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Nutritional status, brain network organization, and general intelligence

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ABSTRACT

The high energy demands of the brain underscore the importance of nutrition in maintaining brain health and further indicate that aspects of nutrition may optimize brain health, in turn enhancing cognitive performance. General intelligence represents a critical cognitive ability that has been well characterized by cognitive neuroscientists and psychologists alike, but the extent to which a driver of brain health, namely nutritional status, impacts the neural mechanisms that underlie general intelligence is not understood. This study therefore examined the relationship between the intrinsic connectivity networks supporting general intelligence and nutritional status, focusing on nutrients known to impact the metabolic processes that drive brain function. We measured general intelligence, favorable connective architecture of seven intrinsic connectivity networks, and seventeen plasma phospholipid monounsaturated and saturated fatty acids in a sample of 99 healthy, older adults. A mediation analysis was implemented to investigate the relationship between empirically derived patterns of fatty acids, general intelligence, and underlying intrinsic connectivity networks. The mediation analysis revealed that small world propensity within one intrinsic connectivity network supporting general intelligence, the dorsal attention network, was promoted by a pattern of monounsaturated fatty acids. These results suggest that the efficiency of functional organization within a core network underlying general intelligence is influenced by nutritional status. This report provides a novel connection between nutritional status and functional network efficiency, and further supports the promise and utility of functional connectivity metrics in studying the impact of nutrition on cognitive and brain health.

1. Introduction

The human brain has high resource demands: the adult brain represents two percent of the body weight but consumes approximately 20 percent of the body's energy (Clarke et al., 1999). This energy requirement underscores a key point: adequate nutrition is needed to support brain health (Goyal et al., 2015). Further, while energy may be derived from a variety of nutritional sources, aspects of nutrition may optimize brain health, in turn enhancing cognitive performance. Recent discoveries in nutritional epidemiology and cognitive neuroscience provide insight into the therapeutic potential of nutrition for enhanced cognitive performance and brain health across the lifespan, with the interdisciplinary field of nutritional cognitive neuroscience leading this effort (reviewed in Zamroziewicz and Barbey (2016)). Unraveling the ways in which nutritional status may influence specific aspects of brain structure and function to support cognition will have profound implications for understanding the nature of brain health and for treating neurological disease.

General intelligence represents a critical cognitive ability that has been well characterized by cognitive neuroscientists and psychologists alike, but the extent to which a vital aspect of brain health, namely nutritional status, impacts the neural mechanisms that underlie general

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intelligence is not understood. General intelligence enables adaptive reasoning and problem solving skills (Colom et al., 2010; Barbey et al., 2012, 2013a, 2013b, 2014) that are important in everyday decision making (Gottfredson, 1997) and are strongly predictive of occupational attainment, social mobility (Strenze, 2007) and job performance (Gottfredson, 1997). Thus, understanding the neural mechanisms underlying this general mental ability, and how they may be modulated by lifestyle factors, such as nutritional status, may provide significant individual and societal benefits (Colom et al., 2010).

A large body of neuroscience evidence indicates that variation in the synchronization or efficiency of communication between brain regions reliably predicts individual differences in general intelligence (reviewed in Deary et al. (2010)). Intrinsic connectivity networks, the fundamental organizational units of human brain architecture (Laird et al., 2011), display consistent spatial patterns of functional connectivity at rest that reflect information processing capabilities (Lowe et al., 1998; Raichle et al., 2001; Beckmann et al., 2005; Damoiseaux et al., 2006). Individual differences in intelligence have been related to traditional measures of resting state connectivity in neural networks involved in self-referential mental activity (i.e., default mode network), attentional control processes (i.e., dorsal attention network), and task-set maintenance (i.e., cingulo-opercular network) (Song et al., 2009; Smith et al., 2015; Yuan et al., 2012; Wang et al., 2011; Pamplona et al., 2015; Santarnecchi et al., 2015). Further, recent evidence suggests a key role for connections between prefrontal and parietal cortices that comprise the dorsal attention network (Hearne et al., 2016). Advances in neuroimaging provide a new tool that implements graph theory principles to measure and assess intrinsic connectivity networks (Watts and Strogatz, 1998). Graph theory metrics enable a precise characterization of the complex network organization of the brain (Bullmore and Sporns, 2009), with efficient information flow across functional brain networks representing a small-world organization defined by a high level of local clustering and a short path length between brain regions (Sporns and Zwi, 2004; van den Heuvel et al., 2008). In particular, small world propensity presents as an accurate measure of small world architecture that is impervious to nuisance variables but sensitive to critical variables of small world organization (Muldoon et al., 2016). Importantly, nutritional status has been shown to improve brain function (Wiesmann et al., 2016; Dumas et al., 2016; Konagai et al., 2013; Boespflug et al., 2016); however, no study has investigated the influence of nutritional status on small world propensity of the intrinsic connectivity networks that support cognition.

The Mediterranean diet is a well-recognized dietary pattern thought to promote healthy brain aging (Feart et al., 2015). Indeed, adherence to Mediterranean-style diets has been shown to support cognitive performance (Hardman et al., 2016) as well as brain structure and function (Staubo et al., 2017; Matthews et al., 2014). Scientific advances in the characterization of dietary patterns and measurement of nutrient biomarkers have led to a new methodology in nutritional epidemiology for the measurement of nutrient biomarker patterns (NBPs). In this approach, nutrients are measured by way of biochemical markers in the blood (i.e., nutrient biomarkers) and principal component analysis is applied to empirically derive patterns of nutrients, referred to as NBPs. This method is highly sensitive to variability within a restricted set of variables (i.e., 5–10 variables per observation; Osborne and Costello, 2004). Thus, in this study, we use NBP analysis to investigate one of the core components of the Mediterranean diet with high sensitivity and specificity: the monounsaturated fatty acid to saturated fatty acid ratio. This fatty acid ratio has been linked to cognitive function (Samieri et al., 2013; Solfrizzi et al., 1999, 2006) as well as brain function (Dumas et al., 2016). In fact, the monounsaturated fatty acid to saturated fatty acid ratio is thought to be one of the driving factors of the metabolic benefits of the Mediterranean diet on the brain (Dyson et al., 2011; Evert et al., 2013; Aranceta and Pérez-Rodrigo, 2012). However, no study has investigated how patterns of monounsaturated fatty acids and saturated fatty acids affect the intrinsic connectivity networks that underlie cognitive function.

In summary, general intelligence is an important predictor of real-world decision making and relies upon the functional integrity of underlying neural networks. The monounsaturated fatty acid to saturated fatty acid ratio, a core component of the Mediterranean diet, is known to promote cognition and brain structure, but how these fatty acids support the intrinsic connectivity networks that underlie general intelligence remains unknown. Therefore, this study applies cutting-edge methodologies from nutritional epidemiology and cognitive neuroscience to explore how nutrient profiles of monounsaturated fatty acids and saturated fatty acids impact small world propensity of intrinsic connectivity networks that support general intelligence in a sample of cognitively intact older adults.

2. Materials and methods

2.1. Participants

This cross-sectional study enrolled 122 healthy elderly adult patients through Carle Foundation Hospital, a local and readily available cohort of well-characterized elderly adults. No participants were cognitively impaired, as defined by a score of lower than 26 on the Mini-Mental State Examination (Folstein et al., 1975). Participants with a diagnosis of mild cognitive impairment, dementia, psychiatric illness within the last three years, stroke within the past twelve months, and cancer within the last three years were excluded. Participants were also excluded for current chemotherapy or radiation, an inability to complete study activities, prior involvement in cognitive training or dietary intervention studies, and contraindications for magnetic resonance imaging (MRI). All participants were right handed with normal, or corrected to normal vision and no contraindication for MRI.

Of these 122 participants, 99 subjects had a complete dataset at time of data analysis, including neuropsychological testing, MRI, and blood biomarker analysis. Participants had a mean age of 69 years (range: 65–75 years) and 63 percent of participants were females. All other participant characteristics are reported in Table 1.

This work was part of a study that aimed to characterize the relationship between nutrition, cognition, and brain health in healthy older adults. This sample presents the opportunity to examine normal brain function in a population in which age-related variability in cognition and brain health may be found and in which nutrition may be used to maintain health.

2.2. Standard protocol approval and participant consent

This study was approved by the University of Illinois Institutional Review Board and the Carle Hospital Institutional Review Board and, in accordance with the stated guidelines, all participants read and signed informed consent documents.

2.3. Neuropsychological tests

General intelligence was measured by the Wechsler Abbreviated Scale of Intelligence – second edition (WASI-II (Wechsler, 1999);). This assessment measured general intelligence by way of an estimated intelligence quotient score. Per scoring guidelines, the estimated intelligence quotient score was the product of four subtests: a block design subtest, a matrix reasoning subtest, a vocabulary subtest, and a similarities subtest. In the block design subtest, participants were asked to reproduce pictured designs using specifically designed blocks as quickly and accurately as possible. In the matrix reasoning subtest, participants were asked to complete a matrix or serial reasoning problem by selecting the missing section from five response items. In the vocabulary subtest, participants were asked to verbally define vocabulary words (i.e., What does lamp mean?) that became progressively more challenging. In the similarities subtest, participants were asked to relate pairs of concepts (i.e., How are