Adolescent brain cognitive development study: Longitudinal methods, developmental findings, and associations with environmental risk factors

In 2004, the New York Academy of Sciences hosted a national symposium focused on adolescent brain and behavioral development (Dahl and Spear, 2004). This effort, which highlighted pressing questions related to the neurobehavioral, psychological, and social changes during adolescent development, is considered by many to have been the impetus for current research in the field. While the emphasis of the meeting was on adolescence as a period of both opportunity and vulnerability, the latter was emphasized more strongly in recognition of an accumulating body of evidence that a wide range of behavioral and emotional health problems emerge at this time. Among problems noted to accelerate during adolescence were substance use problems, sexual risk taking behaviors, and mental health challenges including elevated risks for affective disorder, suicidal behavior, and psychosis. Attended by luminaries in the field, the meeting concluded by encouraging collaboration and integration across preclinical, clinical, and social policy perspectives to generate, from this interdisciplinary perspective, discoveries that would inform early intervention and prevention strategies.

The field responded enthusiastically to this call for action. Developmental neuroimaging was in a state of relative infancy, but rigorous applications of current techniques to adolescent samples were adopted. A number of now-classic theoretical and empirical papers emerged that presented basic mechanisms of cognitive and affective development, their neural correlates, and an increasing recognition of the importance of motivational drives expressed in different contexts in shaping adolescents' decision-making strategies and their potential to engage in risk-taking behavior (Casey et al., 2008; Ernst et al., 2006; Galvan et al., 2006; Gogtay et al., 2004; Luciana et al., 2005; Luna et al., 2004; Paus et al., 2008; Steinberg, 2010). Pubertal development was recognized as a fundamental source of influence (Braams et al., 2015), and other biological processes such as sleep (Carskadon et al., 2004; Short and Weber, 2018) were scrutinized. Over time, it was increasingly acknowledged that not all adolescents are at equivalent risk (Bjork and Pardini, 2015) and that individual difference factors as well as experiential variations likely interact with age-related maturational changes to determine which youth are most vulnerable.

At the same time, a number of limitations in extant approaches to identifying risk were identified. Many reports were based on cross-sectional rather than longitudinal data, limiting the ability to differentiate premorbid sources of vulnerability from neurodevelopmental deviations. In addition, most studies relied on small samples that were not representative of the full population's racial, ethnic and sociodemographic distribution. Heterogeneity across measures and methodologies restricted conclusions that could be drawn from the literature, leading

the National Institutes of Health (NIH) to encourage researchers across laboratories to harmonize their behavioral (Hamilton et al., 2011; Nuechterlein et al., 2008; Weintraub et al., 2013) and neuroimaging (Harms et al., 2018) assessments.

Building upon these efforts and in response to these challenges, the Adolescent Brain Cognitive Development℠ Study (ABCD Study®) was initiated in the Fall of 2016 and is now the largest neuroimaging study of adolescent development worldwide. At the study baseline, 11,878 youth, recruited using a probability sampling approach (Gard et al., 2023; Garavan et al., 2018) from 21 performance sites across the United States, were enrolled with their caregivers to participate in a longitudinal assessment that involved behavioral and neuroimaging probes (see abcdstudy.org). Youth were aged 9–10 years at initial enrollment. Imaging data have been collected every other year, while behavioral assessments occur yearly. Aspects of mental health and substance use are assessed every six months. Now in its 7th year, ABCD is funded by a range of federal institutes, including many of the NIH institutes, the NEA, and the DOJ among others. It is expected to continue until the youth are at least 19–20 years of age. In 2018, *Developmental Cognitive Neuroscience* hosted a special issue to introduce the project's conceptualization, design, recruitment methods, assessment strategy, and plans for longitudinal assessment to the scientific community (c.f., Barch et al., 2018; Feldstein Ewing et al., 2018; Garavan et al., 2018; Luciana et al., 2018; Volkow et al., 2018). To date, hundreds of empirical papers have been published that have utilized the dataset (https://abcdstudy.org/publications/).

With the support of the NIH, ABCD adopted an open science model to promote transparency and data sharing (Saragosa-Harris et al., 2022). De-identified data are shared through the NIH National Institute of Mental Health Data Archive (NDA: www.nda.gov), a collaborative platform that encourages cross-study and cross-site harmonization through common data standards. Approximately once yearly, curated ABCD data from the prior year of assessment are deposited into the NDA repository and may be accessed by members of the scientific community. When the papers for this issue were solicited, the project's baseline, year 1 and portions of year 2 data were available for analysis. Data from year 3 became available as papers were being evaluated for inclusion.

The goal of this issue is to update the field on the study's longitudinal measures, best practices for the analysis of longitudinal data, and emerging findings. When papers were invited, we indicated a particular interest in empirical papers that use best practices to establish robustness and reliability, that leverage the longitudinal nature of the data, and that integrate findings across measurement domains. Given the issue's timing, this was a tall order. Relatively few measures within

ABCD's assessment battery are repeated yearly. However, nearly all investigators who contributed to this issue were able to use at least two waves of data in their analyses (Anokhin et al., 2022; Mattoni et al., 2021; Petrican et al., 2021; Rakesh et al., 2021) and several papers (e.g., Bagot et al., 2022; Barch et al., 2021; Gonzalez et al., 2021) feature three time points. Together the fifteen papers presented within this issue are maximally informative regarding the nature and psychometric integrity of the assessment battery, longitudinal methods and trends that can be fruitfully applied across future assessment waves, and the importance of capturing and modeling sociodemographic variation in assessing developmental trajectories.

1. Psychometric integrity of study measures

Rigorous and robust longitudinal assessment of developmental samples relies on the psychometric integrity of measures and designs that can differentiate patterns of maturational change from practice effects and other sources of measurement error (see Anokhin et al., this issue). In this issue, several components of the assessment battery, such as the culture and environment variables (Gonzalez et al., 2021), linked external data including geocoding (Fan et al., 2021), and measures for the assessment of gender identification and sexual health (Potter et al., 2022) are described in comprehensive detail to guide researchers who plan to use these instruments. Several papers present psychometric data on the retest stability, internal consistency, and validity of select measures such as ABCD's screen time questionnaires (Bagot et al.), assessments of neurocognition (Anokhin et al.), mental health (Barch et al.), and culture and environment (Gonzalez et al., 2021) questionnaires. A validation of the Emotional Stroop Task, administered at post-baseline years 1, 3 and 5 (to date), is presented for the first time (Smolker et al., 2022) and indicates that the task is working as designed in capturing aspects of attention, inhibitory control, and emotional processing.

Psychometric data presented for these components of the battery is encouraging. Anokhin et al. found that retest stability for ABCD's ten neurocognitive outcomes that were measured longitudinally from baseline to year 2 ranged from fair (NIH Toolbox Flanker Task: r = 0.44) to excellent (NIH Toolbox Crystallized Cognition Composite: r = 0.82). Nearly all measures showed significant improvement with increasing age, although practice effects were observed for several variables including accuracy of performance on the NIH Toolbox Flanker, Pattern Comparison Processing Speed, and Picture Sequence Memory tests, and both accuracy and reaction time of the Little Man Task, which measures visuospatial processing (see Luciana et al., 2018). For two measures, the Rey Auditory Verbal Learning Test and the Little Man Task, assessment strategies were altered between baseline and year 2, and these alterations had measurable impacts on performance. Researchers are encouraged to take this information into account when analyzing ABCD's neurocognition data.

Similarly, Gonzalez et al. (2021) presented data from baseline, year 1, and year 2 and found that ABCD's measures of culture and environment showed modest to good retest stability for all measures completed by caregivers. However, all youth measures showed relatively poor retest stability, despite adequate internal consistency. Importantly, the retest stability of youth reported measures was greater from year 1 to year 2 than it was from baseline to year 1, suggesting possible improvements in the reliability of youth report over time. Moreover, almost all culture and environment measures administered to youth and caregivers demonstrated statistically significant differences between those youth identified as "lower" versus "higher risk", based on caregiver endorsements of youth externalizing behaviors as well as parental substance use, at study enrollment. These findings validate the notion that youth who are at high risk for ongoing externalizing behaviors may experience a number of potential challenges based on characteristics of their proximal environments.

Barch et al. presents information regarding plans for ABCD's longitudinal assessment of mental health, including ways in which the Consortium will address known issues with some measures. For instance, an upgrade from KSADS version 1.0 to 2.0. will improve diagnostic precision, particularly for neurodevelopmental and psychotic disorders. In keeping with ABCD's principles of justice, equity, diversity and inclusion (Simmons et al., 2021), the Self-Reported Delinquency Scale (SRD) has been discontinued by ABCD due to evidence of differential item functioning in a manner that is biased against Black youth. ABCD's mental health assessment includes categorical (e.g., KSADS) as well as dimensional (Achenbach System of Empirically Based Assessment: ASEBA)) measures. Benefits of the latter approach are emphasized, including data collection across multiple informants, the ability over time to integrate parent and youth reports, and cross-cultural alignment with methods being used by other large-scale developmental studies (e.g., Generation R) that are ongoing. Further, as described below, Barch et al. presents data on the longitudinal trajectories of youth mental health and how these are impacted by a variety of socioeconomic related factors.

Bagot et al. presents psychometric information for the Social Media Addiction Questionnaire (SMAQ) and Videogame Addiction Questionnaire (VGAQ), both of which demonstrate excellent internal consistency reliability. Tests for measurement invariance indicated that the SMAQ showed a similar factor structure and item loadings across sex and race/ethnicities. However, item intercepts varied across both sex and race/ethnicity such that scalar invariance was not supported. Accordingly, the researchers cautioned against comparing group means on the SMAQ across different demographic groups. For the VGAQ, full configural, metric, and scalar invariance was found across racial and ethnic groups. However, item loadings and intercepts differed between female youth and male youth. Screen time increased significantly over time with variations by sex-assigned-at-birth for measures such as online social activities, which were more frequent for girls, versus gaming and screen watching, which were more frequent for boys. For all types of screen usage, use was reportedly more frequent on weekends versus weekdays. Given ongoing questions and concerns about associations between screen usage and health outcomes, these findings set the stage for future analyses that will assess longitudinal associations between screen usage, mental health outcomes, problematic substance use, and other youth characteristics.

Longitudinal Retention and Methods. A longstanding goal within developmental psychology is to understand how various aspects of behavior are expressed over time, factors that predict variations in behavior, and how variations in behavior at one point in time might be associated with longer term outcomes. To make proper inferences, it is essential to be able to measure between-person differences in the context of within-person change over time (Curran et al., 2010), a goal that is particularly challenging in the context of developmental neuroimaging (Herting, Sowell, 2017; Pfeifer et al., 2018). To reliably and accurately model growth over time, at least three repeated observations are recommended, the sample must be sufficiently large to accommodate person by time interactions across observed variables, and missing observations should be relatively minimal in number, though missing data within large samples can usually be accommodated by newer analytic methods.

The ABCD Study boasted an impressive retention record between 2016 and 2020 as indicated in the paper by Feldstein Ewing et al. (2022), which focused on pre-pandemic metrics. Across 49,525 scheduled visits between the study baseline and post-baseline year 3, 3.9% of visits were classified as missing, and the participant withdrawal rate was very low, at 1.1%. Importantly, missed visits and withdrawals between the study baseline and year 3 were more likely within select racial/ethnic groups (e.g., Spanish speakers) and in families with lower levels of parental education, lower levels of parental employment, and residences that are greater distances from the relevant study site. Earlier missed visits were found to increase the likelihood of later study withdrawal, suggesting that implementing timely assistance and incentives

to promote continued engagement for families showing signs of reduced participation may be fruitful in order to encourage sustained involvement. Ongoing attention to differential patterns of attrition is needed to reduce potential retention bias in research using the ABCD data.

In the context of these excellent retention patterns, ABCD's large sample size and repeated measures approach allows change over time to be reliably modeled as a function of a variety of factors. Within this issue, Barch et al. illustrate this approach with respect to ABCD's measures of mental health. When multiple indices were assessed, there was a consistent pattern of age by sex interaction, such that youth-reported internalizing, externalizing, and total problem scores increased with age in females but decreased with age in males. When SES metrics were included in the models, metrics that reflect lower SES were related to greater youth-reported total, internalizing, and externalizing problems. While relatively few differences by race and ethnicity were found for youth reports, these effects were more substantial for caregiver reports.

Indeed, several papers within this issue report differences in caregiver versus youth reports of various behaviors. For instance, in their report of screen time usage in the ABCD sample, Bagot et al. also report differences in caregiver versus youth endorsements with youth reporting greater levels of screen usage. Potter et al. report low to modest correlations between caregiver and youth reports on measures of gender identity and sexuality. As described above, Gonzalez et al. (2021) reported better retest stability across caregiver-reported versus youth-reported measures. Similar patterns have been found for ABCD's measures of pubertal development (Herting et al., 2021). Thus, researchers are encouraged to consider this information when selecting which informant's data to utilize, as findings may vary depending on the measure, the age of the ABCD sample, and which informant is likely to have and report the most accurate information. Attention to possible sex effects in salient outcomes is warranted given differences reported by Barch et al. and Bagot et al.

In an analysis of neurodevelopmental change, Palmer et al. (2022) utilized a novel approach, restriction spectrum imaging (RSI), a framework for modeling diffusion-weighted imaging, to quantify voxelwise restricted diffusion across the brain as well as associations with age. Across both gray and white matter, increasing age was associated with an increase in the proportion of restricted diffusion with the largest changes evident in the basal ganglia and midbrain. Moreover, age associations varied with respect to the cytoarchitecture within white matter fiber tracts and subcortical structures, indicating that future studies should incorporate a voxelwise approach to assessing the behavioral significance of these findings.

Using a different approach that also emphasizes the relevance of subcortical structures and their development, Mattoni et al. conducted a latent profile analysis to identify distinct neuroanatomical profiles of subcortical region volume and orbitofrontal cortical thickness in ABCD's baseline sample. The analysis yielded a five-profile solution consisting of a reduced subcortical volume profile, a reduced orbitofrontal thickness profile, a reduced limbic and elevated striatal volume profile, an elevated orbitofrontal thickness and reduced striatal volume profile, and an elevated orbitofrontal thickness and subcortical volume profile. After controlling for age, sex, and intracranial volume, it was found that there were differences between individuals in their levels of concurrent psychopathology measured both dimensionally and categorically and in psychopathology at the year 1 follow-up, which was measured dimensionally, based on profile membership. A robust finding was that at baseline, youth in the profile characterized by reduced subcortical volumes had greater psychopathology across multiple domains, measured both dimensionally and diagnostically, relative to youth in other profiles. In contrast, youth characterized by elevated OFC thickness and subcortical volumes had fewer concurrent neurodevelopmental problems than youth in all other profiles.

In an elegant analysis that incorporated a dimensional perspective on the structure of psychopathology, Romer and Pizzagalli (2021) examined prospective relations over two years between executive function, operationalized through several of ABCD's neurocognitive measures, and general psychopathology (p), which was factor analytically derived. A higher-order factor model of psychopathology was identified at baseline and validated at the one- and two-year follow-up waves. Consistent with previous research, a cross-sectional inverse relationship between executive function and general psychopathology emerged such that lower EF was associated with greater psychopathology. Using residualized-change models, it was then demonstrated that baseline EF prospectively predicted p factor scores two years later, even while controlling for prior p, sex, age, race/ethnicity, parental education, and family income. Baseline p factor scores also prospectively predicted change in EF two years later. These bi-directional prospective relations between EF and p appeared to be generalizable across multiple sub-domains of psychopathology, supporting the notion that executive dysfunction is both a transdiagnostic risk marker as well as a consequence of general psychopathology. Together, these papers cohere to illustrate the field's interest in behavioral and neural predictors of mental health outcomes in the ABCD sample.

2. Associations with environmental risk factors

There is compelling evidence to suggest that early social adversity, reflected by lower family socioeconomic status (SES) in childhood, impacts neurodevelopmental trajectories with potential negative impacts on emotional and cognitive development, disruptions in brain development, and, as a result, increased risks for mental health challenges (Barch, 2022; Farah, 2018; Peverill et al., 2021; Palacios-Barrios and Hanson, 2019). These challenges may become evident during the adolescent period, particularly after the onset of puberty (Herting et al., 2017; Pfeifer and Allen, 2021), which may mediate associations between adverse early environmental experiences and later brain development (Sisk and Gee, 2022; Thijssen et al., 2020, 2022). Neuroimaging studies that have focused on these associations have traditionally involved smaller samples and a bias toward majority versus underrepresented groups. A novel aspect of ABCD's design concerns its inclusion of large numbers of participants from various racial, ethnic and socioeconomic backgrounds (Garavan et al., 2018). Consideration of socioeconomic background is crucial in evaluating risk for the emergence of mental health problems as illustrated by Barch et al. (this issue), who found that indicators of lower SES were related to greater total, internalizing, and externalizing problems based on youth reports. DeJoseph et al. (2022) examined ABCD's baseline data and implemented a moderated nonlinear factor analysis to psychometrically decompose aspects of socioeconomic status and demonstrated that socioeconomic indices and psychosocial threat, as measured by aspects of the family home environment, have different effects on variations in resting state frontolimbic connectivity. Rakesh et al. further demonstrate that socioeconomic measures have both common and unique associations with resting state brain activity, stressing the importance of examining these factors alone and in combination. Incorporating ABCD's second wave of imaging data, Brieant et al. (2021) show that corticolimbic resting state connectivity becomes more strongly negative between baseline and year 2. Exposure to negative life events, measured at year 1, is associated with a more strongly negative, and apparently more mature, pattern of corticolimbic connectivity at year 2, which, in turn, predicts lower levels of parent-rated Child Behavior Checklist (CBCL) internalizing symptomatology. Thus, there is a significant indirect effect of experiential adversity on the association between corticolimbic resting state connectivity and indices of psychopathology.

Going forward, the ABCD Study is well-positioned to expand upon these findings given its comprehensive assessment of participant demographics, proximal aspects of each youth's culture and environmental context, as well as distal environmental factors (see Fan et al., this issue) that capture aspects of the exposome (see Barch, 2022), such as environmental toxins and pollutants, urbanicity and its correlates, and neighborhood levels of poverty and crime, that may elevate risk for

psychopathology.

3. Conclusions

As illustrated within this issue, the scientific community is only beginning to harness the potential of the ABCD dataset to comprehensively describe mechanistic pathways of neurodevelopment and how these pathways and trajectories are impacted by variations in experience. In the context of excellent retention over the first several years of the study and compelling data regarding the psychometric integrity of the overall assessment battery, several important trends are already evident, indicating that the course of early adolescent neurodevelopment from late childhood to mid-adolescence varies as a function of sociodemographic characteristics and life experiences. As additional longitudinal data becomes available, we and other members of the Consortium look forward to ABCD's generation of novel insights that will advance our understanding of adolescent development and young adult health outcomes.

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