Developmental cognitive neuroscience is an evolving field that investigates the relations between neural and cognitive development. Lying at the intersection of diverse disciplines, work in this area promises to shed light on classic developmental questions, mechanisms subserving developmental change, diagnosis and treatment of developmental disorders, and cognitive and neuroscientific topics traditionally considered outside the domain of development. Fundamental questions include: What are the interrelations between developmental changes in the brain (e.g. in connectivity, chemistry, morphology) and developmental changes in children’s behavior and cognitive abilities (e.g. representational complexity, ability to sustain selective attention, speed of processing)? Why, and how, is learning enhanced during certain periods in development? How is our knowledge organized, and how does this change with development? We discuss preliminary investigations of such questions and directions for future work.

Developmental cognitive neuroscience research can inform a variety of practical applications, such as earlier diagnosis and more effective treatment of developmental disorders. For example, such research has demonstrated how specific genes can affect the pruning and maturation of synapses, which in turn affects the ability to learn from experience [1], and how experience can affect which genes are turned on, when, and how they are expressed (e.g. [2]). Computational models have demonstrated how small variations in initial processing, which might be genetically governed, can lead through experience to large differences in cognitive outcomes [3,4].

By investigating both typical and atypical development, developmental cognitive neuroscience research can inform a variety of practical applications, such as earlier diagnosis and more effective treatment of developmental disorders. For example, such research has informed the
Box 2. Terminology in the study of development

**Early terminology focused on hard-and-fast contrasts in development** (such as nature vs. nurture, genes vs. environment, and maturation vs. learning) and hard-and-fast time windows (such as critical periods):

- **Learning**: changes in response to experience with the environment (the nurture side of nature–nurture, when this experience comes from a caretaker)
- **Maturation**: changes driven by genetic processes according to specific time tables (the nature side of nature–nurture)
- **Critical periods**: time-limited windows when specific experiences must occur to drive typical or maximal development. Learning is ineffective outside these time windows.
- **Experience-expectant processes** ([33]): processes that utilize environmental information that is highly reliable for all members of the species (e.g. for humans, hearing a language)
- **Experience-dependent processes** ([33]): processes that utilize environmental information that can vary across individuals (e.g. for humans, the particular language that is heard)
- **Sensitive periods**: time-limited windows when specific experiences have their largest effects. Learning can still be effective outside those time windows.
- **Plasticity**: the capacity for modification
- **Development**: processes of change across the lifespan

**Treatment for the genetic disorder, phenylketonuria (PKU).** Individuals with PKU cannot convert phenylalanine to tyrosine, the precursor to the neurotransmitter dopamine. Treatment involves restricting dietary intake of phenylalanine, thus allowing ingested tyrosine more opportunity to compete with phenylalanine for transport into the brain. Developmental cognitive neuroscience research showed that the recommended diet had not restricted phenylalanine intake enough and resulted in deficits in executive control functions, but that a stricter diet could prevent and reverse those deficits ([5,6]). Further, if the gross elevations in blood phenylalanine levels are not reduced before Postnatal Day 11, they impair the visual system, which develops rapidly after birth, and deficits in sensitivity to low contrast images are seen immediately, but are evident years later in heightened reactivity to stress and poorer executive control, which are characteristic of schizophrenia. Similar perturbation of the hippocampus in adulthood does not produce such effects. Not only might this provide insight into schizophrenia etiology, it also provides insight into the complex interactions that are important for normal development. This is but one example of how studying

atypical development can inform understanding of typical development.

**Developmental cognitive neuroscience work can also inform issues that have traditionally been considered outside the domain of development.** For example, to what extent is adult cognition subserved by domain-specific systems that are intrinsically specialized for particular kinds of inputs (e.g. a face processing system [11]), as opposed to domain-general systems that become shaped for particular kinds of inputs through learning [12]? Both possibilities are compatible with newborn preferences to look towards face-like patterns, which probably reflect subcortical processes rather than the cortical specializations debated in adults [13]. Developmental cognitive neuroscience research could inform these debates [14] by evaluating whether domain-specific systems appear early in development, before much learning has occurred (supporting the intrinsically specialized view), or only later with the development of expertise (supporting the domain-general view).

In the selective review that follows, we discuss several specific questions of investigation in the field and assess preliminary answers (for additional discussion and coverage of a broad range of topics in developmental cognitive neuroscience, see [15–20]).

**Neural changes during learning**

How does brain organization and function change during the process of learning, and how does this compare with changes observed across development? The increasing availability of non-invasive tools, such as functional magnetic resonance imaging (fMRI, [21,22]), provides us with the opportunity to ask such brain- and behavior-related questions in the developing human that was not possible only a decade ago. With fMRI, we can safely track changes in cortical activation following extensive learning in the same individual, and we can compare such changes with those observed in younger versus older children.

One of the first studies to track cortical changes over an extensive period of time with fMRI [23] showed rapid learning effects in primary motor areas. Changes were shown during motor sequence learning within a single session and increased over weeks of training. Cortical activity became less diffuse and increased over time. This example of initial diffuse cortical activity early in learning, followed by an increase in focal activity, parallels results from developmental fMRI studies. These studies show diffuse activity in children relative to adolescents and adults, with adolescents showing the greatest focal activity during performance of behavioral tasks, even when performance across groups is equated [24–29].

Differences in brain activity between age groups are not due to experience alone, as even without normal stimulation, changes in neuronal connections and synaptic pruning occur with brain maturation [30]. Rather, these findings highlight a possible approach for investigating maturational and experiential contributions. For example, to determine whether the immature brain after extended practice engages in the same neural processes as the mature one, we could compare brain activity in the mature system with brain activity in the immature system both.
before and following extended experience. This use of fMRI to trace learning-related changes in cortical areas is currently being used to investigate the impact of behavioral and cognitive interventions on developmental disorders like dyslexia and obsessive-compulsive disorder.

Neuroanatomical changes also occur with learning and development, notably changes in the strength and number of neuronal connections and the myelination of fibers. During early development, the neural connections in the brain undergo dramatic organization, generating more neuronal processes and connections than will ultimately survive (e.g. [31,32]). Learning plays a key role in an activity-mediated competition process through which some of these synapses are eliminated or pruned, and others are stabilized and strengthened [1,33,34].

Developmental studies have challenged some accepted notions about neural organization and learning. It has long been known that monocular deprivation causes changes in oculomotor dominance columns in primary visual cortex (V1), but it had been assumed that the effects of visual experience were passed along from the eye to the thalamus (the lateral geniculate) and from there to V1. However, recent work has shown that physiological changes occur more rapidly in V1 than in the thalamus [35]. Moreover, protein synthesis in V1 is necessary for rapid plasticity; anatomical changes in thalamo–cortical afferents are not [36]. This work suggests that cortical circuitry is probably the substrate of the rapid plasticity in response to visual experience (or the lack thereof), whereas thalamo–cortical changes might then make those changes hard to reverse.

**Learning across development**

Why is learning sometimes enhanced during certain periods in development? That is, why do there appear to be ‘sensitive periods’ in development, during which learning is most effective? For example, the ability to learn the grammar of a language declines with age [37,38]. Sensitive periods for other kinds of learning fall within the first few years or months of life, for example, for the phonemes of one’s mother tongue [39] and for certain aspects of face processing [40].

Computational models, specifically neural network simulations, have been used to investigate potential mechanisms for such sensitive periods (e.g. [41,42]). These models allow researchers complete control over simulated learning systems and their environments, to help identify factors contributing to enhanced learning during particular points in development.

One set of simulations [43] investigated the possibility that sensitive periods in language learning arise from the advantages of ‘starting small’ (see also [38]). Specifically, less-developed working memory abilities might facilitate language learning, by restricting attention to key elements of language input, highlighting the grammatical structure of the language. Simulations testing this idea demonstrated that limitations in working memory could in fact lead to advantages in language processing. Other simulations have demonstrated that such advantages to starting small might not be present under all circumstances [44], and that networks have a tendency to start small on their own, abstracting basic structure before abstracting more complex structure, even without limitations imposed on their processing [45]. In this way, computational models have proven to be a useful tool for investigating how and when starting small might assist in learning.

Neural network simulations have also been used to investigate the possibility that sensitive periods arise because knowledge becomes entrenched as a system learns, making it more difficult to alter the system with subsequent learning. Such simulations have demonstrated that entrenchment can occur as some units and connections become committed and unused connections are pruned [41,42]. The result is that stimuli encountered early are learned more robustly than stimuli encountered later.

Entrenchment can also occur as a result of counterproductive learning, where attempts to learn new information actually lead to the strengthening of incorrect responses. Simulations have shown how such processes can explain sensitive periods in phoneme discrimination [46]. Specifically, an infant (or network) might start with an auditory perceptual system that responds differentially to sounds in the environment, and strengthens these responses with experience. For example, a learner in a Japanese language environment will experience a sound that is a blend of the English /r/ and /l/ sounds. This sound will activate relevant neurons, and learning will lead to a strengthening of their response. When later faced with an English /r/ or /l/, the existing representation of the single blended sound will be activated in this system. Learning will again tend to strengthen this response, but in this case the learning will be counterproductive, strengthening the tendency to hear the English /r/ and /l/ sounds as the single blended sound. The interaction of these learning processes and environmental inputs can thus lead to sensitive periods for learning phonemes.

**Organization and development of knowledge**

Just as it is clear that nature versus nurture is a false dichotomy, so it is clear that cognition, emotion, perception and motor functions are not nearly as separate as previously thought. They are fundamentally, multiply intertwined. For example, which variant a child has of the COMT gene (the gene that codes for the COMT enzyme, important for clearing dopamine from extracellular space in prefrontal cortex [47]) can affect that child’s cognitive and affective function.

Another example involves the interaction of social and affective systems with perceptual and attentional systems. Aberrant social experience (i.e. early physical abuse) appears to affect children’s perceptual processing and discrimination abilities (e.g. [50,51]). Children with and without histories of severe physical abuse identify happiness, sadness and fear equally well, but physically abused children are expert at recognizing subtle signs of anger. They have a much lower perceptual threshold for seeing faces as angry, both at the behavioral and neural levels.
They also require greater attentional and neural resources than other children to disengage their attention from an angry face to focus on a target.

Interrelations between motor and cognitive processing provide another example where systems are more intertwined than previously thought. Fine motor skills and visual-motor coordination mature together with higher cognitive functions, neither reaching full maturity until late adolescence [52,53]. Attention-deficit hyperactivity disorder (ADHD) is a developmental disorder that affects not only cognitive functioning [54,55], but the motivational system [56,57] and motor functioning [58]. Just as ADHD and developmental coordination disorder are overlapping diagnoses in many children, movement deficits are evident in many children with ‘cognitive’ developmental disorders (such as dyslexia, specific language disorder, and autism; [59,60]). In addition, children who have undergone resection of cerebellar tumors (without cranial irradiation or chemotherapy) show not only motor deficits, but also impairments in executive cognitive functions, such as planning, sequencing and working memory, and deficits in affect modulation [61,62]. Pre-supplementary motor cortex and part of premotor cortex are active during motor and mental (numerical, verbal, and spatial) sequential operations [63].

Mirror neurons provide another example. Originally discovered in monkeys [64], these neurons fire when an individual performs a particular action or observes another individual performing that action. Such mirror neurons are found in humans in roughly the same location as in monkeys (premotor cortex and Area 44 in prefrontal cortex). They fire during imitation or observation of gestures [65] and during imitation or observation of emotional expression [66]. Such neurons provide a mechanism for integrating perception and action at the neuronal level. Mirror neurons might contribute to several developmental processes, such as the imitative behavior of infants (which requires the integration of perceived and performed actions [67]), the correlation between infants’ abilities to perform actions and to comprehend those actions in others [68], and the development of empathy (understanding how another feels because you can identify with that feeling in yourself [64]).

Future directions
Progress in the field of developmental cognitive neuroscience has been rapid, but much potential remains to be tapped (see also Box 3 for some areas where caution is needed). We close with a brief consideration of issues that we view as central to the endeavor of understanding relations between brain and cognitive development.

Interactions and integrations
Future work should, and probably will, continue to move away from dichotomies (e.g. nature vs. nurture, domain-specific vs. domain-general systems, and cognition vs. emotion) and from studying aspects of the developing system in isolation. Future work is likely to focus on specifying the complex interactions among various processes (including interactions among different neurotransmitters, and among chemical, physiological and structural changes in the brain), and how they affect, and are affected by, behavior and psychological development (see also Box 4). For example, the role of hormones and stress should be considered within a full picture of the relation between brain development and cognitive development [69].

Another area concerns the interaction of genetic and environmental factors during development. In addition to the factors contributing to sensitive periods discussed earlier, the timing of biological events is clearly important. For example, one type of post-synaptic receptor molecule, the NMDA receptor, changes during development in a way that could contribute to learning being easier when we are
young [70]. Although this might appear to be a maturation of the process under genetic control, the change in the NMDA receptor is experience-dependent, and can be reversed if experience is withheld [71]. Understanding such interplay between genes and environment is likely to be crucial for understanding sensitive periods, and development more generally.

Complementarity

The use of complementary methods will become increasingly important in developmental cognitive neuroscience, as new tools are developed and as thinking regarding the relations among multiple levels of developmental processes advances. For example, combining fMRI with electroencephalography (EEG) allows researchers to take advantage of the spatial resolution of fMRI for identifying precisely where in the brain activity changes are occurring, and the temporal resolution of EEG for capturing neural changes linked to rapidly occurring cognitive changes [72].

Such complementary methods are informative in cognitive neuroscience in general, but could be particularly fruitful in the study of development. For example, neuroimaging methods might allow infants and young children to be tested with relatively simple tasks or with no task at all (where stimuli are simply presented for viewing). This would support testing children across a wide range of ages in the same experiment, thus advancing understanding of developmental changes [14]. In addition, altered cognitive processing might be revealed earlier through neuroimaging than in behavior, because compensatory cognitive and behavioral strategies can mask problems. This is particularly relevant in development, for example allowing teachers, parents and doctors to detect problems earlier and so intervene earlier and more successfully.

Diffusion tensor imaging (DTI) is a relatively new imaging tool, providing a non-invasive means for assessing brain connectivity [73]. The human brain undergoes extensive postnatal development in neuronal connectivity, as axons, dendrites and synapses are formed or enlarged and others are pruned, and the strength of this connectivity is modulated as neural tracts undergo an on-going process of myelination. In combination with fMRI and EEG, DTI might ultimately provide us with the opportunity to relate changes in connectivity and myelination to behavioral and neurophysiological measures of changes in the speed and efficiency of cognitive and neural processing during development. From a basic neuroscience perspective, it provides the unique ability to determine in vivo both function and connectivity within developing and mature brains. Such complementary approaches will be essential for informing our understanding of how the brain and behavior change with development.

Conclusion

The field of developmental cognitive neuroscience is advancing rapidly, along with the many fields that it draws upon. Developmental cognitive neuroscience research promises to provide a rich understanding of the interrelations among developmental changes in cognitive, perceptual, emotion and motor processing and in the brain's anatomy, chemistry and physiology, and the interaction of genetic and environmental factors in driving such development. This kind of understanding should inform the study of classic developmental and cognitive issues, and may in some cases redefine the form such questions take.

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