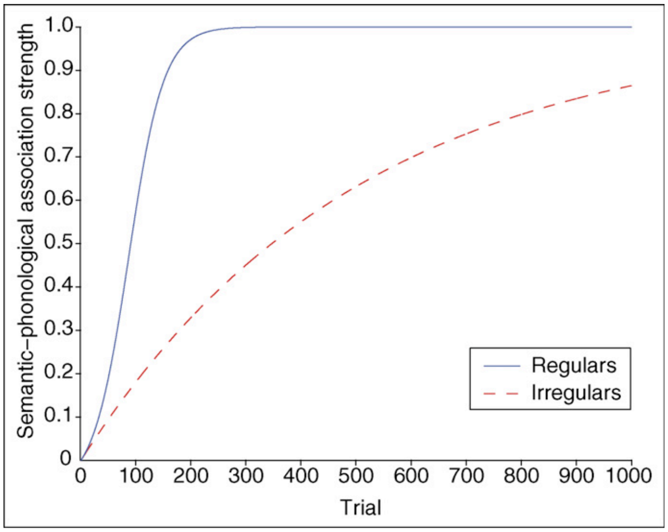

Figure 1. Plots showing the rate at which the semantic–phonological couplets representing a regular (unbroken blue line) and an irregular (broken red line) item are learned by the Ramscar and Yarlett [30] model. Early in learning, the high frequency of regular items results in rapid strengthening of the mapping associating plural semantics with a final sibilant. However, once the representation of the plural semantics to final sibilant association asymptotes, learning of irregular representations incrementally reduces the difference in the learned strengths of the two representations. Reproduced, with permission, from Ref. [30].

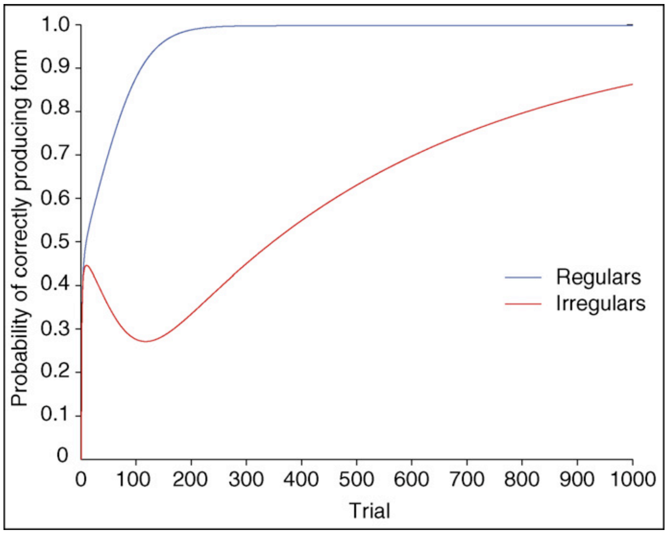

Figure 2. Plot showing the probability of correctly producing regular (unbroken blue line) and irregular (broken red line) forms after varying amounts of experience in the Ramscar and Yarlett [30] model. Note the clear U-shaped trend in the learning profile of the irregular plurals predicted by the model and that production performance on regular forms is always predicted to be better than production performance on irregular forms. Reproduced, with permission, from Ref. [30].

depends on whether the other phonological forms activated by the semantic cues share features with it or not; thus, regular plurals receive much support from other forms that also associate plurality with a final sibilant.

Early in learning, the high frequency of regular items causes a rapid strengthening of the mapping associating plural semantics with a final sibilant, and high levels of competition and over-regularization. However, because learning is negatively accelerated and asymptotic, the regular frequency advantage ameliorates over time, as the representation of the plural semantics to final sibilant association asymptotes. However, learning of less frequent, irregular representations continues, strengthening them relative to the competing regular pattern. This pattern of interference and its resolution follows the 'U-shape' characteristic of children's morphological acquisition (Figure 2).

Predictions from the model

The model makes two strong, unique predictions:

(i) In the absence of feedback, children can converge on the correct output by repeating over-regularizations, because over-regularizations result from activation of the correct items [32].

(ii) Without feedback, the pattern of responses will follow a 'U-shape' (performance on irregulars will get worse before improving as a simple result of the subtraction of the two nonlinear functions).

The results of a series of experiments support these predictions [30]. For example, children who over-regularized (saying childs) were asked to demonstrate correct plural naming to a doll. After several blocks of trials, older children began to produce correct irregular plurals (saying children not childs), without any new input or corrective feedback. Under the same conditions, over-regularization in younger children got worse (consistent with 'U-shaped' learning). A similar pattern was observed when a memory task was interspersed between elicited pre- and post-tests on irregular plurals: older children who performed an old/new task on pictures of regular and irregular plural items over-regularized less in a post-test, whereas younger children over-regularized more, even though neither group produced any plurals in training. These results suggest that children's error patterns, and their recovery from them, need not necessitate an innate language faculty.

Language acquisition and patterns of learning

The finding that older learners achieve native fluency in second languages at markedly lower rates than children [37–39,60] has also been seen to support linguistic nativism, the suggestion being that there are critical periods for second-language acquisition. However, although there is evidence that average success at second-language learning declines with age, individuals learn second languages to native-like fluency well into late adulthood [40,41]. Furthermore, few concrete proposals have been put forward regarding the specific mechanisms that allow early learning and then change to affect it later.

Ramscar and Yarlett's model of morphosyntactic development (which is consistent with general principles of memory and learning) provides a point from which to consider the differences between adults and children when it comes to the acquisition of morphosyntax, language and learning more generally. In the model, the unsupervised nature of learning suggests an alternative account of developmental problems associated with morphosyntax (in English, inflectional morphology is the best documented problem for late learners [37]).

Inherent in the model of children's acquisition of morphosyntactic patterns is a period in which, as a result of competition, the forms children utter are not necessarily those they learn or comprehend. Moreover, the process by which the model (and by extension, children) ceases to over-regularize and habitually produce correct irregular forms necessarily involves a great deal of response conflict [30] (Figure 2; response conflict is high whenever the response propensities for regular and irregular items are similar). Numerous studies have shown that repeating errors produces detrimental effects in adult memory and one might not expect adults to show the same improvements observed in the children in these studies [42].

Support for this idea comes from a series of elegant and ingenious studies by Newport and colleagues, which have revealed, in both naturalistic and experimental settings [37,43,44], that the patterns of learning exhibited in children's acquisition of morphosyntax are at considerable variance with those of adults. Children tend to maximize, or overmatch, probabilistic language input: if two forms of the same item occur in the input, children tend to adopt the dominant pattern. However, adults tend to match the probabilities for the alternative forms on which they were trained in their output. We suggest that many progressive difficulties with morphosyntactic learning in adults and older children stem from their increasing ability to monitor and respond to conflict in their representations of probabilistic information about language as they change from unsupervised learners to self-monitoring, supervised learners.

This incremental change in learning – from maximization to strategic probability matching – is illustrated by studies addressing the ability of children and adults to probability match (such as guessing which hand an M&M candy is in when the hands are 'loaded' 25:75). Generally, before the fourth year, children overmatch (over-favoring or maximizing their responses to the 'good' hand), after which 'probability matching' (selecting the good and bad hands in rough proportion to the likelihood they will contain an M&M) begins to emerge [7] (Figure 3).

The Ramscar and Yarlett model maximizes in learning in much the same way as children do. Items reactivate associatively in memory as a function of experience and output results from simple brute strength competition – the strongest activation gets produced. In a straight competition between alternate responses, the more frequent form dominates. For the model to select between responses, a component would have to be added to modulate attention between the strengths of the two competing responses in accordance with goal-related information, so that a less supported response could be selected if goal relevant. This component would essentially implement ACC/PFC functions in other models [12].

Where language learning and the M&M task differ is that 'probability matching' in the M&M task can be achieved simply by error switching (switching hands when the M&M is not in the one just selected [7]; error detection is an ACC function [12]). However, probability matching in language cannot be achieved in this way, because a child will not inevitably get feedback on the correctness or otherwise of a production [27]. Language learning strategy requires monitoring and responding to representations in memory, and it involves a wider range of executive functions [5] in both the ACC and PFC. This idea is supported by the different ages at which 'probability matching' behavior is exhibited in the M&M task [7] and similarly constructed language learning tasks [44]. Consistent with this developmental account of strategizing, 9–12-year-old children show significantly more ACC activation when making a prediction about the likelihood of two alternatives on the basis of visual evidence that was weighted 3:6 or 4:5 than when the evidence was 1:8 or 2:7 (in the latter cases, response conflict is minimal); adults, who have far more experience of making this kinds of prediction, do not show any increased activation [45].

We propose that maturational disadvantages for native-language learning reflect the development of cognitive control processes. Because signaling between the ACC and PFC improves in the fourth year, it enables response selection. Because the PFC matures throughout childhood, it increases working memory [46] and attention [47]. This results in an incremental accrual of abilities that allow adults to represent and selectively attend to goals, subgoals and context [5]. The maturation of executive function enables adults to shortcut the unsupervised learning patterns characteristic of children's language learning (native-patterns), such that adults develop patterns of production that are both different to those acquired by children (i.e. are non-native [37]) and often idiosyncratic [48]. This, in turn, suggests an adaptive advantage for the

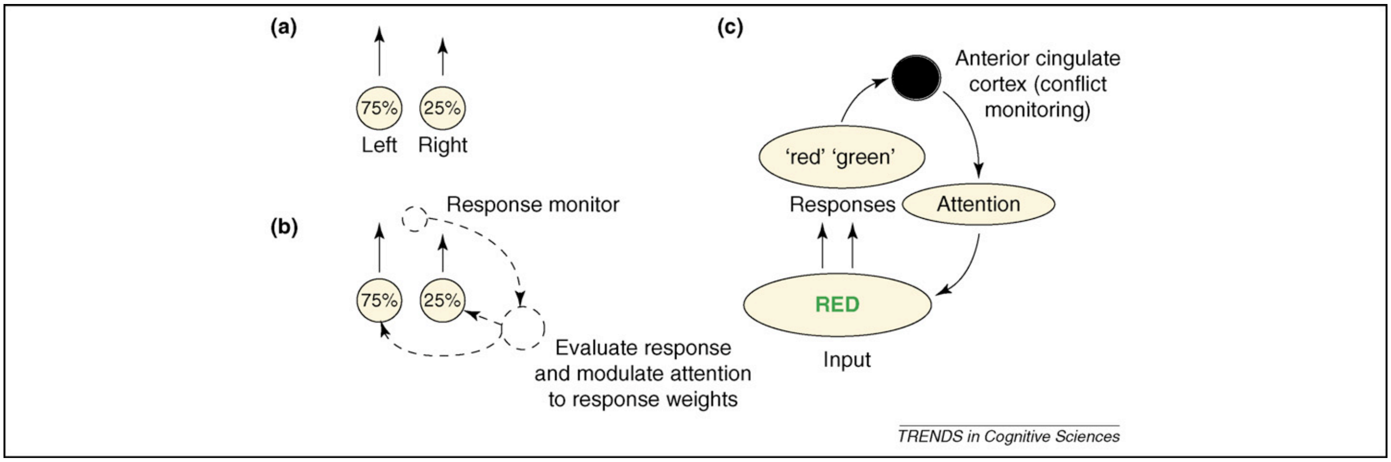

Figure 3. In a 75:25 probabilistic task the unsupervised model **(a)** would maximize. Modifications allowing response conflicts to be monitored and integrated with goal or task outcome information is depicted in **(b)**. A functional characterization of Yeung *et al.*'s [12] model of the ACC and associated PFC circuits in conflict monitoring and response selection is shown in **(c)**.

late development of the ACC and PFC in humans: an essential property of language is conventionality (communication requires some agreement between what one person says and another takes this to mean [49]). Conventionality will be maximized if children are unable to selectively attend to and control their patterns of learning. The inability of young children to learn anything other than the most supported patterns they are exposed to might result from developmental adaptations that support the learning and transmission of the conventions that underpin language and culture [49,50].

False belief

Zelazo and colleagues [5,10] argue that changes in children's performance on tasks measuring false belief in the fourth year are also related to the acquisition of response-conflict processing and response selection. In a standard test of false belief, a puppet hides an object, which is moved after the puppet 'leaves'. The puppet is re-introduced, and children are asked where the puppet will look for the object. Under age 4, children reply with the actual location, not the correct, original hiding location [52]. Understanding appearance-reality follows a similar trajectory. Before age four, children systematically show below-chance performance when asked about, for example, a sponge that looks like a rock, often producing the same answer for both appearance and reality questions [53]. Both of these tasks involve selecting between two conflicting dimensions of a representation. To solve the false-belief task, children have to indicate that an object is believed to be at location X, a response that is in conflict with their knowledge that it is actually at location Y. To understand appearance-reality children have to select an appropriate label, X instead of a competing label Y, according to context. Studies have shown that performance on these tasks is highly correlated with measures of cognitive control (e.g. Refs [51,54]). The pattern of learning in this domain is entirely consistent with the more general changes we propose.

Conclusion

To date, the cognitive sciences have been somewhat divided on the question of how to deal with the question of biological inheritance. In general, the field is split between those who believe that high-level cognitive processes are best explained in terms of learning and plasticity (e.g Ref. [55]), and those who believe that a vast array of cognitive content is inherited in 'domain modules' (e.g. Ref. [56]).

We have tried to show how developmental changes that have been used to argue for nativist, domain specific proposals might be better explained in terms of domain general changes to the architecture of learning (which are, of course, modulated by inherited genetic factors). The idea that this architecture changes in development, beginning in a largely imitative fashion and developing into a more agentive, self-controlled process over the course of childhood enables us to outline a computational account of why some language conventions are hard to master in adulthood, and to ground this account in broader functional models from cognitive neuroscience. We hope that future improvements to, and increases in, our understanding of the timing and impact of these changes to the way children learn, and the neural underpinnings of these, might provide a framework for connecting developmental, cognitive and computational neuroscience with broader theories of cultural and cognitive development [49], and in particular, of the nature and development of conventions. Language and culture set *Homo sapiens* apart. Both capacities rely on the acquisition and utilization of convention [49,57]. Understanding how the unsupervised learning processes that lead to conventionalized learning (see also [43,44]) interact with the development of the cognitive processes that allow humans to exert more cognitive control over their responses over the course of development will ultimately result, we believe, in a much deeper understanding of human development (Box 1).

Box 1. Questions for future research

- How do these different learning styles interact in the evolution of social and linguistic conventions? Can these simple computational changes account for real linguistic phenomena, such as the development of creoles from pidgins [44]?
- Can we find evidence of ACC/PFC involvement in probabilistic language learning tasks [44] in adults? Do difficulties in second language learning correlate with measures of response conflict sensitivity?
- How can behavioral measures, such as those reviewed here, be better correlated with neural development? Measuring the neural correlates of behavior in children of this age is not straightforward because children lack the self/cognitive control to meet the behavioral requirements of many functional imaging techniques [19,20].
- Autistic children struggle to acquire ordinary competence in language, false belief and other high-level cognitive processes [15]. Will the development of the VENs and aPFC influence the language, false belief and other high-level cognitive processes?
- The gene expressions that give rise to postnatal cortical development are themselves influenced by learning and the environment [58]. 'Normal brain maturation' has been charted in few social and economic environments [4]. To what extent do different experiences and requirements affect these patterns?

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