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PERSPECTIVES

NEUROSCIENCE

Childhood environments shape the brain

Socioeconomic factors top the list of influences on children's brain structure and function

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Associations between the structure or function of the human brain and measures of behavior are typically small, and major sources of variation across individuals remain incompletely understood. On page 1147 of this issue, Marek *et al.* (*1*) report associations between a wide range of phenotypic variables and brain structure and function in a large sample of youth. The study found that childhood environments—and socioeconomic factors specifically—showed the strongest associations with brain measures, exceeding those for associations with cognition and mental health. Although previous work has found that socioeconomics can affect brain structure and function, Marek *et al.* demonstrate these effects with notable scale and consistency. The results suggest that the socioeconomic contexts in which youth grow up may be a key source of individual differences in brain organization.

Brain-wide association studies examine how variability in brain structure or function across many individuals relates to differences in behavior, mental health, or environmental exposures. By examining these associations one variable at a time across hundreds of measures and brain regions, researchers can rank which variables are most strongly linked to specific brain regions and compute the effect size of each association. Such insights can provide information on the factors that influence brain variability across people. In human neuroscience, brain structure and function are often noninvasively measured using magnetic resonance imaging scans. Cortical thickness, a measure of brain structure, is obtained from anatomical scans similar to those used in clinical practice and indexes the depth of the cortical mantle. Functional connectivity captures fluctuations in brain activation over time and represents how regions communicate as networks. Both measures change over the course of development and vary substantially across individuals.

Marek *et al.* sought to identify which of 649 phenotypic measures were most strongly associated with functional connectivity and cortical thickness in a large, demographically diverse sample of youth aged 9 to 10 years. They found that a composite index of neighborhood-level social and economic opportunity—capturing factors such as poverty rate and median household income (*2*)—was the variable most strongly associated with functional connectivity; it was also among the strongest for cortical thickness. Indeed, socioeconomic variables, such as household income and percentage of students eligible for free lunches in schools, dominated the strongest brain-wide associations, accounting for 37 of the top 40 associations with functional connectivity and 35 of the top 40 associations with cortical thickness. Socioeconomic status is a complex construct that encompasses family income, parental education, income-to-needs ratio, and neighborhood quality. It has long been linked with physical and psychiatric health, educational attainment, and measures of cognition (*3*), in part through differences in brain structure and function (*4, 5*).

Notably, Marek *et al.* also observed associations between socioeco-

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nomic status and functional connectivity in overlapping regions of the brain in a separate large adult dataset that predominantly comprised participants with white British or Irish backgrounds. Combined with analyses stratified by genetic ancestry in the original youth sample, these findings indicate that the brain differences associated with socioeconomic factors are unlikely to be related to genetic ancestry. Instead, results appear to be driven by socioeconomic variation in the childhood environment.

Marek *et al.* found that socioeconomic status–related differences in functional connectivity were strongest in brain regions involved in sensory and motor processing (the sensorimotor cortex) rather than in regions typically linked with higher-order cognition (the association cortex). Increased screen time and reduced sleep duration, both of which are linked to lower socioeconomic status, also showed strong associations with functional connectivity in convergent sensorimotor regions. The implicated sensorimotor regions resembled maps of brain regions related to arousal, which is the body's overall state of wakefulness and physiological activation. Arousal operates as a global, dynamic regulator of brain activity, physiology, and behavior (*6*). Thus, socioeconomic status–related stressors may alter arousal patterns over time and produce durable differences in brain function. Marek *et al.* speculate that the overlap between sensorimotor regions associated with socioeconomic status and brain maps relating to arousal may reflect the embedding of chronic environmental stress. How these results relate to substantial evidence that higher-order association regions are also sensitive to socioeconomic status, particularly during development, remains an important question for longitudinal work (*7*).

The putative effects of socioeconomic status on the brain may also complicate associations between brain structure or function and measures of cognition. Marek *et al.* initially found that brain-cognition associations were primarily localized to sensorimotor areas, spatially aligning with the regions showing the strongest brain–socioeconomic status effects. However, after statistically accounting for individual differences in socioeconomic status when evaluating associations with cognition, the resultant brain-cognition associations were weaker but better aligned with brain areas that support complex cognition. Notably, Marek *et al.* also found that brain-cognition associations did not generalize to broader samples when statistical models were trained only in high–socioeconomic status samples. This highlights a common limitation of neuroimaging studies, which are often conducted with predominantly high–socioeconomic status participants. In future work, measuring socioeconomic status alongside brain and cognitive variables and prioritizing recruitment of socioeconomically representative participant samples will facilitate deeper understanding of how the brain supports cognition. These results also underscore the ongoing challenge of identifying robust relationships between the brain and individual differences in cognition.

When during development might socioeconomic status affect the brain most strongly? Research suggests that socioeconomic factors may affect neurodevelopment as early as the prenatal period. For instance, maternal socioeconomic status during pregnancy has been linked to alterations in infants' functional connectivity (*8*) and to the development of children's brain networks and language skills (*9*). Marek *et al.* found that associations between socioeconomic status and the brain are evident by 10 years of age and are largely replicable in adults, which suggests that these patterns may emerge early in life. However, because socioeconomic environments are often stable across development, it is challenging to disentangle when socioeconomic status–related brain differences first arise, how much such differences are shaped by early versus later experience, or how reversible these patterns may be.

Over the course of development, the brain passes through sensitive periods of plasticity—windows of time when environmental input can have especially strong effects on organization (*10*). Increased sensitivity to the environment may create both vulnerability to environmental insults and opportunity for fostering resilience. Convergent evidence indicates that brain development follows an organizational hierarchy: Core sensory and motor systems develop earlier, whereas association systems involved in complex cognition and emotion processing undergo protracted development throughout adolescence and into early adulthood (*7*). The timing of sensitive periods follows a similar hierarchical structure, with windows of increased plasticity occurring earlier in sensorimotor circuits and later in association circuits (*11*). Marek *et al.*'s findings might be explained, in part, by early embedding of environmental stress during sensitive periods of sensorimotor development. Nonetheless, patterns established during sensitive periods may not remain permanently fixed. Experience-dependent plasticity continues across development and into adulthood, allowing neural circuits to adapt to changing environments (*12*). Socioeconomic status–related brain differences may thus reflect dynamic developmental histories rather than fixed biological states.

At the population level, access to fewer socioeconomic resources is linked with greater risk for worsened physical and mental health, educational attainment, and cognitive performance (*3*). Marek *et al.* did not directly examine associations between socioeconomic status–related brain patterns and outcomes such as physical and mental health. As such, it is unclear whether the specific patterns of brain differences that they describe have long-term implications for health and behavior. Further, associations observed across populations cannot predict the potential or outcomes of any individual child. Although the effect sizes reported for socioeconomic status are large by field standards, 84% or more of the variation in brain measures was not explained by socioeconomic status. Youth from lower–socioeconomic status backgrounds may frequently have brain patterns that are similar to those of their higher–socioeconomic status peers, and vice versa. The developing brain also has substantial capacity for adaptation and resilience, and individuals growing up with fewer socioeconomic resources can develop distinct, context-specific strengths (*13*). Evidence from a randomized controlled trial indicates that children's outcomes can shift markedly when environments improve (*14*), underscoring that early circumstance is not destiny. At the same time, Marek *et al.*'s findings that socioeconomic status–related differences in the brain are already present before adolescence highlight the need for societal-level policies that provide early support for families (*15*). □

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