Meat and Muscle Biology™

The Importance of Meat for Cognitive Development

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Abstract: Over 200 million children worldwide suffer from malnutrition and, as a result, are underdeveloped both physically and mentally. Meat has more bioavailable essential micronutrients than plants and is the best source of nutrient-rich foods for children aged 6 to 23 mo, according to the World Health Organization. By consuming meat, which contributes essential bioavailable micronutrients to diets, children in particular can reduce undernutrition and the associated growth and cognitive impairment. This review aims to elucidate the effect of meat consumption on cognitive development by systematically reviewing and synthesizing results from available studies. Of 241 pertinent studies initially retrieved from the literature, only 9 met the inclusion criteria, and these included 28 cognition variables covering data from 10,617 children aged 3 mo to 17 y. Twelve (42.8%) of the variables showed improvements in cognition with increased meat consumption, 6 (21.4%) showed no effect, and 10 (35.7%; including 8 from HIV-positive children) showed a decrease in cognition with increased meat consumption. Across all variables, the study reveals some evidence of an association between meat consumption and improved cognition, which becomes more compelling when data from the HIV-positive children are excluded. More research on the effect of meat consumption on cognitive development from randomized controlled studies is needed.

Key words: meat, cognitive development, stunting, intelligence quotient, Raven's progressive matrices
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Introduction

Over 200 million children worldwide suffer from malnutrition and fail to meet their development potential; in particular, 150 million children under 5, mostly in low- and middle-income countries (LMIC), are stunted (UNICEF, 2019). Though there are different views about its definition and use as an indicator of population health, stunting (low height for age or linear growth failure) is a widely used measure of chronic malnutrition (Perumal et al., 2018). Stunting is defined as the proportion of children whose height for age is below −2 standard deviations from a reference population (UNICEF, 2013). Stunting in children under 5 y is associated with reduced growth and physical development, compromised cognitive development, lower intelligence quotient (IQ) scores, lower school performance, greater susceptibility to chronic diseases, increased behavioral problems, and reduced earning potential as adults (De Onis & Branca, 2016). In a recent multi-country cohort study among 943 children under 5, those with early-onset persistent stunting had significantly lower cognitive scores compared with those who were never stunted (Alam et al., 2020). Eight-year-old stunted children in

Ethiopia scored 16.1% and 48.8% less than normal children in 2 measures of cognitive development, namely, the Peabody Picture Vocabulary Test (Stockman, 2000) and Quantitative Assessment test, respectively (Woldehanna et al., 2017). Among 1,674 Peruvian children, both early stunting (stunted at 6–18 mo of age) and concurrent stunting (stunted at 4.5–6 y of age) significantly reduced cognitive development and school achievement, as measured by the standardized picture vocabulary test given to children at 6 to 18 mo of age and 4.5 to 6 y of age (Crookston et al., 2011.

Stunting also affects national economies. In a report by authors from the World Bank, countries in which the workforce was stunted in childhood had 7% lower gross domestic product on average globally, and Africa and Southeast Asia had 10% to 17% lower gross domestic product (Galasso et al., 2016). This difference is mainly due to the much higher stunting rates in these regions compared with other parts of the world (De Onis et al., 2012).

Stunting is a multifaceted problem (Theron et al., 2007). In addition to poor diet, other contributing factors include poor water, sanitation, and hygiene, poor gut health, poor maternal health and nutrition, infection, short birth spacing, and adolescent pregnancy (WHO, 2014). Poor-diet–induced stunting, perhaps the most commonly attributed type (Lartey, 2015), is caused by an inadequate diet, particularly due to deficiencies of essential micro- and macronutrients, especially during the first 1,000 d of life (Black et al., 2013).

Even when there is adequate supply of total protein and calories, stunting reflects hidden hunger—a condition in which consumed food is deficient in the essential micronutrients necessary for proper physical and mental development (Muthayya et al., 2013), including iron, zinc, copper, chromium, selenium, iodine, manganese, and molybdenum, as well as 13 vitamins (vitamins A, B1, B2, B6, and B12, niacin, folate, pantothenic acid, vitamin C, vitamin D, biotin, vitamin E, and vitamin K). Deficiency in various combinations of these essential nutrients may adversely impact growth and development; however, evidence is lacking regarding the effect of the timing of consumption, magnitude of effect, and the long-term impact on health (Branca and Ferrari, 2002; McNeill and Van Elswyk, 2012). Animal-source foods (ASF)—particularly meat—contain more bioavailable forms of these nutrients than other food groups, giving them distinct, unique advantages in diet-based efforts to reduce stunting.

Given that one of the most important causes of stunting and its consequent cognitive impairment is malnutrition or poor diet—and, specifically, micronutrient deficiency or hidden hunger—the intake of meat in adequate amounts, which supplies the missing essential micronutrients, can reduce nutrition-related stunting and the consequent cognitive impairment (Neumann et al., 2007; Krebs et al., 2011; Hulett et al., 2014). A literature review surmised that introducing meat products as a component of the diet may benefit the micronutrient status of weaning infants, especially in marginalized environments, where there is infectious morbidity and few dietary supplement options (Krebs, 2000). In fact, national stunting rates are inversely related to per capita annual meat consumption, and similar trends were evident for other ASF (Figure 1; Adesogan et al., 2020). Importantly, this correlation does not imply causality, as meat consumption levels may reflect other important differences, such as in income or other factors, but the association merits further exploration.

This review provides the background and rationale for the notion that meat consumption improves cognitive development in children, systematically analyzes the existing evidence on the relationship between meat supplementation and cognitive development in children, and then discusses some wider implications.

Uniqueness of Macro- and Microminerals: Association With Cognition and Health

Macronutrients

Meat is a major source of energy, macronutrients (including protein and fats), and key micronutrients in diets. Relative to other food groups, ASF—especially meat—typically has higher protein concentration and quality than other food items. The higher biological value of ASF protein is primarily due to its high concentration and digestibility of essential amino acids. Among these, the most notable is lysine, which is limited in many plant-source foods (PSF) and yet critical for myriad outcomes, including growth and development; the absorption of calcium, iron, and zinc; building all proteins in the body; recovery from injury; and production of hormones, enzymes, and antibodies (Singh et al., 2011). Owing to the relatively high concentration of digestible lysine and other essential amino acids in meat and other ASF, tools developed to

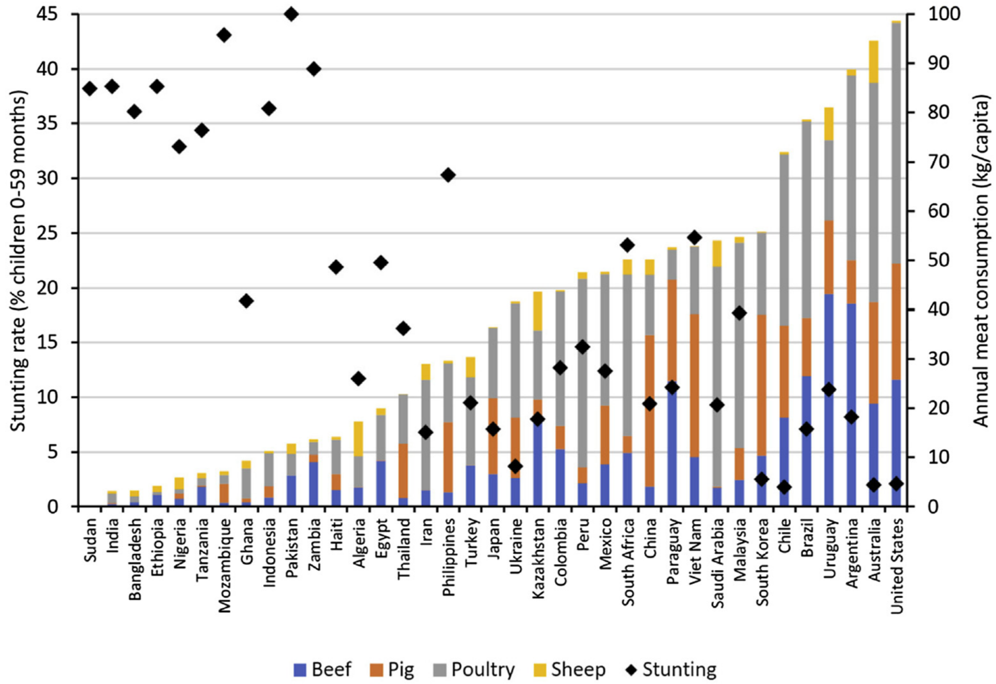

Figure 1. Meat consumption per capita and stunting rate estimates in different countries (adapted from Adesogan et al. (2020); Data from OECD (2018) and UNICEF-WHO-World Bank (2017).

indicate the protein quality of foods—such as the Protein Digestibility-Corrected Amino Acid Score and Digestible Indispensable Amino Acid Score—rank them higher than natural PSF for protein quality (Hoffman and Falvo, 2004; Ertl et al., 2016).

Meat is also a major source of saturated fats and n-3 polyunsaturated fatty acids (Nohr and Biesalski, 2007). Long chain n-3 polyunsaturated fatty acids have been associated with positive health impacts in humans. For instance, eicosapentaenoic acid and decosahexaenoic acid play a key role in communication networks in the brain (Bentsen, 2017) and have anti-atherogenic, anti-thrombotic, and anti-inflammatory characteristics, and their increased intake reduced the risk of coronary heart diseases (Givens et al., 2006). Meat is also a good source of arachidonic acid, which can also predispose the kidney to inflammatory damage, but is a precursor of eicosanoids, which are effective autocrine and paracrine bioactive mediators that are widely involved in a variety of physiological and pathological processes (Wang et al., 2019). The overconsumption of saturated fat from processed meat has been traditionally thought to increase the risk of coronary heart disease (Micha et al., 2010). However, an expert panel recently concluded that the risk of this disease was increased when dietary saturated fatty acids replace *cis* polyunsaturated fats but not carbohydrates in the diet (Micha and Mozaffarian, 2010; Givens, 2017; Nettleton et al., 2017).

Overconsumption of red meat results in excessive intake of cholesterol and saturated fats, both of which have been associated with obesity (Wang and Beydoun, 2009) and increased prevalence of chronic diseases, including cardiovascular diseases and diabetes (Vang et al., 2008). However, meat consumption has also been advocated in moderate amounts as part of a healthy diet (Nohr and Biesalski, 2007; Klurfeld, 2018), especially to diversify diets high in processed carbohydrates that predispose to diabetes.

The overconsumption of processed meat has been associated with increased cancer (Chan et al., 2011), and the International Agency for Research on Cancer classified processed meat as "carcinogenic to humans" and red meat as "probably carcinogenic to humans" for colorectal cancer, indicating that the evidence for association between red meat and colorectal cancer was inconclusive. However, these classifications and similar conclusions by the World Health Organization (WHO) have been challenged and attributed to weak associations, confounding, and unmeasured factors (Klurfeld, 2018), as processing, cooking, and preservation methods may be the sources of some carcinogens rather than the meat itself (Santarelli, et al., 2008; Ferguson, 2010). The foregoing evidence demonstrates both the benefits of macronutrients from consuming meat as well as the complex nuanced health effects, pointing toward benefits when consumed in moderation and some possible deleterious health effects when overconsumed.

Micronutrients

ASF are nutrient dense and offer a significant quota of micronutrients for daily nutrition. ASF provide the only preformed or active form of vitamin A (retinol), are the most bioavailable source of iron and zinc, and are a good source of B vitamins, especially B6 (pyridoxine), B12 (cobalamin), niacin (B3), folate (B9), pantothenic acid (B5), and biotin (B7) (Branca and Ferrari, 2002; Nohr and Biesalski, 2007; McNeill and Van Elswyk, 2012; De Smet and Vossen, 2016). In addition, meat is also a major source of other B vitamins like riboflavin (B2) and thiamine (B1), as well as additional essential trace minerals, including selenium, manganese, iodine, phosphorous, and copper (Nohr and Biesalski, 2007; De Smet and Vossen, 2016). However, the concentration of each of these nutrients in a specific cut and piece of meat varies (Lawrie and Ledward, 2014).

PSF—including fruits, nuts, and vegetables—are typically more affordable and accessible than ASF globally. However, compared with meat, PSF have limited concentration and lower bioavailability of several essential micronutrients, including iron, zinc, and vitamin B12 (Gibson et al., 2018). For example, the low bioavailability of plant-derived (non-heme) iron relative to animal-derived (heme) iron would require a woman of reproductive age to consume 6 times as much spinach and 3 times as much beef to obtain the same amount of iron to meet her daily iron requirements (Gupta, 2016; Figure 2). Figure 3 clearly shows the greater bioavailability of iron from animal versus plant sources. Beyond limited intake, the low amount and bioavailability of iron in plant-based diets are the main reasons why it is one of the most deficient micronutrients in diets globally. Estimates indicate that about 33% of all women of reproductive age, 40% of pregnant women, and 42% of children globally are iron deficient (WHO, 2021). Iron deficiency anemia affects nearly 600 million preschool- and school-aged children and is an important predisposing factor to stunting (McNeill and Van Elswyk, 2012). In addition to iron, other micronutrients that top the list of those with global deficiency include iodine, vitamin A, and zinc, all of which are more bioavailable in meat than PSF (Derbyshire 2017). In fact, the 4 most deficient micronutrients globally (iron, iodine, vitamin A, and zinc) are all more bioavailable in meat and ASF than PSF, partly because some of them interact with antinutrients such as tannins and phytate in the gut, reducing their absorption (Gibson et al., 2018).

Vitamin B12 is required for synthesis of DNA, neurotransmitters, and membrane phospholipids; consequently, it is essential for maintaining the integrity of the nervous and blood cellular or hematopoietic systems (Malouf and Sastre, 2003). Deficiency of this vitamin is associated with megaloblastic anemia and neuropathy (Ekabe et al., 2017; Socha et al., 2020). Meat and other ASF consumption are often critical for meeting the recommended daily allowance of vitamin B12 (recommended daily allowance of 2.4 µg/d for adult humans and 0.5 µg/d for infants), which is absent in quantities sufficient for human benefit from PSF. Deficiency of this vitamin is more common in vegetarians and vegans than meat eaters, particularly in infants and pregnant and lactating women in rural parts of LMIC, who often subsist on carbohydrate-dense diets (Adesogan et al., 2020). Many published studies give false positives for B12 concentrations in plants, because 80% of the activity detected by common measurement methods are due to inactive analogues (Herbert, 1988; Rizzo et al., 2016). Watanabe et al. (2014) reviewed the literature on naturally occurring B12 sources for vegetarians and noted that, because most PSF had low concentrations, they could not be consumed in sufficient amounts to meet the 2.4 µg/d recommended dietary allowance of vitamin B12

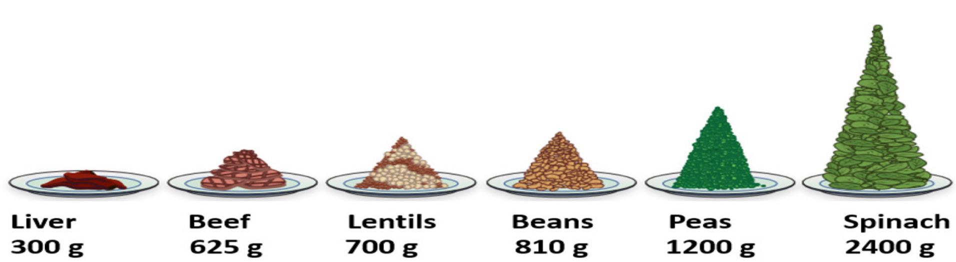

Figure 2. Amount of various types of foods that provide the same amount of iron to meet the iron needs of a woman of reproductive age (Gupta, 2016). Less liver and beef relative to spinach are required because of the greater bioavailability of iron in animal-source foods relative to plant-source foods. Iron content of these foods per 100-g portion are 1.05 mg (spinach), 1.47 mg (peas), 5.34 mg (beans), 6.51 mg (lentils), 1.69 mg (beef), and 6.54 mg (liver) (USDA, 2021).

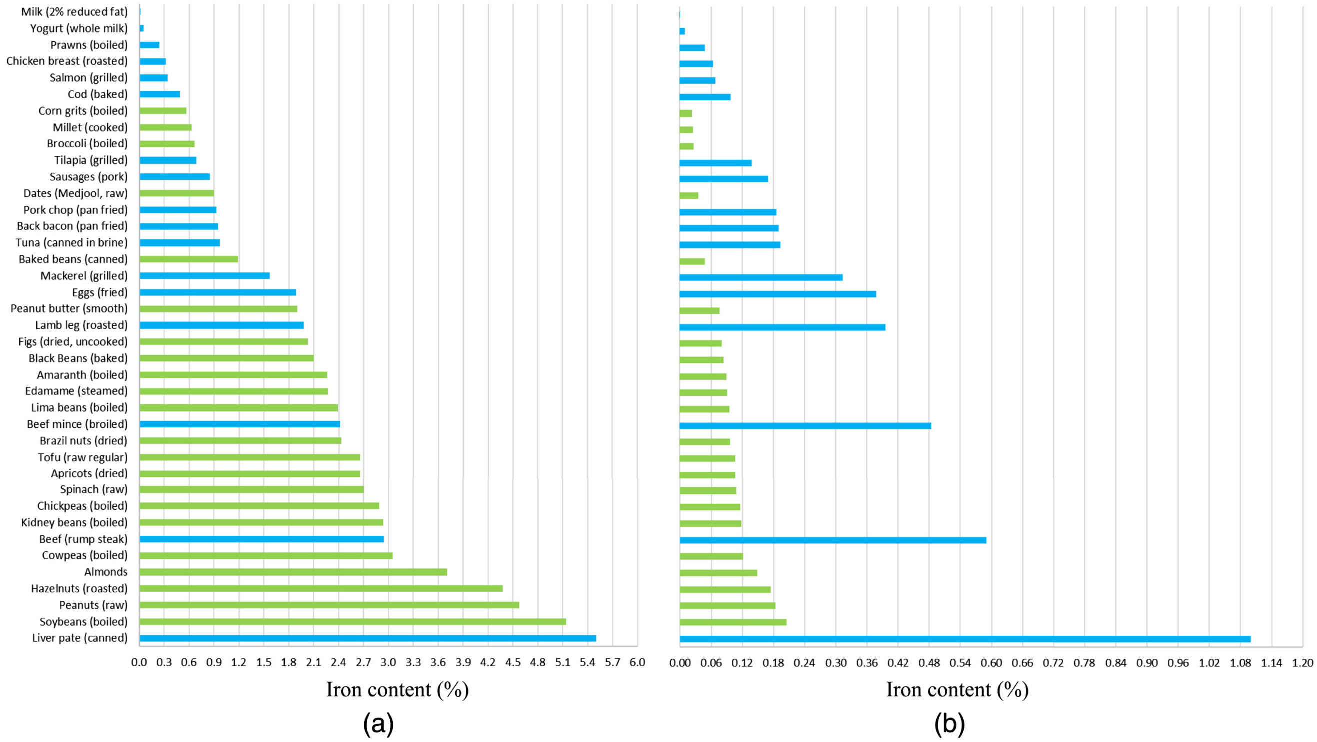

Figure 3. Iron content (%) in several food sources according to the USDA (2021) (modified from Tarnowski [2013] by authors). (A) Iron content as found in 100-g portion as cooked. (B) Iron content after correction for bioavailability, i.e., 20% for animal-source foods and 4% for plant-source foods (Hurrel and Egli, 2010).

(Pitkin et al., 2000). They recommended nori, an edible algal laver consumed in Japanese cuisine, as an alternative for vegetarians. Yet unlike in Japan, nori is not consumed in many other cultures, and studies have shown conflicting evidence on the efficacy of using nori to ameliorate B12 deficiency in children (Rizzo et al., 2016). Rizzo et al. (2016) noted that literature evidence is still insufficient to determine whether vitamin B12 in PSF is the active form and, if it is, whether regular consumption of these foods is behaviorally sustainable in terms of fulfilling the demand, given the variability in production processes. They concluded that although some seaweed, mushrooms, and fermented foods can be considered at best contributing sources of vitamin B12, the data are still insufficient, and production is too heterogeneous for PSF to be categorized as a viable source of B12. These studies clearly illustrate that meeting dietary B12 requirements without ASF is challenging. In Western countries, B12 supplements are widely available, but they are unavailable in rural areas of most LMIC, many of which have high livestock populations that can supply this micronutrient.

In discussions about the pros and cons of meat and ASF production and consumption, an often overlooked fact is the unique attribute that meat and other ASF simultaneously supply bioavailable forms of several of the essential and high-value, stunting-associated macro- and micronutrients. This sets them apart from many other important food groups that contain essential but less bioavailable or fewer simultaneously supplied micronutrients. These unique attributes explain why WHO has pointed to ASF as the best form of nutrient-rich food for infants aged 6 to 23 mo (WHO, 2014). Unfortunately, 59% of children worldwide do not get these much-needed nutrients from ASF (UNICEF, 2020).

Both intrinsic (e.g., biofortified iron-rich legumes) and extrinsic (e.g., iron-enriched maize flour) fortification approaches have been successfully implemented to augment micronutrient supply from nutritionally inadequate staple diets across the world (Dary and Hurrell, 2006; Andrade et al., 2021). While these approaches are vitally important for addressing hidden hunger, these efforts are constrained—firstly because such efforts are often short-lived in LMIC, owing to limited government or donor funding (Adesogan et al., 2020), and secondly because, in most cases, only a few nutrients are supplied in the same staples, potentially discouraging policies directed at improving dietary diversity. This starkly contrasts with the simultaneous supply of several essential macro- and micronutrients from meat and other ASF.

The foregoing provides the rationale and background for the notion that consumption of ASF, including meat, can increase cognitive development. The following systematic review was conducted to investigate the validity of the latter notion.

Systematic Review Methods

Although diet quality is an important determinant of cognitive development in children (Haapala et al., 2015), it is important to note that over 100 unique lifestyle and nutrition factors influence cognitive development in children (Ruiz et al., 2016; Jirout et al., 2019). When observational studies are undertaken, it is practically impossible to avoid all other confounders that influence cognitive development in children. Therefore, randomized controlled prospective interventional studies that properly control for confounding genetic, environmental, and social factors are needed to generate robust evidence of association. Few of these studies exist on the impact of meat consumption on cognitive development; rather, most of the available evidence from humans is from cross-sectional or retrospective observational studies that attempt to relate cognitive function to meat consumption. This is in part due to the logistical, methodological, and ethical challenges associated with controlling what human subjects—especially children—consume. We attempted to conduct a systematic review of studies examining the relationship between meat consumption and cognitive development as described subsequently.

We collated studies examining the relationship between meat consumption and cognitive development by searching Web of Science, Google Scholar, and PubMed databases. Search terms included various combinations of meat with cognition, cognitive development, IQ, school achievement, or exam scores. Search terms included Meat OR Red meat AND [Cognitive development OR any of measure of cognitive development]," "Animal sourced foods AND [Cognitive Development OR Any of the measure of cognitive development]."

Inclusion criteria included the following: (1) compared the effect of inclusion or supplementation with meat with a control diet with little or no meat (vegetarian or vegan-dominated basal diet); (2) examination of treatment effects on or association with cognitive development; (3) clearly stated treatment means and standard deviations or errors; (4) clearly stated numbers of study participants; (5) publication in the English language; (6) involvement of an interventional or observational study on effects of or correlation between meat consumption and cognition; and (7) targeted children (up to 17 years of age). Exclusion criteria included the following: (1) not examining effects of control versus meat supplemented diets; (2) not examining treatment effects on cognition; (3) not stating the mean and/or standard deviations or errors of treatments or the number of study participants; (4) publishing the study in a language other than English; or (5) not using an interventional or observational study. Interventional studies are those that supplemented meat to their experimental subjects and then measured the change in cognition, whereas observational studies relied on self-report for historical meat intake pattern of their subjects and tried to associate that with cognitive development. Cognitive function or development was measured using different variables that generally fall into 9 categories, namely, general written exams or tests, Raven's progressive matrices, digital span or memory, verbal skills, embedded figure tests, psychomotor or physical skills, IQ, cranial volume, and general cognitive and mental development measures; these are described in Table 1.

Authors originally intended to conduct a meta-analysis of the data from the studies; this effort was abandoned because no 3 of the 9 selected studies met all of the following criteria: (1) had the same measure for cognition, (2) stated the treatment means and standard errors or deviations, and (3) stated the number of study participants. These reasons also prevented use of descriptive statistics to summarize the data.

Results

Figure 4 shows a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram that outlines the total number of articles initially surveyed, the number included and excluded for this review, and the underlying reasons. The total number of initial references retrieved was 241, of which 9 were considered pertinent after screening data from 10,617 children aged 3 mo to 17 y (Figure 5). The selected studies included 5 interventional studies, in which a meat-supplemented diet was compared with non-meat diets to examine effects on a cognitive development variable. The remaining 4 studies were observational studies that examined the relationship between a given food habit and cognitive variables. It is important to note that for most of the observational studies, the food habits compared do not have clearly defined levels or proportions of meat consumed.

Table 1. Summary of reviewed studies on effect of meat consumption on or relationship with cognitive development

Treatment	Age range of subjects	Country	Duration	Number of subjects	Impact on cognitive measure investigated	Variable	Value for meat-supplemented or ASF-based diet	Value for unsupplemented or vegetarian diet	Significance	Difference	Reference
A randomized controlled Interventional study of beef supplementation vs. plain githeri[1] fed to school children for 2.25 y	6–14 y	Kenya		$N = 900$	Increases in end-of-term total test scores over time (Raven's progressive matrices test)	Mean	20	10	$P < 0.02$-0.03	10	Neumann et al., 2007
A randomized controlled Interventional study of beef supplementation vs. plain githeri[1] fed to school children for 2.25 y	6–14 y	Kenya		$N = 900$	Increase in end-of-term arithmetic scores (Raven's progressive matrices test[2])	Mean	3	2	$P < 0.02$-0.03	1	Neumann et al., 2007
An interventional (clustered randomized) study of comparison of a local plant-based stew (githeri)[1] with meat, or a control group for 2 school y	7 y	Kenya		$N = 166$ (99 plant-based group, 67 meat group)	Change in combined test scores, as a result of meat intervention compared with control in arithmetic, English, Kiembu, Kiswahili, geography, science, and arts	Mean ± SD			$P < 0.05$	57.5 ± 16.3	Hulett et al., 2014
An interventional (clustered randomized) study of comparison of a local plant-based stew (githeri)[1] with meat, or a control group for 2 school y	7 y	Kenya		$N = 166$ (99 plant-based group, 67 meat group)	Change in combined test scores as a result of meat intervention compared with plain githeri, in arithmetic, English, Kiembu[3], Kiswahili, geography, science, and arts	Mean ± SE			$P < 0.06$	44.8 ± 15.22	Hulett et al., 2014
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	5 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Raven's progressive matrices	Est ± SE, P	2.19 ± 0.5, $P < 0.001$	2.33 ± 2.33, $P = 0.061$		−0.14	Khee et al., 2017

Table 1. (*Continued*)

Treatment	Age range of subjects	Country	Duration	Number of subjects	Impact on cognitive measure investigated	Variable	Value for meat-supplemented or ASF-based diet	Value for unsupplemented or vegetarian diet	Significance	Difference	Reference
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	5 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Raven's progressive matrices	Est ± SE, P	2.19 ± 0.5, $P < 0.002$	4.06 ± 4.06, $P = 0.65$		−1.87	Khee et al., 2017
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	5 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Digital span[4] total	Est ± SE, P	1.40 ± 0.21, $P < 0.001$	1.21 ± 0.26, $P < 0.001$		0.19	Khee et al., 2017
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	5 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Digital span total	Est ± SE, P	1.40 ± 0.21, $P < 0.001$	1.73 ± 0.24, $P < 0.001$		−0.33	Khee et al., 2017
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	9 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Verbal meaning total	Est ± SE, P	3.90 ± 0.57, $P < 0.001$	4.40 ± 0.69, $P < 0.001$		−0.5	Khee et al., 2017

A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	10 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Verbal meaning total	Est ± SE, P	3.90 ± 0.57, $P < 0.001$	4.99 ± 0.64, $P < 0.001$		−1.09	Khee et al., 2017
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	5 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Arithmetic total	Est ± SE, P	1.75 ± 0.20, $P < 0.001$	1.73 ± 0.25, $P < 0.001$		0.02	Khee et al., 2017
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	12 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Arithmetic total	Est ± SE, P	1.75 ± 0.20, $P < 0.001$	2.30 ± 0.23, $P < 0.001$		−0.55	Khee et al., 2017
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	13 d/wk for 18 mo	N = 31 (11 wheat biscuit and 20 beef biscuit [school-aged children]); N = 38 (18 soy biscuit and 20 beef biscuit [school-aged children])	Embedded figure test[5] total	Est ± SE, P	1.07 ± 0.21, $P < 0.001$	1.28 ± 0.26, $P < 0.001$		−0.21	Khee et al., 2017
A randomized, double-blind, controlled interventional study in which beef biscuit supplementation was compared with wheat biscuit or soy biscuit supplementation for school-aged children 5 d/wk	School aged	Kenya	14 d/wk for 18 mo	$N = 31$ (11 wheat biscuit and 20 beef biscuit [school-aged children]); $N = 38$ (18 soy biscuit and 20 beef biscuit [school-aged children])	Embedded figure test total	Est ± SE, P	1.07 ± 0.21, $P < 0.001$	1.13 ± 0.23, $P < 0.001$		−0.06	Khee et al., 2017
An interventional study that compared pork-supplemented vs. unsupplemented local cereal diets for babies	3–5 mo	China	6–8 mo	$N = 116$	Cognitive scores	Mean ± SD	21.3 ± 1.9	20.4 ± 2.0	$P = 0.020$	0.9	Sheng et al., 2019

Table 1. (*Continued*)

Treatment	Age range of subjects	Country	Duration	Number of subjects	Impact on cognitive measure investigated	Variable	Value for meat-supplemented or ASF-based diet	Value for unsupplemented or vegetarian diet	Significance	Difference	Reference
An interventional study that compared pork-supplemented vs. unsupplemented local cereal diets for babies	3–5 mo	China	6–8 mo	$N = 116$	Fine motor[6] score	Mean ± SD	18.3 ± 1.1	18 ± 1.0	$P = 0.199$	0.3	Sheng et al., 2019
An interventional study that compared pork-supplemented vs. unsupplemented local cereal diets for babies	3–5 mo	China	6–8 mo	$N = 116$	Gross motor[7] score	Mean ± SD	20.2 ± 1.4	20.1 ± 1.1	$P = 0.513$	0.1	Sheng et al., 2020
A longitudinal population-based birth cohort comparison of traditional diets, which include meat, with so-called "healthy" diets, which mainly contain breast feeding and fruits and vegetables	6–24 mo	UK		$N = 7,652$	Full-scale IQ[8] measured using a short form of the Wechsler Intelligence Scale for Children	β (95% CI), P	0.69 (0.18 to 1.21), $P = 0.009$	0.97 (0.49 to 1.45), $P < 0.001$			Smithers et al., 2012
A longitudinal population-based birth cohort comparison of traditional diets, which include meat, with so-called "healthy" diets, which mainly contain breast feeding and fruits and vegetables	6–24 mo	UK		$N = 7,652$	Verbal IQ measured at age 8 y	β (95% CI), P	0.59 (0.04 to 1.15), $P = 0.037$	1.13 (0.65 to 1.61), $P < 0.001$			Smithers et al., 2012
A longitudinal population-based birth cohort comparison of traditional diets, which include meat, with so-called "healthy" diets, which mainly contain breast feeding and fruits and vegetables	6–24 mo	UK		$N = 7,652$	Performance IQ measured using a short form of the Wechsler Intelligence Scale for Children	β (95% CI), P	0.63 (0.13 to 1.13), $P = 0.014$	0.51 (0.04 to 1.06), $P = 0.068$			Smithers et al., 2012
School children supplemented with meat and energy food	7.41–8.07 y	Kenya		$N = 277$ (148 supplemented with meat and 129 not supplemented with meat)	Change in Raven's score between meat and control group	β + SE	1.41 + 0.15	1.07 + 0.14	$P = 0.045$	0.34 + 0.20	Whaley et al., 2003
School children diets supplemented with meat vs. no supplementation	7.41–8.07 y	Kenya		$N = 277$ (148 supplemented with meat and 129 not supplemented with meat)	Change in verbal meaning (0–40) between meat and control group	β + SE	4.03 + 0.17	3.83 + 0.17	ns	0.20 + 0.23	Whaley et al., 2003

School children diets supplemented with meat vs. no supplementation	7.41–8.07 y	Kenya		$N = 277$ (148 supplemented with meat and 129 not supplemented with meat)	Difference in change in arithmetic score between meat and control group	β + SE	1.02 + 0.07	0.85 + 0.07	$P = 0.033$	0.18 + 0.10	Whaley et al., 2003
Relationship between red meat and sausage (in Baltic Sea Diet) consumption	6–8 y	Finland	4–12 and 4–16 mo	$N = 512$	Association coefficient with Raven's colored progressive matrices score	β, P	−0.114, 0.021	0.055, 0.025			Haapala et al., 2015
Relationship between red meat and sausage consumption (g/d) with Raven's colored progressive matrices score; comparison between lowest quartile (in the dietary approaches to stop hypertension) and highest quartile	6–8 y	Finland	4–12 and 4–16 mo	$N = 512$	Association coefficient with Raven's colored progressive matrices score	β, P	−0.109, 0.026	0.021, 0.440			Haapala et al., 2015
A longitudinal cohort comparison using regression analysis of breastfed and meat-supplemented babies	22 mo	UK		$N = 109$ meat intake measured	Psychomotor development[9] indices at 22 mo	R2 (95% CI)	0.73 (0.07 to 1.4)		$P = 0.03$		Morgan et al., 2004
A longitudinal cohort comparison using regression analysis of breastfed and meat-supplemented babies	22 mo	UK		$N = 144$ meat intake measured; 4–12 and 4–16 mo	Mental development indices at 22 mo	R2 (95% CI)	0.0.5 (−2.6 to 1.3)		$P = 0.2$		Morgan et al., 2002
A cross sectional correlational study of association between meat shortage (reported by parents) and cranial volume	13.8 y	Estonia		$N = 672$ (87 meat shortage reported, 585 no meat shortage reported); mean age	Cranial volume	Mean ± SD (n)	0.032 ± 0.972 (581)	−0.308 ± 1.181 (87)	$P = 0.003$	0.034	Lauringson et al., 2020

[1]Githeri, also called muthere or mutheri, is a Kenyan traditional meal of maize or corn and legumes, typically beans of any type, mixed and boiled together.

[2]Raven's progressive matrices are a nonverbal test typically used to measure general human intelligence and abstract reasoning; they are regarded as a nonverbal estimate of intelligence.

[3]Kiembu is a language in Kenya.

[4]Digit Span is a measure of verbal short-term and working memory.

[5]Embedded figure test is a test that consists of finding and tracing a simple form embedded within a complex figure, in some cases further complicated by an irregularly colored background. The test, for use with individuals aged 10 y and older, was designed to evaluate cognitive style, particularly field dependence and field independence.

[6]Fine motor skills are the ability to make movements using the small muscles in hands and wrists and are related to mental ability to control and guide muscles and movements.

[7]Gross motor skills are the ability to make movements using the large muscles and are related to mental ability to control and guide one's muscles and movements.

[8]IQ, or an intelligence quotient, is a total score derived from a set of standardized tests or subtests designed to assess human intelligence.

[9]Psychomotor development is generally a measure of the relationship between cognitive development and physical abilities.

β = beta coefficient, the degree of change in the outcome variable for every 1-unit change in the predictor variable; ASF = animal-source foods; CI = confidence interval; Est = estimate; ns = nonsignificant; R^2 = correlation coefficient; SD = standard deviation; SE = standard error.

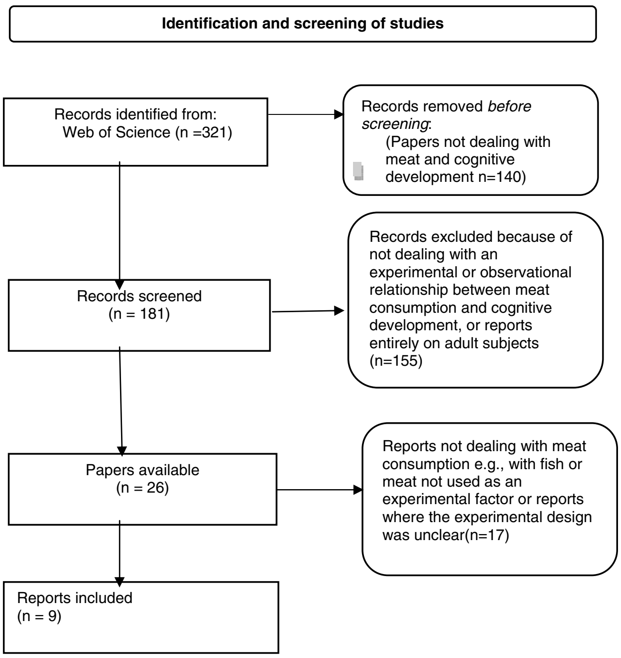

Figure 4. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram showing the total number of articles initially surveyed and the number included and excluded for this review.

Twelve (42.8%; from 5 studies) of the 28 variables used to measure cognition in the 9 selected studies showed improvements in cognition with increased meat consumption, 6 variables (21.4%; from 2 studies) showed no effect, and 10 variables (35.7%; from 3 studies) (Figure 6; Table 1) (including 8 from HIV-positive children in one study) showed a decrease in cognition with increased meat consumption.

Discussion

Almost half of the 28 variables and more than half of the selected studies showed a positive relationship between meat supplementation and cognitive development (Table 1). One of the studies reviewed, Hulett et al. (2014), showed that meat supplementation in the diets of healthy school-aged children in Kenya increased exam scores by 45% when averaged across all subjects and school semesters and improved leadership skills and overall behavior of children. In the earlier reported part of the study, meat supplementation resulted in improved performance in arithmetic tests and initiative in leadership among school children

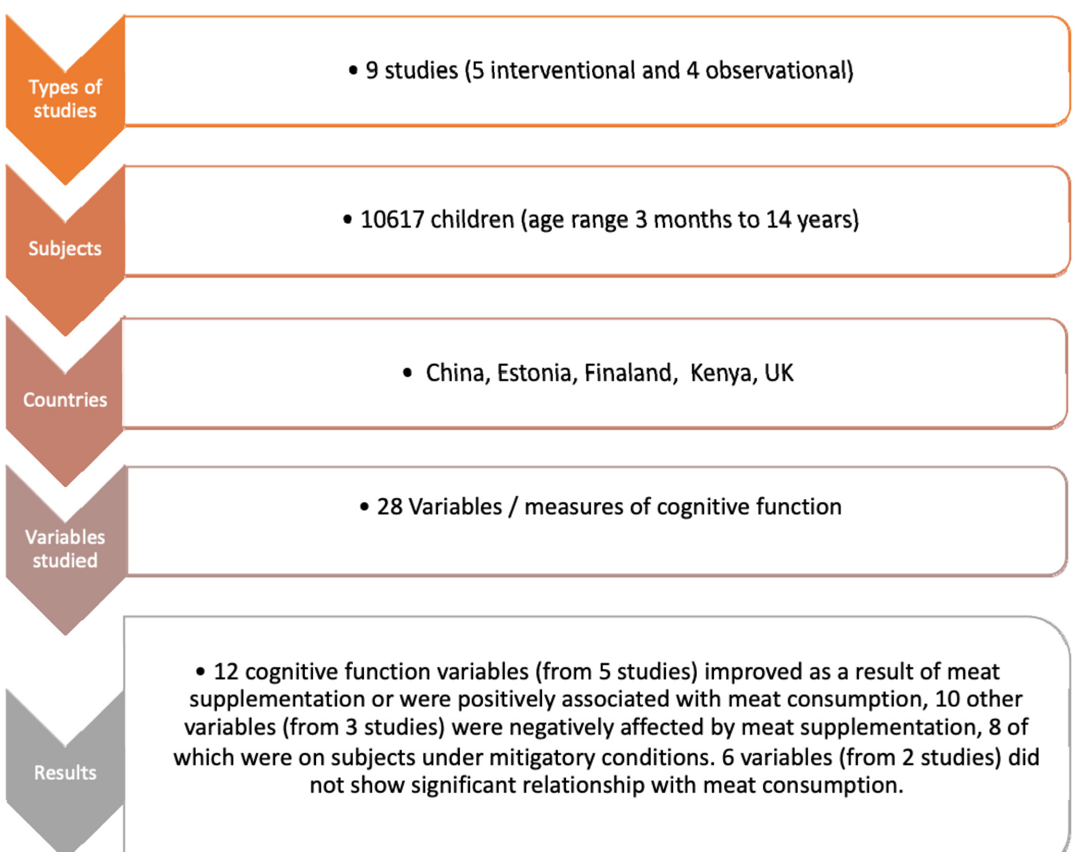

Figure 5. Summary of reviewed evidence on the effect of meat consumption on or its relationship with cognitive development.

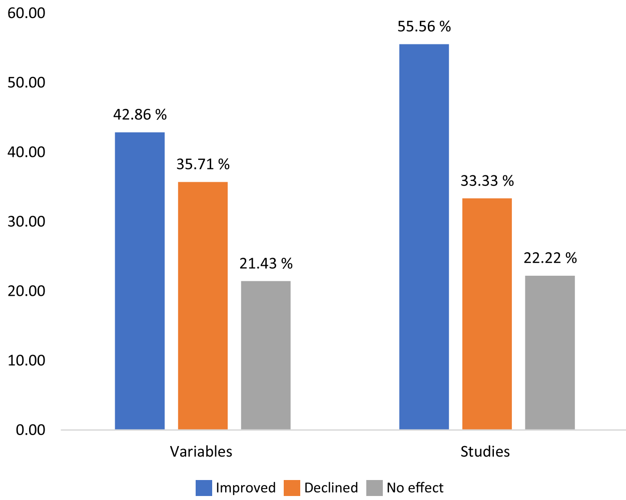

Figure 6. Summary of reported results (by variable and by study) on the relationship between meat intake or meat-dominated dietary patterns and cognitive development. Bar graphs show percentage of variables and percentage of studies. A total of 28 variables were recorded, and these were grouped into 9 categories, namely, general written exams or tests, Raven's progressive matrices, digital span or memory, verbal skills, embedded figure tests, psychomotor or physical skills, intelligence quotient (IQ), cranial volume, and general cognitive and mental development measures.

compared with those that were not supplemented (Neumann et al., 2003). This supports the notion that meat consumption is associated with improved cognition in children, as reported in studies that were not included in the analysis because they did not meet the inclusion criteria. For instance, meat intake from 4- to 12-mo-olds and 4- to 16-mo-olds was positively and significantly related to psychomotor developmental indices (Morgan et al., 2004). A cross sectional study among 672 children that measured cranial volume (Lauringson et al., 2020), a proxy of cognitive development (Nave et al., 2019; Valge et al., 2019), reported a negative correlation between meat shortage in childhood and cranial size in adolescents. A longitudinal study on rural children in Nepal by Miller et al. (2016) indicated that 43% of the variation in cranial circumference was explained by weight for age scores and consumption of meats, with those consuming more meats having greater cranial circumference scores. In Nigeria, nutritional diversity—defined as including various types of foods, typically meats—was associated with improved academic performance among school children (Omuemu and Ogboghodo, 2020). In Uganda, meat consumption at 6 to 8 mo was positively associated with normal fine-motor skills development at 20 to 24 mo (Kakwangire et al., 2021). In addition, oral supplementation of creatine, which is found in high amounts in meat, improved cognition and memory among young adults in Australia (Rae et al., 2003). Similar positive relationships between meat consumption and cognitive development are reported in other studies (Maluccio et al., 2009; Prado et al, 2016; Hoang et al., 2019).

It is important to note that, of the 10 variables, which showed a decline in cognitive development as a result of meat consumption, 8 were measured from a single study on children that were HIV positive (Khee et al., 2017). If the data from these HIV-positive children are omitted from the analysis, the evidence for the association between meat consumption and cognitive development becomes more compelling. In that case, 60% of the 20 remaining variables showed an improvement in cognition with increased meat consumption. This illustrates the importance of properly controlling for confounding factors in these studies. Cognition has been clearly demonstrated to be a result of the interaction of a complex set of factors, including nutrition, sanitation, gut health, psychosocial environment, and upbringing (Ruiz et al., 2016; Jirout et al., 2019). Ruiz et al. (2016) surmised that the relationship between micronutrient deficiency and cognitive and behavioral functions is embedded in a host of other biological and psychosocial risk factors, making meat consumption alone a necessary but insufficient condition for producing cognitive benefits. When the confounding effect of HIV on our study is accounted for by eliminating such studies, the results more strongly support the notion that meat consumption is associated with cognitive development.

Some of the studies in our review lacked methodological clarity. In fact, 4 of 9 studies examined retrospective eating patterns, based on respondents' self reports, and did not necessarily have a clearly defined experimental meat and non-meat dichotomous diet comparison. The last 2 variables that showed a decline in cognition with meat consumption were from a study that had no clearly defined meat and non-meat diet; instead, the non-meat group was the so called "healthy" diet, which is assumed to contain "less meat," and it was compared to a "traditional" diet with more meat (Smithers et al., 2012). In this case—as well as other studies not included in our analysis that reported a negative relationship between meat consumption and cognition, especially in children or adults (Khanna et al., 2019; Corley et al., 2020; Mofrad et al., 2021)—the results may reflect contributions of counfounding factors.

Given the association between meat supplementation in children and improved cognitive development in many studies, some have suggested that vegetarian diets may not be appropriate for children

(Cofnas, 2019). In one study, Dutch adolescents fed vegetarian diets had delays in gross motor development and in speech and language development compared with those fed omnivore diets (Louwman et al., 2000). Due to such findings, various countries, including Belgium (Livni, 2019), Italy (Nadeau, 2016; Samuels, 2016), and France (Haurant, 2011), have considered or enacted laws that prevent feeding of vegan diets to children. The German Society for Nutrition discourages vegan diets for children and infants (Richter et al., 2000). The European Union, in an effort to reduce the inadvertent replacement of meat by vegan-based foods, prohibits labelling of vegan products with meat names such as sausages and burgers (Morini, 2018). Based on what they termed "controversial diets," the Royal Academy of Medicine of Belgium declared that it is not ethical to impose veganism on children because of the need for ongoing monitoring of children to avoid nutrient deficiencies and irreversible growth failure (Satherley, 2019). However, to our knowledge, no country has enacted laws that prevent feeding of vegan diets to children.

The timing of meat supplementation is also very critical as the effects of meat on cognitive development may be more pronounced in the long term than in the short term (Hoang et al., 2019). Existing evidence suggests that the first 1,000 d of life is a critically important window of opportunity for preventing the lifetime consequences of undernutrition. This is because 90% of the brain develops in the first 1,000 d, and the absence of critical nutrients for brain development in this period causes cognitive decline (Miller et al., 2021). However, methodological constraints make it difficult to examine the impact of the consumption of meat early in life on long-term cognitive outcomes. Nevertheless, several of the few interventional studies that attempted to understand the effect of meat intake early in life have demonstrated that increasing meat consumption among children and pregnant women was associated with improved cognitive function and development in children even later in life (Prado et al., 2016). In the United Kingdom, children whose diets were characterized by a homemade traditional diet pattern containing more meat, from 6 to 24 mo, had greater IQ scores at age 8 compared with those whose diets were dominated by homemade contemporary patterns containing less meat and more herbs, legumes, cheese, and raw fruit and vegetables (Smithers et al., 2012). In Guatemala, supplementation with meat in childhood was associated with improved grades and economic achievement later in life (Maluccio et al., 2009).

In a study of more than 20,000 Chinese older adults (aged ≥50 y old), limited consumption of meat in childhood (ascertained retrospectively), regardless of meat consumption as adults, was associated with poorer performance on the 10-word recall test (which examines new learning ability and screens for mild cognitive impairment; Heys et al., 2010).

How meat consumption affects cognition

Various studies have attempted to understand the association between inclusion of meat in the diet of children and cognitive development. Such studies show that the mechanisms by which various micronutrients enhance cognitive development vary considerably and are not well understood. Results of studies on the effect of essential micronutrient supplementation indicate that meat improves cognitive function through its effect on the supply of bioavailable micronutrients.

Studies indicate that bioavailable nutrients in meat, such as iron, zinc, iodine, and B vitamins (B12, B6, folate, and riboflavin), enhance cognitive development through their impact on structural brain development via enhancement of myelination, dendritic arborization, and synaptic connectivity (Lövblad et al., 1997).

The beneficial effects of meat consumption on stunting are due to direct and simultaneous contribution of essential micronutrients that are lacking or inadequate in most PSF diets and even some fortified cereals. Supplementation with meat and fish to breastfeeding infants resulted in improved serum ferritin (a protein that stores and releases iron) in 6- to 9-mo-old infants (Michaelsen, et al., 1995). This is partly because iron in meat is better absorbed by infants compared with iron in fortified cereals and even breast milk (Engelmann et al., 1998; Jalla et al., 1998). Proper supplementation of meat to 6-mo-old breastfed infants adequately supports both iron and zinc requirements (Krebs, 2000). Consequently, infants and children depending on non-meat and vegan diets are more predisposed to nutrient deficiency. Figure 7 shows a comparison of micronutrient inadequacies in foods consumed by vegans, vegetarians, and meat eaters from a European Prospective Investigation into Cancer and Nutrition–Oxford study. The diets of meat eaters were more adequate in micronutrient supply; however, it should be noted that the vegetarian and vegan subjects in the study may not have had deficiencies of the micronutrients owing to vitamin and mineral supplementation of their diets.

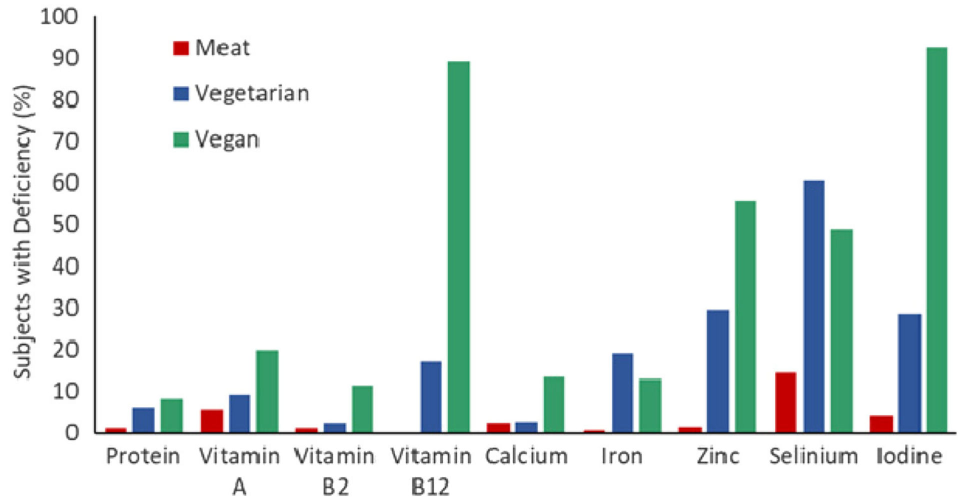

Figure 7. Incidence of inadequate intakes (compared with dietary recommendations) among people consuming meat-, vegetarian-, or vegan-dominated diets. A total of 30,251 adults in the Oxford cohort of the European Prospective Investigation into Cancer and Nutrition (EPIC) comprising 18,244 meat eaters, 4,531 fish eaters, 6,673 vegetarians, and 803 vegans aged 30 to 90 y who completed semiquantitative food frequency questionnaires. Data are expressed as the percentage of subjects with deficiencies of protein, vitamins (A, B2, and B12), and minerals (calcium, iron, zinc, selenium, and iodine). Note: Nutrient deficiencies were estimated from the prevalence of inadequate intakes of essential nutrients from food (adapted from Sobiecki et al., 2016).

Arachidonic and docosahexaenoic acids found in meat jointly account for about one-fifth of the brain's dry weight (Bentsen, 2017). These fatty acids are important for sophisticated communication networks in the brain conducted by transmembrane transfer systems, mainly made of these lipids (Crawford, 1970; Dyall, 2015; Bentsen, 2017). These fatty acids are used in expansion of glial cells, neurons, axons, and dendrites and myelination of nerve fibers during the first 2 y of life, making supplementation with foods (like meat) that contain these fatty acids important during this phase (Hadley et al., 2016).

Correctly accounting for micro- and macronutrient contributions from meat

Many studies advocating reduced meat and ASF consumption for planetary health base their arguments on higher greenhouse gas emissions or land and water requirements for beef and ASF production relative to PSF production (Clune et al., 2017). Such estimates are based on expressing the emissions or land or water use estimates on the basis of weight of food or area required. Such measures fail to account for the vitally important bioavailable macro- and micronutrient contributions of ASF relative to PSF, and their potential effect on cognition in children. When expressed per unit of nutrient density instead of weight, the environmental impacts of ASF are less than those of refined, whole, or unrefined grains (Beal, 2021). Furthermore, when expressed in units of protein quality (such as digestible lysine) instead of weight, most ASF have comparable or even lower land or water emission production requirements and greenhouse gas emissions than wheat or rice (Moughan, 2021). Collectively, these findings reinforce the importance of increasing affordability and accessibility of meat to ensure that it can be included as part of a strategy for sustained enrichment and diversification of diets, particularly in LMIC. In Western countries, moderate meat and ASF consumption can also be used to diversify diets, particularly in food deserts associated with undiversified diets.

The need to increase affordability of meat

Despite the unique attributes and benefits of ASF, meat consumption is highly variable across the world, owing to its low availability and affordability as various other sociocultural factors, including religion and caste, affect meat consumption (Betru and Kawashima, 2009). Mean annual per capita meat consumption in the bottom 4 meat-consuming countries (Sudan, India, Bangladesh, and Ethiopia), for example, is about 97% less than that in the top 4 (Brazil, Uruguay, Australia, and United States), largely owing to low affordability of such foods in the former countries (Adesogan et al., 2020). Consequently, when considered on the basis of cost per unit of nutrient available, meat and ASF supplementation is challenging to justify in certain cases. However, when considered on the basis of cost per unit of bioavailable nutrient content or cost per unit of lysine supplied (a critical essential amino acid limited in several basal LMIC diets), the importance and advantage of meat or ASF supplementation is clear. Because most food labeling systems only account for nutrient content and not bioaccessibility or bioavailability, the cost of a food item per unit of bioavailable nutrient delivered is seldom mentioned in popular and policy discourses about the benefits and challenges of ASF production consumption. The association of cognition with consumption of meat and other ASF is a strong imperative to change this situation.

Conclusions

This paper has described the unique nature and contributions of micronutrients in meat. The systematic review of 9 studies showed that 12 (42.8%) of the 28 variables in the studies showed improvements in cognition with increased meat consumption. However, 6 (21.4%) showed no effect, and 10 (35.7%, including 8 from HIV-positive children) showed a decrease in cognition with increased meat consumption. Across all variables, the study reveals some evidence of an association between meat consumption and improved cognition, which becomes more compelling (60% of variables showed a positive effect or association) when data from the HIV-positive children were excluded. Because these conclusions were drawn from the 9 studies that met the study criteria, more large-scale randomized controlled, prospective interventional studies that properly control for confounding genetic, health, environmental, and social factors are needed on the association between meat consumption and cognitive function in children. In addition, more studies are needed that examine the timing and lifetime impacts of meat consumption on cognition in children, because most of the evidence is from short-term studies on young children.

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