Cognitive and Brain Development in Adolescence

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ABSTRACT

Piaget's theory of formal operations launched empirical work on adolescent cognitive development, with two major outcomes: a lack of confirmation of the key claims of scaling, age of acquisition, and specification of logical requirements; and initiation of further research seeking to identify underlying mechanisms. Important shifts were found in adolescent processing, including speed, working memory capacity, increased inhibitory control, and strategic planning capabilities, all of which continue under the rubric of executive functions. Research on expertise showed it to be an essential component, including the finding that executive functions show improvement in domains where individuals have strong knowledge. More recent is a focus on the context on adolescent cognition, in dual process models that make a distinction between heuristic and more effortful analytic thinking, and also between "hot" and "cool" executive function that varies with the degree of emotional or social investment. Increasing convergence among executive function, dual process models, and developmental neuroscience has focused on the role of myelination in speed of processing, the prominence of the prefrontal cortex (PFC) in judgement and in governance of other neural systems, and the accelerated development of the limbic system, all of which have counterparts in experimental cognitive science. Future work is likely to focus even more directly on the relationship of cognitive and brain development, as imaging technologies rapidly improve.

KEY-WORDS: ADOLESCENT COGNITION, DEVELOPMENTAL NEUROSCIENCE, EXECUTIVE FUNCTION, DUAL PROCESS MODELS

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RÉSUMÉ

Le développement cognitif et cérébral à l'adolescence

La théorie piagétienne des opérations formelles a inauguré le travail empirique sur le développement cognitif de l'adolescent. Ce lancer a abouti à deux résultats principaux. D'une part, il n'y a pas eu confirmation de stades, d'âge d'acquisition ni de conditions logiques spécifiques ; d'autre part, des recherches se sont développées sur les mécanismes sous-tendant les changements liés à l'adolescence. Des changements importants concernent la vitesse de traitement, la mémoire de travail, le contrôle inhibiteur, les capacités de planification stratégique, toutes capacités en rapport avec les fonctions exécutives. Les recherches montrent en particulier que les progrès exécutifs concernent davantage les domaines de plus grande expertise…Plus récemment, on note un focus sur la cognition de l'adolescent dans des modèles duels faisant une distinction entre la pensée heuristique et la pensée analytique plus exigeante, et entre une fonction exécutive raisonnée (*cold*) ou spontanée (*hot*) selon le degré d'investissement émotionnel et social.

Les modèles de traitement duels et les neurosciences développementales s'accordent sur le rôle de la myélinisation dans la vitesse de traitement, sur le développement accéléré du système limbique, sur la prédominance du cortex préfrontal (PFC) dans le jugement et pour l'orchestration des autres systèmes neuraux. Les données expérimentales cognitives confirment. Dans le futur, la relation directe entre le développement cognitif et le développement cérébral sera sans nul doute privilégiée, avec les rapides progrès des technologies d'imagerie.

MOTS CLÉ: COGNITION DE L'ADOLECENT, NEUROSCIENCE DÉVELOPPEMENTALE, FONCTIONS EXÉCUTIVES, MODÈLES DE TRAITEMENT DUEL

Launched by the seminal 1958 work of Jean Piaget and Barbel Inhelder on *The Growth of Logical Thinking from Childhood to Adolescence,* which arose from Piaget's longstanding theoretical and empirical program on the development of logic and on genetic epistemology more generally (Piaget, 1950), research on adolescent cognition became a growth industry building on research across infancy and childhood by Piaget's group (e.g., Piaget, Apostel, Mays, & Morf, 1957) and internationally (Beilin & Pufall, 1992; Berlyne, 1957). This groundbreaking work focused on the development of propositional logic as the mature form of logical reasoning. The focus of the ensuing research was testing empirical claims embedded in formal operations theory (Keating, 1980, 1990). Adolescents were generally found to be more successful than children on the logic tasks described in Inhelder and Piaget (1958), although with wide variations in performance. Variability across tasks posed a significant challenge in that one might expect a shift to formal operational thinking would apply equally to all tasks that made similar logical demands, and variability across individuals (e.g., Keating, 1975) posed a different challenge, in that it gave rise to the possibility that factors other than changes in logical structure were implicated in task performance.

Research on formal operations subsequently coalesced into tests of three broad issues: (1) *scaling*—does performance on tasks occur in the predicted sequence?; (2) *age of acquisition*—do adolescents perform logically as would be expected given the acquisition of formal operations?; and (3) *logical demands*—do the empirical tests of logical performance closely match the empirical claims? Taken together, difficulties in establishing reliable scaling evidence at a suitably fine-grained level, in confirming the age of acquisition of formal reasoning, and in the lack of consensus on what constituted a reasonable test of logical acquisition that balanced competing demands of generalizability and logical precision, led to the conclusion that the explicit empirical claims of formal operations theory were not confirmed (Keating, 2004).

Despite this, a large body of research generated a robust descriptive portrait of major shifts in adolescent thinking. Five broad features that distinguish adolescent from childhood thinking have been identified across a number of research programs (Keating, 2011). *Thinking hypothetically* includes drawing accurate logical conclusions from premises, whether they are concrete, abstract, or counterfactual, as well as the ability to generate ideas about possible future states. *Thinking about and using abstract concepts* is a closely related development that includes both formal abstractions, such as mathematical and scientific constructs (Kuhn, 2009), and informal abstractions, like society, justice, or rights (Ruck, Abramovitch, & Keating, 1998). *Thinking self-reflectively* applies new cognitive sophistication to a growing awareness of one's own thinking processes, cognitive biases, and dispositions or metacognition (Klaczynski, 2005), and to a more advanced theory of mind (Dumontheil, Apperly, & Blakemore, 2010). *Thinking in multiple dimensions* includes combinatorial problems that require attention to all possible combinations of elements, a critical ability for coordinating theory and evidence in scientific reasoning (Kuhn, Iordanou, Pease, & Wirkala, 2008), and planning tasks such as the Tower of London that require joint attention to specific moves, beginning states, and target end states (Albert & Steinberg, 2011a). These overlap substantially with cognitive capacities grouped together as executive function (Prencipe, Kesek, Cohen, Lamm, Lewis, & Zelazo, 2011), which has been related to multiple domains from risk behavior (Keating, Houts, Steinberg, & Morrison, 2010) to academic achievement (Keating, Houts, Morrison, & Steinnberg, 2011). *Thinking about knowledge as relative* reflects a growing awareness arising from the acquisition of thinking that makes it difficult to retain the concrete, black/white certainties of childhood thought. Most adolescents eventually settle into a balanced stance of relativism and reflective judgement (Kitchener, King, Wood, & Davison, 1989), recognizing that even though certainties can always be challenged, the possibility of real knowledge and consistent values persists, and that assertions of fact or belief require conscious attention to evidence. Other adolescents experience what is perhaps best viewed as an overgeneralization of relativism, expressed as an epistemic commitment to skepticism that there exists no possibility of reliable facts, values, or beliefs (Chandler 1987).

COGNITIVE DEVELOPMENT PERSPECTIVES

Processing, Content, Context, and Developmental Neuroscience

Beyond the descriptive level, contemporary research on adolescent cognitive development has focused on several candidate mechanisms that can account for observed changes. These include componential models of information processing, with a current focus on executive function; knowledge-based models that focus on the acquisition of expertise; and contextual models, that highlight the differential deployment of cognitive activity across varying circumstances, with a particular focus on dual process models. Based on research findings that have not supported theories that focus on any single cognitive function as the central, encompassing explanation, the most recent focus has shifted to how these different models may be integrated. Increasingly, one key test of integrative approaches is the degree to which they are compatible with the growing understanding of brain development during adolescence (Keating, 2011).

Information Processing and Executive Function

From its origins in the 1970s, there have been several approaches to understanding the development of the cognitive processing system in adolescence, focusing on different hypothesized features of the system: the speed of processing (Kail & Miller, 2006), core processing capacity (Keating & Bobbitt, 1978), and the central conceptual structures within which processing was organized (Case, 1978). In each case, there were a range of experimental paradigms whose goal was to isolate one or another of these hypothesized features of the processing system.

Evidence rapidly accumulated showing that the speed of processing, even for extremely simple reaction time tasks that looked at information processing while controlling for motor reaction time, increased over the course of childhood and adolescence, with an apparent positive growth inflection point in early adolescence (Kail & Miller, 2006). The evidence also indicated a plateau in basic speed of processing by late adolescence or early adulthood.

A similar pattern emerged in research on processing capacity, most often measured as working memory span, with growth through childhood and into adolescence, with a similar plateau by later adolescence or soon afterwards. There is less clear evidence for a growth inflection in early adolescence, although this may be due to the fact that span is less finely grained in its measurement than reaction time.

Harder to resolve was the question of which aspect of the system was the principal driver of cognitive change: do changes in speed make it possible to handle more items in working memory, or does expanded capacity enhance processing speed? A third perspective, often referred to as neo-Piagetian approaches, argued that both speed and capacity were substrates for changes in central conceptual structures, where the most significant changes were occurring (Case, 1978). In this view, reorganization of the conceptual apparatus, such as in the models of numeracy in mathematics, enabled more information to be handled, and with greater efficiency and speed. Assessments of central conceptual structures also showed a growth pattern similar to what had been observed for speed and capacity of processing, expanding the competition among theories for what should be viewed as the central driver of developmental changes in processing: speed, capacity, or conceptual structures.

More recent research has yielded evidence that these aspects of the system are highly interdependent, and it may prove impossible to identify a specific leading cause (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Demetriou, Christou, Spanoudis, & Platsidou, 2002). Research examining relationships between changes in speed, capacity, or conceptual structures as explanations of performance differences in complex cognitive tasks found in general that the more refined and precise the parameters of each aspect became, the less variance in task performance was explained (Keating, List, & Merriman, 1985). In other words, there appear to be fundamental shifts in each of these processing features, but their coordination across the course of development is what most likely generates observed changes in cognitive activity at the higher order level of problem solving and reasoning. This is reflected in current research on the development of executive function, which focuses on how the core processes of working memory, attentional control, and planning become coordinated in support of complex cognitive activity in adolescence (Albert & Steinberg, 2011a; Keating et al., 2010, 2011; Prencipe et al., 2011).

Knowledge and Expertise

At about the same time, a separate and competing theoretical model focused on the acquisition of knowledge and the development of expertise (Chi, Glaser, & Farr, 1988). There emerged a stronger and a weaker version of this approach vis a vis theoretical claims for the primacy of either logical structures or processing systems. The strong version was that changes in reasoning or processing are effectively secondary to the acquisition of knowledge and expertise. In this view, as one acquires knowledge and expertise in any given domain, enhanced automaticity increases the efficiency of the processing system and enables more advanced reasoning skills (Chi, Hutchinson, & Robin, 1989). Thus, changes in reasoning and processing are subsidiary skills that are enabled by growth in knowledge and expertise. The weaker version of this approach did not relegate changes in processing or reasoning to a secondary level, but did argue that cognitive models that did not take the growth of knowledge and expertise as fundamental to how cognition functions and develops were missing a key element.

The initial evidence for a central role of expertise arose from the study of children and young adolescents who had acquired high levels of performance in specific areas, such as chess or knowledge of dinosaurs (Chi et al., 1988). This line of research found evidence for much better and more efficient problem solving, reasoning, and memory among early adolescents who had substantial expertise in the area being assessed, often surpassing novice or minimally experienced adults. The evidence also suggested more advanced levels of domain-specific planning and metacognitive strategies among these younger subjects. This could arise from either or both of two factors: with greater knowledge and expertise, there is a greater likelihood that the individual will have seen the same or similar patterns previously, allowing one to draw on that past experience to guide current action; and such individuals may also have automated a large number of component skills, allowing spare cognitive capacity to be used to assess the situation more globally or to engage in more sophisticated planning activity. In summary, the evidence supported the claim that advancing knowledge and expertise exercised a significant influence on the functioning of the cognitive system, beyond merely having more knowledge (Chi et al., 1988). On the other hand, the evidence for developmental differences in processing using controlled experimental paradigms that eliminated pre-existing knowledge differences indicated that factors besides expertise were implicated in adolescent cognitive development, and that the generalizing advanced cognitive skills may be limited among children and younger adolescents (Johnson, Scott, & Mervis, 2004).

Another feature of the research on expertise is worth noting, in that it also has implications for understanding how neural developments impact on cognitive functioning during adolescence. The "10,000-hours rule," arising from a research program on expertise (Ericsson & Charness, 1999) and subsequently attaining the status of common knowledge, states that approximately that amount of time is required to achieve proficient to expert performance in virtually any domain.

Dual Process Models

In only the second Nobel Prize awarded to behavioral scientists, Daniel Kahneman was cited in 2002 for his collaborative work with Amos Tversky (who died in 1996 and was thus ineligible to share the prize) on "how human judgement may take heuristic shortcuts that systematically depart from basic principles of probability." This important breakthrough in economic theory called into question a core assumption about the rational maximization of self-interest in decision-making that is central to classical economics. For cognitive scientists, it launched a vigorous line of research on biases and distortions that appear to be endemic to human cognitive architecture.

Research following Kahneman and Tversky (1996) generated a lengthy list of ways in which rational analysis can go awry, including the confusion of correlation with causation (including co-occurrence, or *cum hoc ergo propter hoc* in classical logic, or sequencing, *post hoc ergo propter hoc*), errors of reverse implication ("if A then B" being incorrectly conflated with "if B then A"), as well as more everyday heuristic biases like the "sunk cost fallacy"—having already invested a lot, one may feel compelled to continue pursuing a goal, even if a new analysis ignoring already sunk costs would lead to a different conclusion.

This line of research eventually gave rise to a range of "dual process models" of cognitive activity. In this model, there are two sets of cognitive processes, one that is associated with analytic reasoning, and the other of which relies on more heuristic processes—the latter of which is also characterized as experiential processing or instinctual processing. Evans (1984) characterized analytic reasoning as slow, sequential, requiring substantial central cognitive resources, and is responsive to instructions, whereas in each case the opposite is true of heuristic processing.

Dual process models have subsequently been applied to a wide range of adolescent cognitive functioning (Albert & Steinberg, 2011b; Gibbons, Houlihan, & Gerrard, 2009; Klaczynski, 2005; Reyna & Brainerd, 2011; Shaw, Amsel, & Schillo, 2011; Stanovich, 2006). One common element is the recognition that the context of cognitive activity makes a substantial difference. Because analytic reasoning is effortful and heuristic processing appears to be the default, the former is less readily activated and requires specific circumstances to evoke it.

Most prominently, research on adolescent decision making has drawn on the heuristic-analytic distinction. Because analytic reasoning is both effortful and time-consuming, and many decisions in everyday contexts do not require new analytic approaches on each repeated occasion, invoking *de novo* analytic processing could be debilitating. The difficulty lies in distinguishing between situations in which heuristic processes suffice from those in which a more conscious analytic effort would be beneficial. As noted in the section on expertise, the ability to automatize component skills may be a key support for enabling the deployment of metacognitive strategies, and thus balancing the advantages of fast bur error-prone heuristic processing against slower but more reliable analytic processing presents a significant challenge.

There is evidence that this may be particularly challenging for adolescents, because the analytic skills are relatively recently acquired and thus even more effortful than they are for adults, and because the executive functions of inhibitory control and planning are not fully developed, making it difficult for them to identify situations in which decisions might be better if subjected to more careful cognitive processing. Even in relatively simple laboratory tasks of attentional focus such as anti-saccade, adolescent performance approaches adult levels, but at the cost of ongoing effortful monitoring. Observed in functional Magnetic Resonance Imaging (fMRI) as extended activity in the prefrontal cortex (PFC), such monitoring absorbs cognitive resources at a much higher rate than it does in adults (Luna, Thulborn, Munoz, Merriam, et al., 2001).

The difficulties that adolescents face in identifying situations in which more careful analytic processing might be more beneficial and of deploying such processing in those contexts are exacerbated in socioemotionally challenging contexts, associated with emotional arousal or peer pressures, or both (Albert & Steinberg, 2011b). This distinction is also described as "hot versus cool" executive function (Prencipe et al., 2011). In addition, there is independent evidence suggesting that emotion and reward systems, affiliated with the limbic system of the brain, mature much more rapidly toward adult levels, compared with the slower growth of the PFC-supported executive functions, including self-regulation (Casey, Jones, & Somerville, 2011). There is increasing evidence for the maturational mismatch of prefrontal and limbic systems, which places particularly acute pressures on the adolescent's cognitive system. Enhanced reliance on heuristic processing and reduced invocation of analytic processing has been hypothesized to play a major role in the elevated levels of risky decisions observed among adolescents, a line of research that is receiving substantial research attention (Casey et al., 2011).

Complicating the picture is the seemingly paradoxical observation that directing adolescents' attention to deeper, analytic processing and away from heuristic processing may in some cases exacerbate risk taking. Characterized by Reyna & Farley (2006) as a distinction between verbatim and gist processing, the findings are that enhanced attention to verbatim processing may call additional attention to the desirable benefits of risk taking, A focus on benefits may increase the likelihood of risky behavior, especially for planful risk behavior (Maslowsky, Keating, Monk, & Schulenberg, 2011) and as a mediator from sensation-seeking to risk behavior (Maslowsky, Buvinger, Keating, Cauffman, & Steinberg, 2011).

Cognitive Developmental Neuroscience

Although the search for a central driver of adolescent cognitive development has not yielded a consensus candidate system, it would not be correct to say that the now extensive body of research on adolescent cognitive development does not reveal important points of convergence. First and foremost, the evidence for the interdependence of the development of major cognitive systems is quite strong – the mirror image of not finding a single driving cognitive factor that generates all other observed changes. Reasoning, for example, cannot be understood independent of what is being reasoned about, and the context in which the reasoning is occurring (Demetriou et al., 2002).

A second point of convergence is the emerging prominence of dual processing models across multiple research perspectives. The recognition that heuristic processes are deployed more often than analytic processes requires that more sophisticated models of each type of cognitive activity need to be further elaborated. The fact that contextual variables—especially high socioemotional investment—affect which processing system gets deployed, reinforces the notion that a fuller account of adolescent cognitive development will require a better understanding of when and how different cognitive systems are used.

A third and most important point of convergence is that integrative models, including dual process models that have emerged through the study of adolescent cognitive development, resonate strongly with findings arising out of the developmental neuroscience of adolescence. There are numerous parallels that are unlikely to prove coincidental. Four points of convergence between cognitive or behavioral findings and those from developmental neuroscience are noteworthy and are the focus of significant research activity.

The first parallel is between the findings on increases in speed of processing (Kail & Miller, 2006) and myelination (Giedd, 2004; Giedd, Blumenthal, Jeffries, Castellanos et al., 1999; Lebel & Beaulieu, 2011). Increased myelination of neural pathways—the accretion of insulating material on nerve fibers—substantially enhances the speed of processing, and shows a marked increase during adolescence. (DTI; Giedd, 2004; Thomason & Thompson, 2011).

Another parallel comes from developmental neuroscience evidence that has independently found an early adolescent proliferation of synapses, or synaptogenesis, followed by a period of synaptic pruning, in which those neural subsystems most heavily activated and engaged are selectively retained compared with subsystems not activated (Giedd et al., 1999; Thomason & Thompson, 2011). There is a strong implication that the advances in a wide range of more adult-like skills in adolescence may arise in part from the impact of experience on synaptic pruning, akin to that observed in infancy and early childhood. In particular, the development of expertise is very likely to depend on specifically focused synaptic pruning.

A third parallel is that between the gradual development of the PFC system, including its networked organization with other neural systems, and the gradual growth in executive functions and internal self-regulation during adolescence (Casey et al., 2011).

Finally, increases in internal connectivity among differing brain systems also resonates with the view that interdependency among core processing features is more likely than not, as noted above. Among the specific developments in the PFC system is a greater and more coordinated set of connections to other brain regions (Thomason & Thompson, 2011), findings that line up well with the cognitive evidence. It is clear from these research directions that an integration of psychological and neuroscience investigation is likely to be more productive than exclusive attention to either, or than efforts to reduce all accounts to explanations from neural circuitry.

POLICY AND PRACTICE

In addition to the attempt to integrate research from cognitive development and developmental neuroscience, contemporary research has also highlighted the implications for policy and practice arising from our understanding of adolescent cognitive development. Three especially noteworthy topic areas in which new research on cognitive and brain development has had notable influence include *education*, where developmental neuroscience has focused attention on the prefrontal cortex and the executive functions largely located there (Blakemore & Frith, 2005); *public health*, where behavioral misadventure is the greatest concern during the second decade of life, including driving safety, in which the role of expertise and its interaction with the socioemotional context are deeply implicated (Keating & Halpern-Felsher, 2008); and *juvenile justice*, where mitigation based in part on cognitive immaturity has become a central concern in recent court findings, in the U.S., Canada, and elsewhere (Scott & Steinberg, 2008).

In each of these cases, the integrative model uniting cognitive, behavioral and neuroscience evidence provides a valuable perspective. The implications for education are illustrative (Blakemore & Frith, 2005). The gradual emergence of executive functions and the PFC-system suggests a major opportunity, including direct efforts to scaffold EF/PFC developments. This would support advances in many educational domains, because of the solid evidence for increasing coordination of cognitive functions and their likely underpinning in the increased connectivity of neural circuitry under PFC governance. Finally, the evidence on the development of expertise and synaptic pruning emphasize building procedural and conceptual skills during this developmentally sensitive period.

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