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Executive functions in the brain, development and social context: Early contributions by neuroscientist, Adele Diamond

A seminal moment in my academic career was in the late 1980s while attending one of my first scientific meetings as a graduate student and hearing a fascinating talk by a female neuroscientist, Adele Diamond. She was describing prefrontal cognitive abilities in human and nonhuman primate infants using the A-not-B task (Fig. 1; Diamond and Goldman-Rakic, 1986; Diamond, 1990). This task measures executive functions (e.g., working memory, inhibitory control and mental flexibility) that enable us to focus our attention, remember, plan and juggle multiple tasks. The A-not-B task itself requires the infant to uncover an attractive toy hidden in one of two locations as the child watches, followed by a short delay and then the child's retrieval of the object by uncovering 1 of the 2 locations (Piaget, 1952). The name of the task comes from an error that infants under 8 months of age characteristically make. That is, after correctly finding a toy hidden in location A, when the toy is then placed in location B in plain sight of the infant, the infant nonetheless reaches back to the toy's former location A.

Earlier studies in adult monkeys (Goldman and Rosvold, 1970) had shown dependence of working memory on the dorsolateral prefrontal cortex, a region thought to mature relatively late in development. However, Diamond was showing a developmental progression in a prefrontal function in 8–12 month olds. Specifically, she showed that the necessary length of delay for producing the A-not-B error, between the experimenter hiding the toy and the infant finding it, increased from 2 to 5 s by 8 moths to over 10 s by 12 months. Adult monkeys with lesions of the dorsolateral prefrontal cortex performed like the human infants under 8 months of age suggesting that maturation of the prefrontal cortex supported developmental improvement in this executive function (Diamond and Goldman-Rakic, 1989).

I was fascinated by these findings because my graduate work focused on cognitive development in infants. A recurring question I had was what was going on inside the child's brain to explain the different looking behaviors to familiar and novel objects during the simple cognitive tasks I was using. My postdoctoral fellowship at the National Institutes of Health (NIH) in the 1990 s provided an opportunity for me to begin to address this question. At the time of my arrival, we could see with exquisite detail the structure of the human brain with noninvasive imaging tools like magnetic resonance imaging (MRI). However, we could not see brain activity with the same level of detail without the injection of invasive radioactive isotopes. Within 2 years of my arrival, exciting advances in MRI were providing the ability to observe brain activity noninvasively based on changes in blood oxygenation referred to as functional MRI. This technological advance in human brain imaging opened a door to the investigation of the behaving developing human brain in novel ways, facilitating the emergence of the field of developmental cognitive neuroscience.

Diamond's influential work on executive function no doubt shaped the first functional MRI study of typical human development which examined dorsolateral prefrontal activity in young healthy children during an executive function task (Casey et al., 1995). The task examined working memory and like adults, children activated the dorsolateral prefrontal cortex more during a high memory load condition relative to a low memory load condition. That study consisted of a "whopping" six 9–11 year olds from relatively homogenous backgrounds in race and ethnicity, education and income. Fast forward almost three decades later and we now find numerous studies around the world with 500 or more children for which there is brain imaging data (Rosenberg et al., 2018). For example, the Adolescent Brain Cognitive Development (ABCD) Study®, one of the largest studies of the human brain and cognitive development in the U.S., is following nearly 12,000 9–10 year old children over a 10-year period. Although the ABCD sample is not fully representative of the U.S. demographics, it approximates the population providing not only a large, but more diverse sample than has historically been recruited for brain imaging studies. Taking advantage of these available, open access ABCD imaging data from children of a similar age and performing a similar working memory task as our original 1995 study (Casey et al., 1995), we replicated our early findings (Rosenberg et al., 2020). Moreover, we showed that patterns in brain activity in prefrontal cortical networks during the working memory task predicted individual differences in cognitive performance on other similar executive functioning tasks involving memory, providing a neural signature of working memory ability in children (Rosenberg et al., 2020).

The significance of understanding executive functions, their neural correlates and development are underscored by their disruption in many neuropsychiatric, neurodevelopmental and neurodegenerative disorders. Perhaps this is not surprising given that these functions are essential in regulation of our actions, desires and fears as we adapt to our ever-changing environments, especially early in development. Given the importance of executive functions in everyday life, there have been several attempts to improve these abilities in children with training. Many of these studies have provided evidence of cognitive skill training improving executive functions (Scionti et al., 2020) with those children with the worse performance on executive function tasks showing the most benefit. These training benefits are observed early in childhood, suggesting that early executive-function training may help to prevent widening achievement gaps later in life (Diamond and Lee, 2011). However, cognitive skill training alone, without consideration and support of the emotional, social and physical needs of the child are likely

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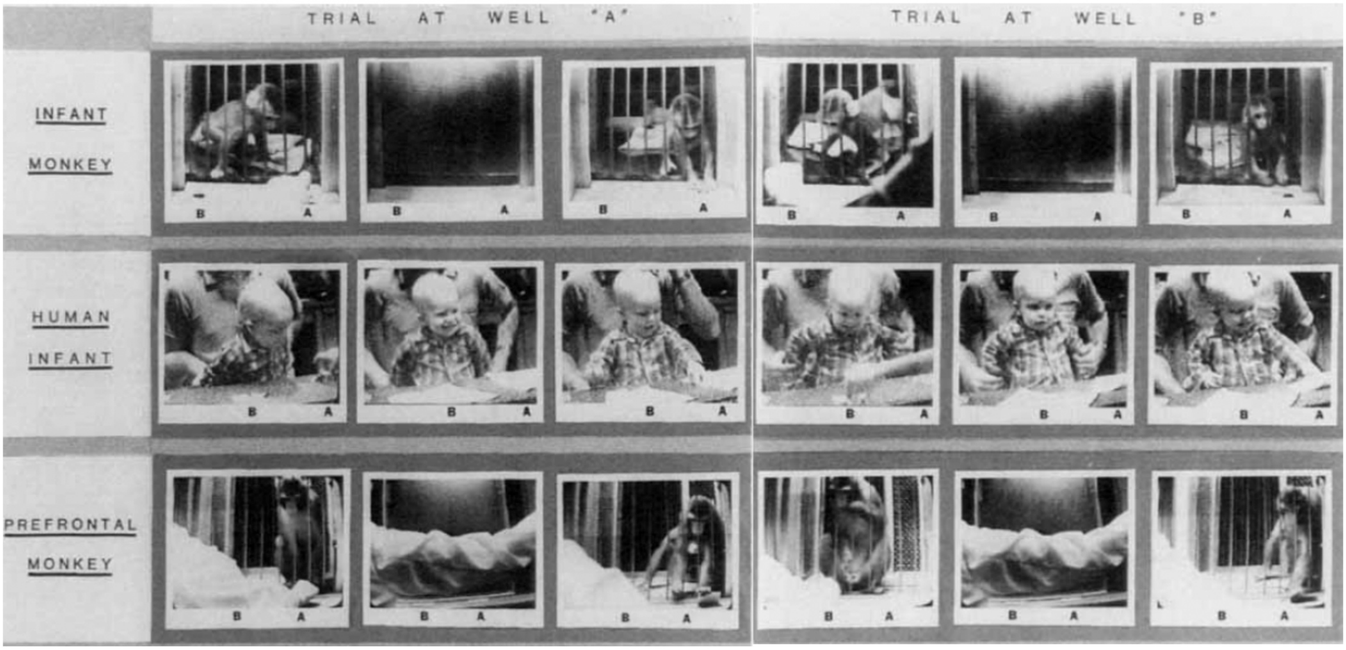

Fig. 1. Comparison of performance of a monkey infant, a human infant and an adult monkey with ablated prefrontal cortex on the A-not-B task. All succeed in finding an object hidden at location A, but when the object is then hidden at location B, both reach back to location A, even though they both observed the object being hidden at location B. From Diamond (1990).

less successful in improving executive functions. In fact, Diamond has advocated for building executive functions through interactive activities, sports and the arts as opposed to instructional teaching alone, suggesting several pathways to increasing cognitive abilities important for everyday life (Diamond and Lee, 2011).

The view that social and emotional needs are important for the development of executive functions is supported by numerous studies showing that impoverished, violent and stressful environments and conditions can diminish the very cognitive (executive) functions and underlying prefrontal networks that we may need to adapt and function in our expanding worlds as we develop (Noble et al., 2015; Rahdar and Galván, 2014). A recent developmental human imaging study conducted at Yale where Diamond's nonhuman primate studies began over 30 years ago examined the influence of diverse environments on executive function in the large sample of ABCD youth. That study focused on associations between perceived threats in the home, school, and neighborhood on executive function and associated prefrontal brain networks. Youth who perceived threats such as violence and crime in their neighborhoods had the most diminished executive function performance and brain network activity relative to youth who perceived threats in their families or at school (Conley et al., 2023). That is not to say to say that executive functions were compromised long-term. The brain is plastic and has the potential for change throughout the life course, especially during the first few decades of life (Simmons et al., 2021). With opportunities and different experiences (i.e., less stressful) we see changes in executive functions and adaptability to our changing world (Liston et al., 2009).

It is important to keep the broader socioemotional context in which cognitive development is occurring in mind. Development and deployment of cognitive abilities in different environments reflect an interactive process of the child's changing biology in a changing environment at different developmental phases and social contexts. Behavior in one environment may be favorable or unfavorable in another environment depending on the child's past and current situation (Nketia et al., 2021; Simmons and Conley et al., 2021). For example, in violent and stressful environments, rapid reactions (flight or fight) may be more adaptive for the child's survival than executive functions like inhibitory control. Considering these important environmental factors may enhance interpretations and mitigate potentially harmful deterministic narratives about cognitive ability for children from impoverished or violent/stressful environments.

This summer I have the wonderful opportunity to speak at a celebration of Adele Diamond's life work and of work that that she has inspired and that has inspired her (see https://tinyurl.com/msvzy7hw for live streaming details). The speakers (http://www.devcogneuro.com/Conf2023/schedule.html) represent a broad community of distinguished neuroscientists, psychologists, educators, and artists because in Diamond's view, all are important in the development of executive functions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Casey, B.J., Cohen, J.D., Jezzard, P., Turner, R., Noll, D.C., Trainor, R.J., Giedd, J., Kaysen, D., Hertz- Pannier, L., Rapoport, J.L., 1995. Activation of prefrontal cortex in children during a nonspatial working memory task with functional MRI. Neuroimage 2 (3), 221–229. https://doi.org/10.1006/nimg.1995.1029.

Conley, M.I., Rapuano, K.M., Benson-Williams, C., Rosenberg, M.D., Watts, R., Bell, C., Casey, B.J., Baskin-Sommers, A., 2023. Executive network activation moderates the association between neighborhood threats and externalizing behavior in youth. Res Child Adolesc. Psychopathol. https://doi.org/10.1007/s10802-022-01003-2.

Diamond, A., 1990. The development and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkeys. Ann. N. Y Acad. Sci. 608, 267–309. https://doi.org/10.1111/j.1749-6632.1990.tb48900.x.

Diamond, A., Goldman-Rakic, P.S., 1986. Comparative development in human infants and infant rhesus monkeys of cognitive functions that depend on prefrontal cortex. Neurosci. Abstr. 12, 742.

Diamond, A., Goldman-Rakic, P.S., 1989. Comparison of human infants and rhesus monkeys on Piaget's AB task:evidence for dependence on dorsolateral prefrontal cortex. Exp. Brain Res. 74, 24–40.

Diamond, A., Lee, K., 2011. Interventions shown to aid executive function development in children 4–12 years old. Science 333 (6045), 959–964. https://doi.org/10.1126/science.1204529.

Goldman, P.S., Rosvold, H.E., 1970. Localization of function within the dorsolateral prefrontal cortex of the rhesus monkey. Exp. Neurol. 27, 291–304.

Liston, C., McEwen, B.S., Casey, B.J., 2009. Psychosocial stress reversibly disrupts prefrontal processing and attentional control. Jan 20 Proc. Natl. Acad. Sci. U. S. A. 106 (3), 912–917. https://doi.org/10.1073/pnas.0807041106.

Nketia, J., Amso, D., Brito, N.H., 2021. Towards a more inclusive and equitable developmental cognitive neuroscience. Dev. Cogn. Neurosci. 52, 101014 https://doi.org/10.1016/j.dcn.2021.101014.

Noble, K., Houston, S., Brito, N., et al., 2015. Family income, parental education and brain structure in children and adolescents. Nat. Neurosci. 18, 773–778. https://doi.org/10.1038/nn.3983.

Piaget, J., 1952. The Origins of Intelligence in Children. Basic Books, New York.

Rahdar, A., Galván, A., 2014. The cognitive and neurobiological effects of daily stress in adolescents. NeuroImage 92, 267–273. https://doi.org/10.1016/j.neuroimage.2014.02.007.

Rosenberg, M.D., Casey, B.J., Holmes, A.J., 2018. Prediction complements explanation in understanding the developing brain. Nat. Commun. 9 (589) https://doi.org/10.1038/s41467-018-02887-9.

Rosenberg, M.D., Martinez, S.A., Rapuano, K.M., Conley, M.I., Cohen, A.O., Cornejo, M. D., Hagler, D.J., Meredith, W.J., Anderson, K.M., Wager, T.D., Feczko, E., Earl, E., Fair, D.A., Barch, D.M., Watts, R., Casey, B.J., 2020. Journal of Neuroscience 40 (26), 5090–5104. https://doi.org/10.1523/JNEUROSCI.2841-19.2020.

Scionti, N., Cavallero, M., Zogmaister, C., Marzocchi, G.M., 2020. Is cognitive training effective for improving executive functions in preschoolers? A systematic review and meta-analysis. Front. Psychol. https://doi.org/10.3389/fpsyg.2019.02812. ⟨https://www.frontiersin.org/articles/10.3389/fpsyg.2019.02812⟩.

Simmons, C., Conley, M.I., Gee, D.G., Baskin-Sommers, A., Casey, B.J., 2021. Responsible use of open-access developmental data: the Adolescent Brain Cognitive Development (ABCD) study (Epub). Psychol. Sci. 32 (6). https://doi.org/10.1177/09567976211003564.

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