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Leveraging Neuroscience to Inform Adolescent Health: The Need for an Innovative Transdisciplinary Developmental Science of Adolescence

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A B S T R A C T

In this article, we consider how to leverage some of the rapid advances in developmental neuroscience in ways that can improve adolescent health. We provide a brief overview of several key areas of scientific progress relevant to these issues. We then focus on two examples of important health problems that increase sharply during adolescence: sleep problems and affective disorders. These examples illustrate how an integrative, developmental science approach provides new insights into treatment and intervention. They also highlight a cornerstone principle: how a deeper understanding of potentially modifiable factors—at key developmental inflection points along the trajectory toward clinical disorders—is beginning to inform, and may eventually transform, a broad range of innovative early intervention strategies to improve adolescent health.

IMPLICATIONS AND CONTRIBUTION

A deeper and more integrative understanding of developmental neuroscience can enhance early intervention efforts by identifying modifiable targets, establishing greater precision in the timing of these processes, and using these insights to inform new strategies.

Adolescence is filled with paradoxes. It is both the healthiest period of the lifespan with respect to the most measureable aspects of physical health and a maturational period marked by surges in overall morbidity and mortality. Moreover, many types of behavioral and educational interventions appear to be relatively ineffective during adolescence, leading some to argue that this is the worst developmental period to try early intervention and prevention efforts [1]. Yet, there is growing evidence that adolescence is a dynamic period of learning and adaptation [2–4]. How can developmental science help to reconcile aspects of these paradoxes? It can do so by helping us to deepen our understanding of adolescence as a dynamic developmental period that creates vulnerabilities and unique opportunities for early intervention and prevention. For example, adolescence appears to create a sensitive period for some kinds of flexible learning and adaptation in ways that contribute to rapid downward spiraling toward some negative health trajectories (e.g., emotional and substance use disorders) as well as upward spirals toward positive developmental trajectories [2].

We believe that recent advances in developmental neuroscience—integrated within a larger transdisciplinary developmental science perspective on adolescence—can provide a new framework for these apparent contradictions. Specifically, we are looking at ways in which understanding the

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neurobiological trajectory of adolescence, including identifying key inflection points such as the onset of puberty, can help to refine and enhance our intervention approaches. Ideally, this can inform how to match the right kinds of behavioral interventions to opportune windows of learning and adaptation. To provide one concrete example, Bryan et al. [5] recently highlighted how a developmentally informed strategy to improve healthy eating (framing educational messages in a way that taps into adolescents' sensitivity to social status and desire for respect and autonomy) had a positive impact on adolescents' food selections, in sharp contrast to traditional educational efforts that typically have no effect (or a negative effect) on eating behavior. The point here is not to imply any simple solution to a complex problem like changing eating behavior but rather to illustrate an example of how developmental science can transform a relatively ineffective intervention into a promising approach. A second point focuses on the value of understanding the developmental neuroscience underpinnings (such as the role of pubertal testosterone effects on neural systems involved in adolescents' increased sensitivity to social status and desire for respect and autonomy). That is, a deeper and more mechanistic understanding as to why an intervention that honors adolescents' sensitivity to status (e.g., as in the study by Bryan et al.) can provide insights which can inform the targets, developmental timing, and other strategies for improving early intervention approaches.

Developmental Neuroscience Informs Developmental Science of Adolescence

On one hand, developmental neuroscience has led to rapid progress in understanding multiple aspects of neurodevelopmental changes in childhood and adolescence. Some of these advances appear promising in their capacity to inform pragmatic issues, adolescent health and well-being. On the other hand, we do not see developmental neuroscience as providing any simple mechanistic answers for treating the complex behavioral, emotional, and social problems that emerge in adolescence. Rather, we believe progress in understanding the interactions among social, emotional, psychological, behavioral, and neurodevelopmental processes that provides insights into both sides of the paradox. These include insights into the vulnerabilities for difficult-to-change negative spirals of health-harming risk behaviors and opportunities to establish positive spirals for health protective behavior [2]. In some cases, a deeper and more mechanistic understanding of these spirals, including their neuroscience underpinnings will map onto existing knowledge about the psychological and social development. In other cases, the developmental neuroscience provides fundamentally new insights and discoveries that help to identify modifiable factors early in the pathways leading to clinical disorders and advance and refine the precision of optimal timing or targets of modifiable factors. We believe that these advances will increasingly inform innovations to improve, and may eventually transform, early intervention approaches.

We will not attempt to summarize comprehensively the incredible range and depth of research that converge in the transdisciplinary developmental science of adolescence. Instead, our goals in this article are (1) to provide a brief, high-altitude overview of several areas of scientific progress in developmental neuroscience that point to leverage points for specific modifiable factors in adolescence and (2) to provide two specific examples to help illustrate how this type of integrative developmental science approach can provide promising opportunities for translational advances.

Developmental Neuroscience, Neuroplasticity, and Specialized Learning

Developmental neuroscience has achieved incredible progress in understanding the cellular and molecular underpinnings of a wide range of early prenatal and postnatal neurodevelopmental processes. Increasingly, researchers are emphasizing the role of early experience and learning in actively shaping neurodevelopment. There is now a nearly universal recognition of the positive opportunities created by early plasticity in developing neural systems—in ways that have major implications for policy, health, education, and national, as well as global, priorities [6].

There is also growing recognition that neuroplasticity is not limited to the first few years of life or even to the childhood years [6]. Broadly, the term neuroplasticity encompasses a wide range of synaptic and nonsynaptic processes that underpin the brain's capacity to instantiate learning, along with the concept of "sensitive windows" for specialized learning. Simply put, this means that many developmental factors influence the brain's capacity to learn, including the fact that the brain may be particularly receptive to specific types of learning at key times. Research into the molecular processes and mechanisms of neuroplasticity underlying sensitive periods of brain development has progressed rapidly (see reviews by Werker and Hensch and Hensch [7,8]). Researchers can now experimentally manipulate the molecular mechanisms underpinning plasticity. For example, in laboratory studies, researchers have successfully removed the molecular "brakes" to reopen critical developmental learning windows for visual processing in animal models [9] and have pharmacologically reopened critical periods for learning precise musical pitch in adult humans [10]. Efforts to manipulate plasticity, however, must be considered with great caution because there is growing recognition that normal brain development involves a changing balance of plasticity (patterns of neural connection that are flexible and adaptive to learning) and stability (neural circuitry that has achieved a relatively stable state of development) [11].

The period of brain development beginning with the onset of puberty and extending through adolescence may represent a unique combination of stability and plasticity—in ways that create an important window of opportunity for learning and experience to actively shape developing neural networks in enduring ways [11–13]. A deeper understanding of how this plasticity creates sensitive periods for learning specific to adolescence can provide important insights for translational advances in adolescent health.

To highlight a key principle relevant to these translational advances, it can be helpful to consider plasticity using an "experience-expectant" framework [14,15]. The infant brain, for example, "expects" some kinds of visual experiences that are necessary to organize and tune the visual systems. By 2 months of age, a typical infant has executed more than 2.5 million eye movements that have fundamentally shaped the relevant neural circuitry [16]. Similarly, the infant brain "expects" language and social experiences during this window of development. The analogous question for adolescent researchers is: How have

evolutionary forces shaped what the adolescent brain "expects" to learn? This points to more specific questions including (1) How does pubertal maturation impact the sensitivity of neural systems for specialized learning; (2) What kinds of information processing does the adolescent brain become naturally more attuned and motivated to engage in for rapid learning; and (3) What are the early adolescent corollaries to an infant's natural attraction to repeatedly practice, and eventually master, control of eye movements and speaking words?

A developmental neuroscience perspective on these issues is starting to emerge. In broad terms, the onset of puberty contributes to reorienting greater attention toward and salience of social and emotional information [17,18]. These changes appear to be particularly evident in two realms: (1) social relationships, including social roles, peers, potential romantic partners, social hierarchies, identity as a sexual being, and interest in sexual behavior [2,17] and (2) learning about the self and finding one's place in these social hierarchies, including an amplified salience of self-conscious emotions (e.g., strong desire for acceptance, belonging, admiration, and respect and increased sensitivity to feelings of rejection, disrespect, embarrassment, and humiliation) [19,20].

These two realms of specialized learning result from a very complex set of neurobehavioral changes that we are just beginning to understand with neural specificity. However, this illustrates a core principle of this article. The translational value of answering the question of what the adolescent brain "expects" to learn can only be achieved through an integrative perspective of adolescent development—one that promotes understanding of the recursive interactions of changes in the brain, behavior, and social context over time. Accordingly, our emerging understanding of sensitive windows for specific kinds of social and emotional learning in adolescence must be informed by multiple disciplines including developmental psychology, the science of learning, education, sociology, anthropology, biology, evolution, and clinical sciences. This broader integrative approach is needed to help shape and sharpen the larger heuristic models that aim to explain the diverging developmental trajectories, beginning with the onset of puberty, that can lead to positive spirals of prosocial behavior or negative spirals of health-harming risk-taking behaviors (see in the following section for a number of examples of frameworks highlighting divergent developmental trajectories) [2]. This kind of integrative approach can also contribute to progress in testing features of the model in ways that can inform real-world clinical and public health approaches to improving adolescent health and well-being.

Developmental Cognitive, Affective, and Social Neuroscience Perspectives on Adolescence

Over the past decade, there has been tremendous progress in the use of structural and functional neuroimaging to investigate normal and abnormal brain development across adolescence. Thousands of empirical studies and many high-quality review articles have covered a wide range of issues in these areas. In addition to many methodological and conceptual advances, there is an increasing recognition of the importance of moving beyond small-sample cross-sectional studies focusing on age differences and the need for larger sample, longitudinal studies focusing on developmental processes [2,21].

Several recent reviews have made efforts to understand adolescent brain development as a period of vulnerabilities and opportunities for a broad range of health outcomes (e.g., see special section of Developmental Cognitive Neuroscience on The Developmental Neuroscience of Adolescence http://bit.ly/20AVWm9 [17,18,22–26] and special issue of Current Directions in Psychological Science on the Teenage Brain http://cdp.sagepub.com/content/22/2.toc [27–41]). Other reviews have focused on the neuroscience implications for preventing or treating specific kinds of health problems that emerge in adolescence (see Table 1).

A central theme across this large body of research has emphasized the interactions between two sets of maturational processes that influence adolescent decision-making and behavior: (1) the gradual improvement in cognitive control, self-regulation, and ability to align behavior toward long-term goals and (2) the increased salience of social and affective influences, particularly those relevant to status, peers, romantic and sexual interests, social acceptance/rejection, as well as an increase in sensation seeking and other emotional changes. The first set of developmental processes tends to follow a gradual, relatively linear, set of increases in cognitive capacities and skills, which appear to be largely a function of age and experience. The second set of developmental processes appears to have an earlier and relatively abrupt onset and is more directly linked to pubertal maturation [21,42]. In contrast to traditional cognitive-based behavior change theories that inform most adolescent health interventions, these concepts have led to several versions of "dual-process" or "imbalance" models, focusing on the interactions between these cognitive and social-affective processes, including a range of opinions about the details of the models [43–49]. Early translational efforts based on these dual-process models included some overly simplistic frameworks, such as interpreting adolescents' risky and health-compromising decisions, as resulting from a weak or immature prefrontal cortex. More recent articles have shown that the neuroimaging data are pointing to a more complex picture of adolescent flexibility in cognitive engagement, depending on the social and motivational context [2,21,50,51]. The gradual improvements in cognitive control and emotion regulation combined with adolescents' increased sensitivity to social and affective motivational cues contributes to greater risks for making decisions with negative health consequences—particularly in social contexts where adolescents are making an abundance of novel decisions in conditions of elevated arousal and emotion [33,52,53]. As such, behavioral interventions must account for these dynamic interactive developmental processes.

Implications for Improving Adolescent Health

How can this general understanding of adolescent brain development help to inform health interventions? First, there is a general convergence around the importance of moving beyond traditional behavior change interventions to target sensitive, fast-acting neural systems which are more likely to respond to affective or implicit learning processes rather than explicit efforts to expand knowledge. This is consistent with other work that suggests that social and affective learning are crucial aspects of behavioral interventions [42]. Second, a deeper understanding of mechanisms can inform the strategies, timing, and traction points for interventions. For example, neurodevelopmental research has pointed to the role of increasing testosterone at the onset of puberty as one important factor impacting the increased salience of social status in adolescence [16,54]. We are very early

Table 1
Additional examples of developmental neuroscience-informed approaches to selected adolescent health issues

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in the process of understanding the precise changes in specific neural systems, the interactions with other changes such as increased sensation seeking and increased affective reactivity, and the role of other hormonal changes at puberty such as estradiol and oxytocin. A more nuanced understanding of the neurodevelopmental mechanisms can provide insights for behavior change strategies during puberty targeting status- and sensation-seeking tendencies. For example, it can provide insights as to why health education interventions that simply provide cognitive understanding of risks and consequences are largely ineffective and why efforts to scare youth about the consequences of experimenting with drugs fail [55]. Most

importantly, it can provide insights as to why some adapting behavioral interventions in ways that honor adolescents' increased need for admiration and respect can have greater success [5]. A deeper understanding of the mechanisms and the related developmental trajectories of social and affective processing systems can also help to sharpen the focus the developmental timing for specific behavior change approaches.

Alternatively, these neurobiological insights can be used to help identify high-risk adolescents who are more prone to certain kinds of behavioral or emotional problems and to effectively target these individuals for specific kinds of early intervention strategies. For example, youth with a biological predisposition for sensation seeking and bold behavior who are also at high risk for substance use and externalizing disorders have been shown to benefit from interventions that promote positive or prosocial versions of risk taking and excitement seeking—particularly during the key maturational window when sensation seeking increases and these neural systems appear more plastic to social and affective learning experiences [56,57]. In contrast, youths with a strong biological predisposition to be anxious, fear-reactive, or highly socially inhibited may be at high risk for developing anxiety and/or depression and have been shown to benefit from early intervention or prevention interventions that specifically target fear reactivity [58]. A developmental neuroscience lens brings unique, yet contrasting, value added to these two specific examples as well as across a wide-range of adolescent behaviors (see Table 1 for additional examples).

However, it is important to acknowledge that neuroscience has, at least to this point, provided very little direct translational benefit beyond what we can understand from other disciplines including clinical (e.g., adolescent medicine and clinical psychology) and social sciences (e.g., developmental psychology). Moreover, there is considerable disagreement within the field about how best is it to translate the findings and their implications. For example, one interpretation of the evidence that the prefrontal cortex and related executive functions are relatively late to fully mature has resulted in health policy recommendations to simply "protect" adolescents until their brains become more fully mature (see [1] for a recent argument in support of this perspective). Yet, we and others have argued a very contrasting perspective—emphasizing that adolescence is a particularly dynamic period of development and adaptation in ways that create unique opportunities for enduring positive change through learning and experience (see [2,18,59,60]).

Puberty and the Transition into Adolescence—One Window of Opportunity

Puberty represents one set of processes for which a developmental neuroscience lens can provide new insights into several translational opportunities. Given, the multilevel complexity of inter-related maturational processes occurring during puberty, it is necessary to slice into this with greater specificity. To illustrate this approach, we will consider two specific examples of developmental processes: (1) pubertal changes in sleep/circadian regulation and (2) social and affective changes at puberty relevant to anxiety and depression. In each case, the fundamental goal is to illustrate how advancing integrative developmental science can help to identify specific, modifiable factors that can be targeted at key early inflection points along developmental trajectories toward major health problems.

Example 1—pubertal changes in sleep/circadian regulation

There is growing evidence for a broad range of negative consequences associated with late and erratic sleep schedules, sleep deprivation, and social jet lag (the misalignment of sleep and activity schedules resulting from adolescent patterns of staying up late and sleeping in late on weekends but having early school start times on weekdays) [61,62]. A developmental science lens can provide unique insights into these complex and high-impact problems. As has been well documented in elegant studies in humans and animals, the onset of puberty is associated with specific changes in sleep and circadian regulation, which contribute to a slight tendency to prefer staying up late, sleeping in later, and an increase in overall sleepiness [63–65]. Unfortunately, this science has been oversimplified resulting in the interpretation that adolescents are biologically unable to go to sleep and get up early and that the only evidence-based solution is to delay the start time of high schools [66,67].

More careful scrutiny of the developmental science reveals a more complex and nuanced story and points to a broader range of potential interventions. In brief, pubertal hormones contribute to three important changes: (1) increased sensitivity to the biological effects of light—especially light striking the retina when the circadian system "expects" darkness before bedtime [68]; (2) increased motivational salience and arousal response to social stimuli [17]; and (3) changes in the homeostatic sleep system and sleepiness [69,70]. Before the modern era of electric lights, this set of changes was thought to be only weakly associated with changing sleep patterns in adolescence [71,72]. In contemporary society, however, exposure to bright artificial light, screens with arousing and exciting content, and cell phones with continuous social communication, particularly during the sensitive early-dark phase of the circadian system, has resulted in large shifts in bedtime—a trend persisting with the increasing availability of light and technology [73]. Social stimulation and emotional arousal, both embedded in much of current electronic communication, can also serve as a biological zeitgeber (time-setting cue) for the circadian system.

In addition to the physiological cues, behavior also drives much of the shift in sleep schedules. It is often during weekends, holidays, and summer that young adolescents begin to slip into very late bedtime patterns—in small part because of the pubertal change in sensitivity but in large part because of the patterns of behavior that amplify these effects [62,74]. Once these late night and erratic sleep schedules are established, they can be very hard to reverse not only because well-established habits are hard to change but also because the organization of the neural systems underpinning sleep and circadian regulation make it more difficult to adapt to phase advances (earlier bedtimes and wake times) than to phase delays (later bedtimes and wake times) [75]. Moreover, there is growing evidence that increasing use of electronic devices in bedrooms and around bedtime further amplifies these problems and their related health impacts [76].

These mechanistic insights built on developmental science nuances are important because they add precision regarding behavioral targets and the developmental windows of opportunity for early intervention strategies. The deeper understanding of the developmental changes provides insights into the developmental timing (the onset of puberty) and the process (sleep patterns, evening light exposure, social stimulation, and emotional arousal near bedtime)—crucial proximal intervention targets. Rather than focusing solely on a structural intervention

well after these behavioral patterns have been established, such as changing high school start times, developmental neuroscience can refine our intervention approaches to target early intervention and prevention. Beyond illustrating that exposure to light and social stimuli are crucial mediators and amplifiers of subtle biological changes, developmental neuroscience highlights the social and affective influences that put youth at very high risk for developing delayed sleep patterns early in adolescence. Most importantly, an integrative developmental science approach can provide insights into possible early leverage points and targets for early interventions during the onset of puberty (e.g., age: 9–11 years) when sleep-wake patterns are first nudged by these biological changes—before these tendencies spiral into well-ingrained patterns of very late night and erratic sleep schedules in high school.

It is important to acknowledge that there may be many good reasons to delay high school start times to help compensate for adolescents' strong tendencies toward sleep delay. At the same time, later school start times alone are unlikely to solve the larger complex set of problems with late and erratic sleep/wake schedules. Moreover, the simplistic focus on structural changes implies that it is normal and acceptable for teens to go to bed and sleep in late, whereas the neuroscience clearly shows that in a structured environment without access to artificial light or exciting social activities, adolescents are quite capable of going to sleep early and getting up early—and likely to benefit from stable sleep schedules at this important period of learning and maturation.

Pubertal changes in sleep and circadian rhythms are also associated with increases in internalizing symptoms, including anxiety and depression [77]. The precise causal and directional relationships at this interface are not well understood. There is ample evidence for bisectional effects—that is, sleep disruption has negative effects on mood and affect regulation, and anxiety and depression are associated with disruptions in sleep and sleep/wake schedules [78–81]. Moreover, the onset of puberty is window of vulnerability for the development of anxiety and depression as well as vulnerability for sleep and circadian problems. Taken together, these represent a source of negative spirals across inter-related regulatory systems. However, a deeper understanding of the development neural systems and their interactions may provide new insights into the most promising proximal targets for early intervention (see [37,58,82] for further discussion).

Example 2—anxiety and depression in adolescence

The sharp increase in depression and anxiety disorders following the onset of puberty represents another area of opportunity for an integrative developmental science approach to inform early intervention. Affective disorders increase sharply during adolescence [83], and the onset of puberty is also the developmental inflection point when rates of depression accelerate in girls at least twice as fast as in boys, providing strong evidence that gonadal hormones play a crucial role [84]. A provocative follow-up to a large epidemiologic study of the development of depression showed that very low–birth weight girls accounted for a huge proportion of the girls who developed depression at the onset of puberty [85]. These findings fit within a larger developmental science framework that examines two interacting windows of vulnerability—one during early postnatal development (when gonadal hormone levels are high and individuals are highly sensitized to variance in parental care taking and/or nutritional challenges such as food scarcity or low-birth weight) and a second window at the onset of puberty (when rising gonadal hormone levels coincide with complex changes in social, emotional, and cognitive processes) [86,87]. It is crucial to emphasize the truly transdisciplinary nature of understanding a complex disorder like depression, including interactions spanning psychological, emotional, social, motivational, family, and complex neurodevelopmental processes [19,58,88–90]. At the same time, the primary point relevant to this article is the converging evidence that the onset of puberty represents an inflection point relevant to the life course of affective disorders. From a developmental science perspective, the onset of puberty appears to create a window of opportunity for early intervention. Although significant changes have yet to be made in clinical treatment approaches, numerous studies are currently underway leveraging developmental science informed treatment approaches and testing specific kinds of targets ranging from sleep [91] to attention bias modification (learning to shift attention away from one set of stimuli toward something else) [92] to cognitive behavioral therapy (CBT) [93,94].

There are also some interesting and very specific controversies regarding the developmental neuroscience insights for anxiety disorder treatment in adolescence, focusing on CBT. Given the important role of attention in anxiety, CBT is a commonly used treatment [95]. A crucial element of CBT is not only the cognitive focus on changing someone's patterns of thought but also, and perhaps most importantly, the graded behavioral exposure (incrementally increasing experience) and mastery of one's sources of fear. An exploration of the desired behavioral outcomes and their neural underpinnings in the laboratory has informed research on novel pharmacological (e.g., utilization of d-cycloserine to enhance fear relevant learning for patients undergoing CBT) and nonpharmacological treatment approaches that only emerged as a result of the developmental neuroscience [96]. One interpretation of current developmental science has led to the prediction that the onset of puberty, accompanied by increased sensation seeking, exploratory behavior, and capacity for fear mastery [54], should be an opportune time for employing the approach strategy of CBT for treatment of social anxiety [97,98]. A second contrasting neuroscience-informed model of fear extinction (learning that a previous threat is no longer threatening) based on animal models has made the opposite prediction due to the natural contextual suppression of fear expression normally occurring during adolescence, fear extinction efforts during adolescence may be particularly ineffective [99]. This model proposes that the discordant developmental trajectories of the prefrontal cortex and subcortical limbic regions, leading to high emotional reactivity contribute to CBT being particularly ineffective during puberty and adolescence [100]. In this debate between fear extinction and exposure, the goal of the developmental science may not be to claim one as correct but rather continue to inform the emergence of contrasting models that include testable hypotheses. By helping to focus the mechanistic question, developmental science refines the direction of future interventions.

Developmentally informed understanding of anxiety has also begun to inform exciting innovation that integrates advances in mechanistic understanding of adolescence with the principle of motivated learning through gamification (using gaming principles to motivate learning and behavioral outcomes).

Wijnhoven et al. [101] have developed a game to reduce anxiety in young adolescents called Mindlight. To create a better bridge between the skills young people learn through CBT and their capacity to apply them in daily life, Mindlight uses a video game format to achieve fear exposure, neurofeedback, and attention bias modification to help youth manage anxiety symptoms and electroencephalogram technology to measure the level of relaxation. As participants navigate the game's protagonist through a virtual setting, encountering unpredictable scary stimuli, Mindlight uses electroencephalogram technology to measure the level of relaxation among participants. As participants become more relaxed, it increases the brightness of the "mindlight" to illuminate the game. By successfully maintaining relaxation and completing attention bias modification puzzles, participants gain points. Employing the developmental neuroscience-informed model promoting adolescence as an ideal time for CBT in partnership with the principles of gamification that maximize motivated learning in adolescence, Mindlight serves as an excellent example of the ways developmental science can inform and transform clinical care.

Discussion

Neither developmental science broadly nor developmental neuroscience more specifically promise to be a silver bullet that will solve the complex health problems associated with adolescence. In addition, developmental science research advances do not easily lend themselves to simple translation into new clinical and public health approaches to adolescent health. The primary limitations and barriers are inherently interwoven into the diversity of the problems, coupled with the nuances of the scientific advances. In particular, the interactions of multiple factors influencing adolescent behavior (e.g., biological, behavioral, social, affective, and contextual) make it very difficult to translate an exciting discovery about a mechanism at the individual neural level into a specific population-level intervention or prevention program. There are similar challenges to using broad principles emerging from the neuroscience in a way that does not result in overly simplistic, and likely ineffective, approaches. Despite these challenges, developmental science does offer an opportunity to increase our reciprocal understanding of how behavioral and environmental contexts influence neural development and how neural developmental changes influence changes in behavior. A developmental science framework can add unique contributions to the field of adolescent health, by slicing across the complexity in ways that address tractable focused questions and offering deeper, more mechanistic understandings of disorder etiology and health-harming decision-making processes.

A broad framework of integrative developmental science—and its focus on understanding how environment, learning, and experience—particularly at key points in development—can synergistically influence connectivity across maturing neural circuits, in ways that can have enduring effects on behavior, has great potential to increase the impact of services and intervention [100,102]. While the field of public health has a long-standing history of using behavioral research to explore how a range of individual contextual experiences and exposure to adverse experiences at particular times affect health throughout the life course [103], developmental affective and social neuroscience is deepening this understanding by exploring how these experiences sculpt neural systems during periods of relative plasticity—in ways that may create particular vulnerabilities, as well as special opportunities for early intervention or prevention.

Leveraging developmental science to improve adolescent health requires transdisciplinary teams working together to identify precise questions that can be explored by taking deep "slices" into the complex, multilevel developmental science evidence. As such, shifts need to occur at multiple levels—in funding for research, training for young scholars, and evaluation of existing adolescent health programs. One of the greatest barriers to progress is the specialization and fragmentation of science, resulting in relatively separate silos of knowledge. To overcome this barrier, there is need for innovative integration across disciplines to develop a common theoretical model of adolescent behavior change, which is developed and refined through iterative interactions, in ways that embrace several differing approaches and perspectives, with a high priority on working together toward common goals. Integrated, transdisciplinary funding opportunities and research agendas will help foster this essential collaboration and ultimately improve the health trajectories for all adolescents.

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