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The Relationship Between Physical Activity and Diet and Young Children's Cognitive Development: A Systematic Review

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Review article

The relationship between physical activity and diet and young children's cognitive development: A systematic review

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A B S T R A C T

Objective. Given the high prevalence of suboptimal nutrition and low activity levels in children, we systematically reviewed the literature on the relationship between physical activity and dietary patterns and cognitive development in early childhood (six months to five years).

Methods. In February 2016, we conducted two different searches of MEDLINE, PsycINFO, and ERIC. Each search included either physical activity (including gross motor skills) or diet terms, and neurocognitive development outcome terms. Included studies were in English, published since 2005, and of any study design in which the physical activity or diet measure occurred prior to age five.

Results. For physical activity, twelve studies (5 cross-sectional, 3 longitudinal and 4 experimental) were included. Eleven studies reported evidence suggesting that physical activity or gross motor skills are related to cognition or learning. Both acute bouts and longer term exposures showed benefit. For diet, eight studies were included consisting of secondary analyses from longitudinal cohort studies. A healthier dietary pattern was associated with better cognitive outcomes in all studies, although some of the reported associations were weak and the measures used varied across the studies.

Conclusions. Physical activity and healthy diets in early childhood are associated with better cognitive outcomes in young children. The paucity of literature and the variability in the type and quality of measures used highlight the need for more rigorous research. Given that the early childhood years are critical for both obesity prevention and neurocognitive development, evidence that the same healthy behaviors could promote both should inform future interventions.

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1. Introduction

Early life experiences shape a child's health and developmental trajectory. Increasing evidence suggests that obesity prevention needs to begin in early childhood because weight-related behaviors, such as food preferences and routine levels of physical activity, have early origins (McGuire, 2011). Unfortunately, many young children in the U.S. are not meeting dietary and physical activity recommendations, increasing their risk for obesity and obesity-related health conditions (Kranz et al., 2008; Reedy and Krebs-Smith, 2010; Beets et al., 2011; Sisson et al., 2009; American Academy of Pediatrics APHA, and National Resource Center for Health and Safety in Child Care and Early Education, 2012). Independent of weight status, poor diet and activity levels may also have consequences for children's current and future health and development. The early childhood years are a time for rapid and robust growth in cognitive development, but also a time of great vulnerability in this regard (National Research, 2000). Currently, limited evidence exists about the associations between children's diet quality, physical activity and cognitive outcomes. Although two papers were recently published describing activity and sedentary exposures and cognitive outcomes, additional reviews are warranted especially ones focused on both diet and activity (Carson et al., 2015a; Carson et al., 2015b). Thus, given the high prevalence of suboptimal nutrition and activity levels in children today and our limited knowledge of the effect on cognitive outcomes, a systematic review of the associations between physical activity, nutrition, and cognitive development in early childhood is needed.

Although the relationship between physical activity and cognitive development in young children is not well understood, there are at least three pathways through which aerobic (Carson et al., 2015b) exercise may facilitate cognitive functioning: (1) the acute cognitive demands of goal-directed and engaging exercise, (Kranz et al., 2008) the cognition required to execute complex motor movements, and (Reedy and Krebs-Smith, 2010) the short- and long-term physiological changes in the brain induced by aerobic exercise (Best, 2010). Compelling evidence exists in older children and adults that physical activity, particularly aerobic exercise and progressively challenging activities, and physical fitness, enhance cognitive performance (Hillman et al., 2009; Hillman et al., 2004; Fedewa and Ahn, 2011; Diamond and Lee, 2011a). Research among school-aged children has demonstrated that physical activity is associated with academic achievement and desirable classroom behavior (Trost, 2009; Welk et al., 2010; Carlson et al., 2008; Davenport, 2010; Mahar et al., 2006; Rasberry et al., 2011). Previous assumptions that younger children are sufficiently active along with the unique challenges of measuring both physical activity and cognitive outcomes in early childhood may have limited the amount and quality of research in this age group.

Similar to physical activity, studies on animals, older children and adults have found that dietary factors influence cognitive processes and brain structure (Gomez-Pinilla, 2008). Studies in older children and adults have found that a higher intake of a "Western style diet" high in saturated fat and refined sugars can impair cognitive and academic performance possibly through its link to inflammation, oxidative stress, the gut microbiome and the involvement of the hippocampus (Jacka et al., 2015). The relationship between diet and cognitive development in young children however has largely focused on nutrient deficiencies, such as Vitamin B, which interfere with key cognitive processes. Although the role of specific nutrients is important, it is unclear if early exposure to overall unhealthy dietary patterns, which are low in nutrient-dense foods and high in added sugars and saturated fat, negatively impact children's cognitive development. It is plausible that healthier dietary patterns, which are rich in fruits and vegetables, lean proteins and whole grains may promote cognitive ability via changes to cellular processes, neuroplasticity, or epigenetic mechanisms, but it is also plausible that an unhealthy diet limits optimal neurological development (Bryan et al., 2004; Kussmann et al., 2010). In addition the high brain growth velocity during early childhood may be particularly sensitive to dietary factors (Isaacs et al., 2008). While the underlying physiologic mechanisms are being researched, understanding the relationships is important given that the typical diet of children globally is suboptimal, with calories typically coming from solid fat and added sugars, including high-fat milk, high-fat meats, cheese, grain desserts, fruit drinks, soda, and candy (Reedy and Krebs-Smith, 2010; Piernas and Popkin, 2011; Kiefte-de Jong et al., 2013; Lazarou et al., 2009; Malik et al., 2013; Alexy et al., 2011). Since children consume combinations of foods and nutrients, it is important to investigate the relationship of dietary patterns more broadly with regard to cognitive outcomes.

Given that early childhood is a formative developmental period, this study addresses important knowledge gaps by systematically reviewing the current literature on the relationship between physical activity and dietary patterns with cognitive outcomes in early childhood (6 months to five years).

2. Methods

This systematic review followed the PRISMA guidelines and the details of the protocol were registered on PROSPERO which can be accessed at http://www.crd.york.ac.uk/PROSPERO/ (Registration No. CRD42015025116) (Moher et al., 2009).

In February of 2016, we conducted two separate searches of three electronic databases — MEDLINE, PsycINFO, and ERIC. In both searches two elements were used in the search strategy. The first element included either physical activity terms common for both young children and for general aerobic activity (e.g., physical activity, active play, or exercise) or diet terms that captured overall dietary patterns for young children (e.g., diet* pattern, diet* index, infant* diet*); the second element included in both searches consisted of outcome terms of neurocognitive development (e.g., cognition, brain development, neurocognitive, executive function or self-regulation). Search terms were broad, including truncated terms and variations of the same meaning to capture all relevant articles. (Appendix A lists full search strings).

2.1. Physical activity

Studies related to physical activity were included they consisted of a measure of non-sedentary activity assessed by accelerometers or direct observation. We made this decision based on considerable research suggesting that self- or proxy-reporting of physical activity has numerous limitations including recall bias, social desirability bias, and varying definitions of what constitutes physical activity (Sallis and Saelens, 2000; Welk et al., 2000). Both observational or intervention studies could be included. We also recognized gross motor skills, specifically fundamental movement skills (FMS), as a basis for physical activity given that numerous studies, including those in preschool age children, have found evidence for a positive association between FMS competency and physical activity (Lubans et al., 2010; Stodden et al., 2008). FMS include locomotor (e.g., running and hopping) and object control (e.g., catching and throwing) skills, both of which are acquired largely by participation in specific movements and overall physical activity. Therefore studies that included a standardized measure of gross motor skills or fundamental movement skills were included.

2.2. Dietary patterns

The USDA defines dietary patterns as the quantities, proportions, variety or combination of different foods, drinks, and nutrients (when available) in diets, and the frequency with which they are habitually consumed (Library, 2014). Studies were included if there was a quantitative method of assessing total diet (e.g., diet diary, 24-hour recall, food frequency questionnaire), dietary pattern, diet index score, meal composition or other indicator of overall diet quality. Studies were excluded if they focused solely on the effects of breastfeeding or breast milk, as the existing evidence base for this area is strong (Belfort et al., 2013; Smithers et al., 2015). The focus of the current review was on the novel aspects of how dietary patterns are associated with cognitive development.

2.3. Cognitive development & learning

Studies were included if an outcome measure of neurocognitive development, intelligence quotients, and/or academic or school readiness tests was included. In order to be as inclusive as possible and glean whatever information we could from the limited literature that currently exists, we included a variety of age-appropriate "learning outcomes." An important component of neurocognitive development is executive function, which is of particular importance in the preschool years. Executive function is an umbrella term defined as the control, supervisory, or self-regulatory functions of cognition, emotional response, and behavior, and is often considered the foundation of preschool children's neurocognitive development. Core executive functions include inhibitory control, working memory, and cognitive flexibility (Isquith et al., 2005) and studies focusing on these outcomes were therefore included. We also included studies that only focused on IQ or other indirect measures of preschool academic achievement or learning.

To be included, studies had to report that the initial assessment of children's physical activity or diet occurred between six months (to coincide with complementary feeding) and up to five years of age. A few studies also included 6 year old children and were deemed appropriate for the review if the children had not yet entered elementary school. Studies were limited to English language and those published since 2005, to include more recent and current methodologies in the measurement of the exposures and outcomes. Our decision to limit the search to 2005 and later was to improve the likelihood that the studies included quality physical activity and dietary measures. With the exception of case studies, all study designs were eligible for inclusion. Studies were excluded if there was an exclusive focus on psychosocial outcomes, premature infants, a disease state or non-typical development (e.g., autism spectrum disorders, spina bifida, etc.). Studies from low-income countries (based on the World Bank Criteria) were also excluded due to the relationships between malnutrition and cognitive outcomes which were outside the scope of this review (http://data.worldbank.org/income-level/LIC, 2015).

The search strategy was carried out separately for diet and physical activity. Titles and abstracts were screened by two authors. Full article review of all potentially eligible studies was completed by two authors. Disagreements between authors were resolved by consensus. To best address gaps in the literature and be inclusive of varying study designs and quality in this relatively novel field of work, we chose not to include a systematic evaluation of the study quality but have broadly addressed study strengths and weaknesses.

3. Results

Because there were two parallel review processes, we present results separately for diet and physical activity.

3.1. Physical activity

3.1.1. Study and sample characteristics

This search resulted in 8150 unique papers. Title and abstract review eliminated all but 36 studies. Twelve papers met inclusion criteria and are included in the physical activity review (Fig. 1).

Of the 12 studies, five were cross-sectional, three were longitudinal and four experimental or quasi-experimental. Two studies included physical activity interventions which included moderate to vigorous physical activity that ranged between 30–60 min per session. One was a cluster-randomized controlled trial (Mavilidi et al., 2015). Sample sizes varied from 10 to over 10,201 participants, but eight of the studies had less than 100 participants. Most studies were conducted in the US, Europe or Australia; one took place in South Africa. The cognitive outcomes were also assessed in early childhood years in all but one longitudinal study in which the cognitive outcomes assessment occurred when the children were school-aged. Some study samples were drawn from socioeconomically disadvantaged populations, while others provided no socioeconomic data (see Table 1).

3.1.2. Reported associations

Eleven out of the twelve studies reported some level of evidence suggesting that physical activity or gross motor skills are related to the young child's cognitive functioning. Six studies used a measure of physical activity (Becker et al., 2014; Palmer et al., 2013) or described a physical activity intervention, (Kirk et al., 2014; Draper et al., 2012; Mierau et al., 2014) and five of these reported a positive association with learning outcomes. Both acute bouts and longer term exposures to physical activity showed a positive relationship to executive function (particularly self-regulation, sustained attention, and working memory) and academic tasks in these four studies. The Mavilidi et al. study explored and found that children's learning of a foreign language vocabulary was

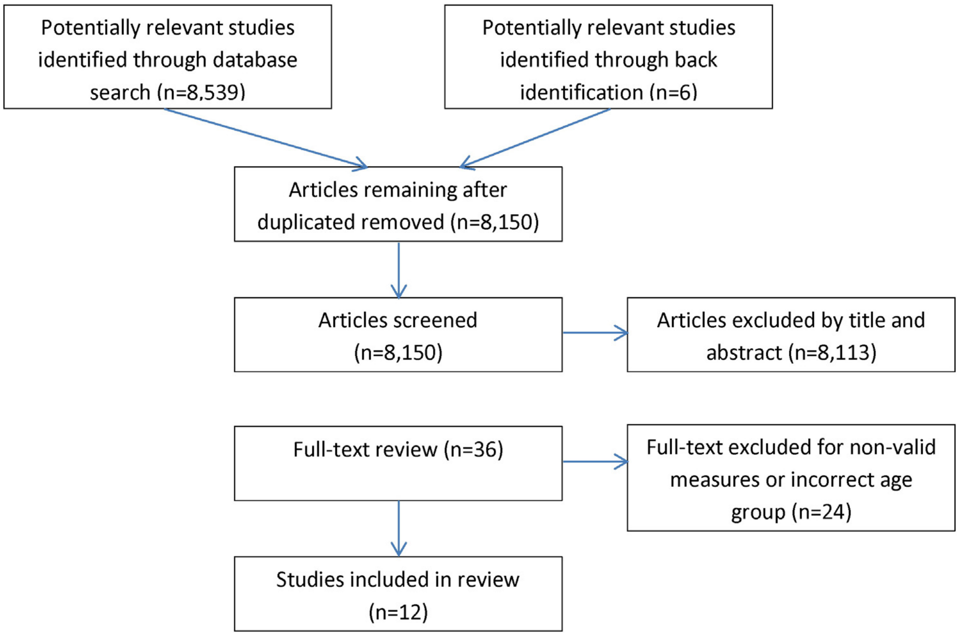

Fig. 1. Physical Activity Search Strategy.

positively associated with enacting the words through physical exercises and movements (Mavilidi et al., 2015). The Mireau study, however, used a cross-over design and found no relationship between the exercise condition and cognitive performance (Mierau et al., 2014).

In the five studies that measured fundamental movement or gross motor skills, a consistent, positive association was noted between those skills and executive function and/or academic oriented tasks (Piek et al., 2008; Livesey et al., 2006; Rhemtulla and Tucker-Drob, 2011; Rosey et al., 2010). Data from the three longitudinal studies reported a significant association of either baseline fitness (Niederer et al., 2011) or motor skills (Draper et al., 2012; Piek et al., 2008) and improved attention and working memory over time.

3.1.3. Strengths and limitations

The generally small sample sizes and correlative nature of most of the studies included do not allow for examination of directional or causal relationships between the exposures and outcomes of interest. Study design and measurement tools varied widely between studies, but 11 of the 12 did find a positive relationship between the exposure and outcomes. Three studies used accelerometers while the rest relied on observation or standardized measures of gross motor skills or active playtime. All studies used validated measures to assess learning outcomes in children, although there was great variability in the measures used, making comparisons across studies difficult. Only two studies examined differences by age or sex (Rosey et al., 2010; Davis et al., 2011).

3.2. Dietary patterns

3.2.1. Study and sample characteristics

This search resulted in 4007 unique papers. Title and abstract review eliminated all but 10 studies which were read for content. Of these, eight studies met inclusion criteria and were included in the final review (Fig. 2).

All eight studies included were secondary analyses from longitudinal cohort studies conducted either in the United Kingdom or Australia (Table 2). Five of the eight papers were from the Avon Longitudinal Study of Parents and Children (ALSPAC) (Golley et al., 2013; Smithers et al., 2012; Smithers et al., 2013; Northstone et al., 2012; Feinstein et al., 2008). Children's dietary data were collected between the ages of 6 months and 3 years in five of the studies, and between the ages of 3 and 5 years in the remaining studies. Although most studies employed food frequency questionnaires to capture dietary exposure, one study used a single parent-reported 24-hour dietary recall (Golley et al., 2013; Smithers et al., 2012; Smithers et al., 2013; Northstone et al., 2012; Feinstein et al., 2008; Gale et al., 2009). Five of the eight studies categorized dietary exposure into different dietary patterns either by utilizing principal component analysis or creating meal patterns (Smithers et al., 2012; Smithers et al., 2013; Northstone et al., 2012; Feinstein et al., 2008; Gale et al., 2009). Two studies categorized dietary exposure using a diet index or diet score and one used main meal type (Golley et al., 2013; Nyaradi et al., 2013; von Stumm, 2012). Each study created its own, slightly varied, definition of “healthy” and “unhealthy” dietary patterns. “Healthy” usually aligned with recommendations, in which fruits, vegetables and whole grains were important while “unhealthy” usually included energy dense foods with high sugar, high fat content.

In all studies, cognitive outcomes were collected between 3–15 years of age (mean age 8.5) and for the majority this was at least 5 years following the assessment of diet quality. Most of the studies used the Wechsler Intelligence Scale for Children (WISC) as one of their measures to assess cognitive development. Other studies assessed language or non-verbal reasoning (Table 2) (Golley et al., 2013; Smithers et al., 2012; Smithers et al., 2013; Northstone et al., 2012; Gale et al., 2009).

3.2.2. Reported associations

Overall, an “unhealthy” dietary pattern early in life was associated with poorer cognitive outcomes in later childhood and a “healthy” dietary pattern was associated with better cognitive outcomes in all of the studies. Some of the reported associations were weak and type of measures used (physical activity and motor development) varied. For example, in both of the Smithers et al. studies, a healthy dietary pattern, high in lean protein and fresh fruits and vegetables, had a weak yet significant, positive association with IQ at 8 years of age; while a discretionary dietary pattern consisting of primarily of chocolate, biscuits, sweets, and soda, was negatively associated with IQ scales (Smithers et al., 2012; Smithers et al., 2013). These associations were attenuated by adjustment, but remained significant.

Dietary patterns high in processed foods and added sugar were associated with lower school achievement, language and nonverbal

Table 1
Studies on physical activity, motor skills and cognitive development.

Reference	Study design/country	Characteristics of study	Physical activity measure	Outcome measure(s)	Main results
Physical activity					
Becker et al. (2014)	Cross-sectional single-group. USA	• N = 51 children • Average age 4.8 years • 43.1% female • 49% enrolled in Head Start • 19.6% Spanish speakers • No SES information	• ActiGraph GT1M accelerometer during 30 min of free outdoor play during preschool	• Head–Toes–Knees–Shoulders task (HTKS) for self-regulation • The Letter-Word Identification subtest of the Woodcock–Johnson (to assess literacy) • The Applied Problems subtest of the Woodcock–Johnson (to assess math skills)	• Active play positively correlated with self-regulation and positively correlated with math achievement • Active play did not significantly predict math or emergent literacy scores • Active play had a significant indirect effect with math scores as well as emergent literacy scores through HTKS
Kirk et al. (2014)	Quasi-experimental. USA	• N = 72 children • Intervention group, n = 51 • average age 3.8 years • 56.9% female • Control group, n = 21 • average age 3.9 years • 42.9% female • No race/ethnicity or SES information	• Direct observation • System for Observing Fitness Instruction Time (SOFIT) • rating 3 times per week • assessed at 3 and 6 months • *Intervention* • Curriculum for 15 min of moderate physical activity 2 × 30 min total	• Pre-school Literacy Individual Growth and Development Indicators (IGDIs) • Assessed at 3 and 6 months of intervention • Measured literacy and language • Picture Naming assessment • Rhyming assessment • Alliteration Assessment	• Compared to control group, intervention group showed significant improvements in alliteration and picture naming between baseline and 3 to 6 months
Mavilidi et al. (2015)	Cluster randomized-controlled rrial. Australia	• N = 111 preschool children • Mean age 4.9 years • 15 child-care centers (4 centers in integrated condition, 4 centers in non-integrated, 4 centers in gesturing, and 3 centers in conventional control)	• Actigraph acceleromter • 4 conditions administered over 4 weeks: 1. Integrated physical exercise condition (vigorous exercise related to the word) 2. Non-integrated physical exercise condition (vigorous exercise not related to the word) 3. Gesturing condition (child seated, gesture related to word) 4. Conventional condition (child seated and repeat the word)	• Free-recall and cued recall of 14 Italian vocabulary words tested during intervention (at 2 weeks), immediately after intervention (at 4 weeks) and 6 weeks after intervention (10 weeks). [Free recall is asking child to name as many words as they can, cued recall is asking the child to use the Italian word for a picture.]	• Children exposed to integrated physical exercise condition could freely recall more Italian words than children exposed to other conditions (non-integrated physical exercise, gesturing condition, and control condition) during, immediately after, and 6 weeks after the intervention • Children exposed to any movement (integrated physical activity, non-integrated exercise, or gesturing) outperformed the children in the sedentary control condition in the cued recall task.
Mierau et al. (2014)	Cross-over design — subjects begin with either exercise or a control condition. Germany	• N = 10 children • Average age 5.8 years • 100% male • Weight and height in the 10th and 90th percentile, respectively • No race/ethnicity or SES information	• Assessed at ages 5 and 6 years • Heart rate was continuously measured • 45 min exercise sessions • 3 ten-minute movement games • 15 min of soccer	• Assessed at ages 5 and 6 years of age • The determination test for children (DTC) • Measures accuracy and reaction speed to rapidly changing visual and acoustic stimuli • Electrical brain activity measured before and after exercise (or control condition) and continuously during the cognitive task	• Reaction time decreased and correct responses increased from pre to post testing however, there was no significant effect by condition
Niederer et al. (2011)	Cross-sectional and longitudinal. Switzerland	• N = 312 children at baseline • N = 245 children at follow-up 9 months later • Average age at baseline 5.2 years • 49.4% female • 79% of parents born outside of Switzerland • 44% with low parental education	• Direct observation at baseline and 9 month follow-up • 45–50 min assessment of 3 tests • Aerobic fitness • Agility • Dynamic balance	• Assessed at baseline and 9 month follow-up • Intelligence and Development Scales – IDS • Spatial working memory • Konzentrations-Handlungverfahrn fur Volrschulkinder -KHV-VK • Attention	• Cross-sectional analyses • Higher aerobic fitness was related to better attention, but not working memory • Greater agility was related to better working memory and attention • No outcome associations with dynamic balance. • Longitudinal analyses • Higher baseline aerobic fitness showed better attention over

(continued on next page)

Table 1 (*continued*)

Reference	Study design/country	Characteristics of study	Physical activity measure	Outcome measure(s)	Main results
					time • Better dynamic balance at baseline showed better spatial working memory over time • No other longitudinal associations
Palmer et al. (2013)	Cross-sectional within-subjects study cohort. USA	• N = 16 children • 18.7% female • Average age 4.1 • Average income $12,000 above national median • No race or ethnicity information	• Acti-Graph GT3X+ accelerometer	• Picture Deletion Task for Preschoolers (PDTP) • Measures response inhibition	• Preschoolers had significantly improved ability to sustain attention after the physical activity condition compared to the sedentary condition
Motor skill					
Davis et al. (2011)	Cross-sectional. England	• N = 248 children • Subsample: 4 year olds n = 30, 5 year olds n = 30 • 50% female • No race/ethnicity or SES information	• Assessed at age 4 or 5 • Bruininks-Oseretsky Test of Motor Proficiency -2nd ed (BOT-2) to test motor ability	• Assessed at age 4 or 5 • Kaufman Assessment Battery for Children -2nd ed (KABC-II) • Measures short-term memory • Visual processing • Long-term storage and retrieval • Fluid reasoning • Crystallized ability	• Positive correlation between overall cognitive score and overall motor score • In 4 year olds, stronger correlation for females than males
Draper et al. (2012)	Quasi-experimental. Pre/post-test with a control group. South Africa	• N = 83 children • Intervention group, n = 43 • average age 4.75 years • 52.5% female • Control group, n = 40 • average age 4.67 years • 32.5% female • From disadvantaged and low-SES settings in South Africa • No race/ethnicity information	• No quantitative measurement of PA • *Intervention* • Little Champs: once/week 45–60 min physical activity program led by a trained coach • Herbst test for fine/gross motor skills administered	• Herbst early childhood development criteria test • Assessed cognitive functions for school readiness in 3 to 6 year old children	• Intervention group showed significant improvement in cognitive scores
Livesey et al. (2006)	Cross-sectional. Australia	• N = 36 children • 58.3% female • Average age 6.25 years • No race/ethnicity or SES information	• Assessed at ages 5 and 6 years • Movement assessment battery for children (MABC - Henerson and Sugden, 1992)	• Assessed at 5 and 6 years of age • Three Tasks • Modified stop-signal task (SST) • Response inhibition • Modified Day-night Stroop task • Response inhibition • Rowe behavior rating inventory (RBRI)	• Lower RBRI scores were associated with better ball skills • Stroop task performance was associated with better fine motor skills • The relationship between motor performance and the SST performance trended in the positive direction but was not significant • Partial correlation showed moderate correlation between go-signal reaction time and fine motor and ball skills
Piek et al. (2008)	Longitudinal cohort. Australia	• N = 33 children • Age at testing 4 months–4 years; age at re-testing 6–12 years • 48.5% female • No race/ethnicity or SES information	• Ages in Stages Questionnaire (ASQ) for motor skills • completed at 4, 6, 8, 12, 16, 18, 20, 24, 30, 36, and 48 months	• Assessed at school age (between ages 6–12 years) • Wechsler Intelligence Scale for Children (WISC-IV fourth edition) • Verbal comprehension (VCI) • Working memory (WMI) • Processing speed (PSI) • Perceptual reasoning (PRI)	• Gross motor trajectory (controlling for SES) did not predict VCI or PRI but was significant for WMI and PSI • The ASQ gross motor trajectory set of predictors accounted for a significant proportion of the variance in cognitive performance once SES was controlled
Rhemtulla and Tucker-Drob (2011)	Longitudinal survey. Early Childhood Longitudinal Study-Birth Cohort (ECLS-B). USA	• N = 10,201 children • n = 8300 at age 4 • n = 6800 at age 5 • n = 1850 at age 6 • 51.1% female • Race/Ethnicity: 41.4% white, 15.9% African-American, 20.5% Hispanic, 11.3% Asian, and 10.8% other	• Assessed at age 4, 5 and 6 • Gross motor skills • Jumping • Balancing • Hopping • Skipping • Walking backwards • Catching a bean bag	• Assessed at age 4, 5, and 6 • Reading • Preschool Language and Assessment Scale – preLAS • Preschool Comprehensive Test of Phonological & Print Processing • Peabody Picture Vocabulary Test • Mathematics • Measures number sense • Oral language • Let's tell stories task from preLAS	• The rates of developmental change in every domain (motor and cognitive) were positively inter-correlated with a common factor, which accounted for an average of 42% of individual differences in change • Findings suggest significant relationships between the development of several cognitive and motor skills in childhood
Rosey et al. (2010)	Cross-sectional within-subjects' design. USA	• N = 61 children • Age groups 3–5 years old • 3-year olds, n = 16 (62.5% female, average age, 3.4 years) • 4-year olds, n = 25 (44% female, average age, 4.25	• Three fundamental movement skills measured • Unipedal balance • Overarm throw • Hopping • Tasks analyzed on film	• Day-Night • verbal inhibition • Hand-Candle • motor inhibition • Tap-Once/Tap-Twice • motor inhibition • Go-No Go task • Delayed inhibition	• Inhibition task performances were correlated with coordination level for the three motor skills for the 3–4 year old children only • Non-verbal inhibition was a coordination level predictor

Table 1 (*continued*)

Reference	Study design/country	Characteristics of study	Physical activity measure	Outcome measure(s)	Main results
		years) • 5-year olds, n = 20 (75% female, average age, 5.25 years) • No race or ethnicity information		• Trail Making Test • 5-year old children only	more than the verbal or delayed inhibition

reasoning (Feinstein et al., 2008; Nyaradi et al., 2013). As part of a longitudinal cohort, von Stumm found that "slow meals" (sit down restaurant, or meal with fresh ingredients) at age 3 were associated with better cognitive performance at age 5 (von Stumm, 2012). They also found that higher socio-economic status was associated with better cognitive performance at children's age 3 and 5 years, and this effect was partially mediated by the frequency of having more slow vs. fast food meals per week.

Both Golley et al. and Gale et al. found that adherence to healthy eating guidelines at 6 months of age was consistently associated with higher IQ at age 4 and age 8 (Golley et al., 2013; Gale et al., 2009). Gale et al. did find that children who adhered to healthy eating guidance at age 6 months tended to be breastfed for longer but adjusting for this, there was no effect on the associations between the guidelines scores and intelligence at age 4 years. Golley et al. on the other hand included "breastfeeding duration" as part of the healthy eating guidelines. In both these studies, associations were attenuated after adjustment. Northstone et al. did not find an association between a "health-conscious" dietary pattern and IQ at age 8 (Northstone et al., 2012) but this study did find associations between a "processed" (foods high in fat and added sugar content that came from processed and convenience foods) and a "snack" dietary pattern (included finger foods such as fruit, biscuits, bread and cakes) at age 3 and decreases and increases in IQ at age 8, respectively.

3.2.3. Strengths and limitations

All of the diet studies consisted of large samples taken from longitudinal cohort studies, which allowed for the analysis of early exposure and long-term cognitive outcomes. However, several of the studies were from the same ALSPAC cohort and had limited data on different racial/ethnic minority groups and incomplete data from some groups, which may limit generalizability. Furthermore, all of the studies are

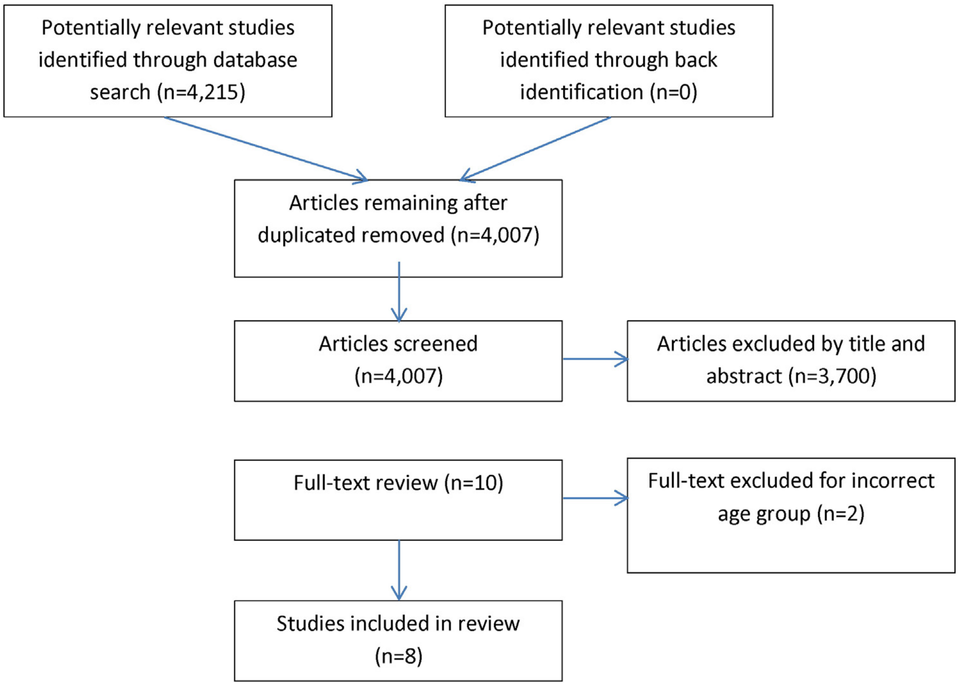

Fig. 2. Diet Search Strategy.

Table 2
Studies on diet and cognitive development.

Reference	Study design/country	Characteristics of study	Diet measure	Outcome measure	Main results
Feinstein et al. (2008)	Longitudinal cohort study: ALSPAC[a]. England.	• N = 5741 • 51% female • 94% white	• Dietary patterns created from FFQ[b] data at 38 months, 54 months and 81 months using factor analysis	• Measured between age 10 & 11 • School Attainment, measured using Key Stages standards • Used KS2[c] for English, Math and Science	• Junk food dietary pattern at age 3 associated with lower results on KS2. • Health conscious pattern at age 3 associated with higher results on KS2. • Only the effect of the junk food pattern remained significant after adjusting for confounding variables.
Gale et al. (2009)	Longitudinal cohort study, the Southampton Women's Survey. England.	• N = 241 • 46% female • No race or ethnicity information	• Dietary patterns created from FFQ data at 6 and 12 months using PCA[d]	• Measured at age 4 • Wechsler Pre-School and Primary Scale of Intelligence test • Measure of FSIQ[e], VIQ[f], and PIQ[g] • Developmental Neuropsychological Assessment • Measure of attention, sensorimotor ability, memory, and language • Test of Visual-Perceptual Skills • Measure of visual perception	• Infant guidelines pattern, described as a pattern that "conforms to feeding guidelines as recommended in infant feeding manuals", at 6 months associated with increases in FSIQ and VIQ. • Borderline significant positive association between the infant guidelines pattern at 6 months and sentence repetition scores. • All other associations were not significant.
Golley et al. (2013)	Longitudinal cohort study: ALSPAC. England.	• N = 4429 • Subsample with maternal IQ N = 1776 • 50% female • No race or ethnicity information	• Dietary intake at 6 months via caregiver completed questionnaire • Created CFUI[h] as a measure of diet quality	• Measured at age 8 • WISC[i] Version III • Measure of FSIQ, VIQ, and PIQ	• CFUI score was positively associated with FSIQ, VIQ, and PIQ. • Upon adjusting for maternal IQ, relationship between CFUI and FSIQ and VIQ remained significant. • All other associations were not significant.
Northstone et al. (2012)	Longitudinal cohort study: ALSPAC. England.	• Overall cohort N = 6944 • 47% female • No race or ethnicity information • Complete data available for N = 3966	• Dietary patterns created from FFQ data at 3, 4, 7, and 8.5 years using PCA	• Measured at age 8.5 • IQ[j] assessed using WISC Version III • Tested picture completion, information, arithmetic, vocabulary, comprehension, and picture arrangement	• Processed food pattern at age 3 associated with a decrease in IQ. • Health-conscious pattern at age 8.5 years associated with increase in IQ. • Snack pattern at age 3 associated with an increase in IQ.
Nyaradi et al. (2013)	Longitudinal cohort study: Raine cohort. Australia.	• N = 1346 for PPVT III[k] measure • 49% female • N = 1455 for Raven's Colored Matrices • 48% female • No race or ethnicity information	• EAT[l] diet score developed using 24-h recall data at ages 1,2, and 3 • EAT score based on Dietary Guidelines for Children and Adolescents in Australia • Includes 7 food categories: whole grains, vegetables, fruits, meat ratio, dairy, snack foods, sweetened beverages	• Measured at age 10 • PPVT III • Measure of receptive vocabulary and verbal ability • Raven's Colored Progressive Matrices • Measure of nonverbal reasoning ability	• EAT score at age 1 associated with higher PPVT III and nonverbal cognitive ability. Dairy consumption at ages 2 and 3 positively associated with verbal cognitive outcomes. • Higher intake of sugar-sweetened beverages negatively associated with nonverbal reasoning ability.
Smithers, et al. (2012)	Longitudinal cohort study: ALSPAC. England.	• N = 1366 • 49% female • 97% white	• Dietary patterns created from FFQ data at 6, 15, and 24 months using PCA	• Measured at age 8 • WISC Version III • Measure of FSIQ, VIQ, and PIQ	• Nutrient-dense dietary patterns associated with increases in FSIQ and VIQ and discretionary patterns associated with decreases in FSIQ and VIQ. • At 6 and 15 months, ready-prepared baby foods associated with decreases in FSIQ and VIQ. • At 24 months, ready-to-eat dietary pattern associated with increases in FSIQ and VIQ. • All other associations were not significant.
Smithers et al. (2013)	Longitudinal cohort study: ALSPAC. England.	• N = 7652 • 50% female • 96% white	• Dietary pattern trajectories created from FFQ data at 6, 15, and 24 months using PCA	• Measured at age 8 and 15 • WISC Version III at age 8 • Measure of FSIQ, VIQ, and PIQ • Abbreviated version of the Weschler Abbreviated Scale of Intelligence at age 15 • Tested vocabulary and matrix reasoning • Measure of IQ	• Healthy dietary pattern trajectory was weakly associated with higher IQ at age 8 but not age 15. • Discretionary and Traditional trajectories were associated with lower IQ at age 15 but not age 8. • The Ready-to-eat trajectory had no association with IQ at either age.
von Stumm et al. (2012)	Longitudinal birth cohort study: The Growing Up in	• At baseline, N = 5217 • 49% female	• Frequency of type of children's main meal type per week, defined as fast or slow food.	• Measured at age 3 and 5 • British Ability Scales II which includes Naming Vocabulary	• Meal types at age 3 positively associated with vocabulary and picture test performance at age 3 and with vocabulary test performance at age 5.

Table 2 (*continued*)

Reference	Study design/country	Characteristics of study	Diet measure	Outcome measure	Main results
	Scotland study. Scotland.	• At age 3, N = 4193 • At age 5, N = 3833 • No race or ethnicity information	• Fast food: frozen/ready prepared, take away meal, fast-food meal • Slow food: sit down restaurant, or meal with fresh ingredients • Obtained through parent interviews	and Picture Similarities tests • Measure of expressive language ability and non-verbal reasoning	• Meal types at age 5 positively associated with cognitive performance at age 5. • Type of meals partially mediated the effects of socioeconomic status on cognitive performance at age 3 and 5. • Having more slow meals was positively associated with changes in vocabulary at ages 3 and 5.

[a] Avon Longitudinal Study of Parents and Children.
[b] Food Frequency Questionnaire.
[c] Key Stage 2.
[d] Principal Component Analysis.
[e] Full Scale Intelligence Quotient.
[f] Verbal Intelligence Quotient.
[g] Performance Intelligence Quotient.
[h] Complementary Feeding Utility Index.
[i] Wechsler Intelligence Scale for Children.
[j] Intelligence Quotient.
[k] Peabody Picture Vocabulary Test.
[l] Eating Assessment in Toddlers.

correlational and non-experimental and utilized only IQ as a measurement rather than utilizing executive function measures or measuring other cognitive domains.

The measurement tools utilized to capture diet (food frequency questionnaires and a single 24-hour recall), may not accurately capture typical dietary intake. In addition, it is possible that children may be spending a large portion of their time in a preschool setting which exposed them to a different food environment. The reviewed studies did not differentiate between dietary intake in these two environments and/or capture information from what was eaten specifically in preschool. Furthermore, several studies used principal component analysis to categorize the diet exposure into certain patterns which allowed for subjective decisions on grouping data. In many studies there was a significant gap in the ages at which diet and cognition were assessed, increasing the likelihood that other factors may have influenced the cognitive outcomes observed. Finally, although seven of the eight studies adjusted for confounding variables, residual confounding may remain.

4. Discussion

The goal of this study was to review the literature on how dietary patterns and physical activity are associated with cognitive development in early childhood (6 months to five years). We found evidence suggesting that being physically active and having a healthy diet before the age of 5 is associated with beneficial cognitive outcomes. The paucity of literature on these topics and the variability in the type and quality of measures used in the reviewed studies, however, highlight the need for additional research utilizing more rigorous methodology. Given that the early childhood years are critical for both obesity prevention and neurocognitive development, evidence that a healthy diet and regular physical activity could promote both is informative and significant. Although none of the studies included in this review took an integrated approach, an opportunity exists to include physical activity and diet together to gain a better understanding of how these health-related behaviors influence cognitive outcomes and child development. In addition, studying these in conjunction may help inform interventions within early childhood care settings, which typically emphasize early learning.

With regard to physical activity, two previous reviews of studies with school-aged children found that aerobic and vigorous physical activity were positively associated with cognition, academic achievement, behavior, and psychosocial function (Diamond and Lee, 2011b; Lees and Hopkins, 2013). Our review extends the finding of these reviews and suggests that this association may be present during early childhood. Some studies in the current review explored a more acute relationship, while others involved long term participation in physical activity. Taken together, there is evidence, albeit weak, to support both short and longer term cognitive benefits of physical activity in the early childhood years. Our findings also support those of a recent review which concluded that while preliminary evidence of the beneficial effects of physical activity was observed, more research is needed (Carson et al., 2015a). Different from past reviews, ours brings together both diet and physical activity and different aspects of cognition (e.g., academic tasks). There is some evidence in adults that dietary factors influence the association between PA and cognitive performance (Leckie et al., 2014), and this relationship has been identified as a gap in the literature (Erickson et al., 2015). While we found no studies that included both PA and diet, this would be an important area for future research both in terms of exploring additive or multiplicative benefits and also because they often can be intervened upon simultaneously.

Our review of the literature also found that fundamental movement/gross motor skills (FMS) were positively associated with cognitive performance in early childhood. While not typically included in the definition of “physical activity,” the development of fundamental movement skills is associated with opportunities for movement, and our findings suggest that FMS, in turn, are associated with cognitive development (Goodway and Branta, 2003; Robinson et al., 2012). Because these papers reported cross-sectional relationships, we can only conclude at best that a relationship exists between motor skills and cognitive functioning in young children, which could be bidirectional or merely due to the inter-relatedness of the various developmental domains in children. Although genetic and physiologic factors influence development, there are also likely environmental and behavioral factors present in the home and/or early learning settings that could promote both motor and cognitive development (Goodway and Branta, 2003; Tucker-Drob et al., 2013). In addition, several studies have noted a decline in preschoolers' motor skills over the past decade which may be reflective of fewer physical activity opportunities (Roth et al., 2010; Hardy et al., 2013). Although we did not find evidence for causality, the interdependence and interrelatedness of motor and cognitive development has been previously recognized (Diamond, 2007) but arguably less emphasized in current early learning efforts.

Young children are likely to achieve physical activity through play, which is also essential for their cognitive, physical, social, and emotional growth and development (Copeland et al., 2012; Pellegrini and Smith, 1998). Suggestions of ways to integrate physical activity into preschool models are available but more work is needed on how to integrate these examples into the preschool curriculum to create physically active learning environments (Gagne and Harnois, 2013; Gartrell and Sonsteng, 2008). The recent robust interest in the importance of birth-to-five early childhood education may be having the unintended consequence of squeezing out opportunities for active play at the expense of traditional and sedentary learning activities. Understanding the relationship of physical activity with learning in the early years would be of potential interest to educators, policy makers, and others interested in promoting environments and programs that support health, learning and well-being in the early childhood years and beyond. In fact, best practices recommendations in the US suggest 60–120 min of daily physical activity for preschool age children (American Academy of Pediatrics APHA, and National Resource Center for Health and Safety in Child Care and Early Education, 2012; McWilliams et al., 2009; Physical Activity and Fitness Recommendations for Physical Activity Professionals, 2002); considerably less than other countries, such as Australia (Australia's Physical Activity and Sedentary Behaviour Guidelines's, 2014), Canada (Lipnowski and Leblanc, 2012) and the U.K. (Physical Activity Guidelines, 2011), which recommend 180 min per day for this age. Evidence that characteristics of active play support key aspects of cognitive functioning involved in learning would bolster efforts to increase active play in young children.

Our review also found preliminary evidence suggesting a positive association between healthy dietary patterns (defined as diets high in fruits, vegetables, whole grains) before the age of 5 and later childhood cognitive outcomes. Although the findings provide some indication of positive associations, the limitations of the work point towards the need for additional investigations in this area. Historically, the focus of the relationship between diet and cognition has been on how certain nutrient deficiencies can interfere with cognitive function. Similarly, much attention has been placed on the role of breast milk and better development of brain function (Belfort et al., 2013; Smithers et al., 2015), which was outside the scope of the current literature review. Given that the typical diet of children globally is low in fruits, vegetables and whole grains, and high in energy dense snack foods such as candy, soda and desserts, it is important to explore young children's dietary patterns and their association with cognitive outcomes. If future studies in this area confirm a causal relationship, there would be additional motivations for improving healthy eating across different environments (home and early learning settings) where a young child spends time.

Providing young children with healthy early education and care environments, which include sufficient opportunities for physical activity and provision of healthy diets, is challenging for many reasons including competing interests, cost and beliefs. Priorities for school readiness results in child care providers feeling pressured to focus on academics at the expense of active play (Gaus and Simpson, 2009). Also, a recent survey of parents found that while they reported that outdoor active play was important for preschoolers, they placed more value on other academic activities (*manuscript under review*). Similarly, creating a healthy food environment within early child care settings has been a challenge and a study found that foods served in child care centers did not meet USDA guidelines (Schwartz et al., 2015). While the United States has federal performance and program standards for child care settings, barriers to serving healthy foods remain. The link between physical activity, dietary patterns and preschooler's cognitive outcomes are gaps in the literature; which, once filled, could provide additional motivation for programs and policies to promote healthier foods and more active childhoods.

Strengths of this review include the systematic and thorough search strategy that builds on previous reviews by focusing on a younger age range and addressing both nutrition and physical activity components. Several limitations also existed. The review was limited to the past 11 years and studies in English, thus we may have missed the contributions of literature outside of those parameters. Not all studies reported the children's weight status or adjusted for it in their analyses, limiting our ability to specifically look at obesity as a variable. Our pool of studies was limited and study design and measurement tools varied widely, which precluded our ability to make direct comparisons between studies. Also, unmeasured characteristics such as prenatal and genetic factors may exist which could explain some significant associations between exposure and outcomes. Unfortunately with small samples, studies may have not been able to account for potentially confounding variables. In addition, because the studies included are not pre-registered randomized controlled trials, we are unable to account for publication bias. Finally, the cognitive outcome measures used may not accurately capture those most sensitive to physical activity and diet exposures. For example, several studies focus on academic outcomes while others use tasks for specific executive functions. Future research should consider the best way to measure cognitive outcomes of interest that would also be sensitive to change.

Healthy dietary patterns and physical activity behaviors in the first five years of life are fundamental to health, including weight status, both in the early childhood years and beyond (McGuire, 2011). While not the focus of this systematic review, it is also possible that obesity and cognitive status are linked. There is inconsistent evidence that increased adiposity in children is associated with poorer neurocognitive functioning and academic performance, although the directionality of that relationship is not well understood (Datar and Sturm, 2006; Yau et al., 2012; Liang et al., 2014; Afzal and Gortmaker, 2015). Research has demonstrated an association between obesity and abnormalities in brain tissue; perhaps parts of the developing brain may be sensitive to the metabolic changes associated with excess adipose tissue (Miller et al., 2009). Alternatively, poor neurocognitive function could lead to behaviors that increase risk of obesity. Although additional research in this area is required, our findings support efforts to improve nutrition and physical activity in the early childhood years, including those focused on early learning environments.

Beyond the known benefits for weight status, our systematic literature reviews suggest that there is some evidence that physical activity and diet patterns are also important to cognitive development. Since there are racial/ethnic disparities in early life risk factors for childhood obesity, such as early feeding practices and screen time behaviors, and many of the same children are at higher risk for poor cognitive and academic achievement, the relationships examined in this study also have implications for socioeconomic disparities (Martin et al., 2014; Taveras et al., 2013). Future research should utilize more rigorous methodology to better explore causality, dose–response and issues of disparities. As early learning has rightfully become an area of priority, research on children's diet and activity behaviors should include cognitive and developmental outcomes. Efforts to promote healthy eating and active living from birth, important components of recommendations for obesity prevention, could be bolstered by increasing the evidence for how these health behaviors could also contribute to children's cognition and learning.

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Appendix A. Search strings by database

A.1. Medline

(physical fitness OR exercis* OR physical activit* OR exertion OR play* OR active play* OR activit* OR (play & playthings) OR gross motor skills OR fundamental movement skills) AND (cognitive control OR working memory OR inhibitory control OR reasoning OR task flexibility OR problem solving OR child development OR neurocognit* OR brain growth and development OR cognit* OR executive function OR self-regulation OR executive flexibility OR child development OR academic OR achievement OR kindergarten readiness OR IQ OR intelligence quotient) NOT (autism OR adhd OR cerebral palsy OR preterm OR physical disability OR review OR microbiology).

(diet* pattern OR diet* quality OR diet quality index OR dietary index OR diet OR nutrition OR diet* intake OR infan* diet* OR infant feeding OR eating behavior OR breast milk) AND (cognitive control OR working memory OR inhibitory control OR reasoning OR task flexibility OR problem solving OR child development OR neurocognit* OR brain growth and development OR cognit* OR executive function OR self-regulation OR executive flexibility OR child development OR academic OR achievement OR kindergarten readiness OR IQ OR intelligence quotient OR test score*) NOT (autism OR adhd OR cerebral palsy OR preterm OR physical disability OR review OR microbiology).

Filters: publication dates: 10 years; species: humans; ages: infant: birth-23 months, preschool child: 2-5 years; language: English.

A.2. ERIC

("physical fitness" OR exercise OR "physical activity" OR exertion OR play OR "active play" OR activity OR "play & playthings" OR "gross motor skills" OR "fundamental movement skills") AND ("young child" OR preschool OR "preschool child" OR preschooler OR "early childhood") AND ("cognitive control" OR "working memory" OR reasoning OR "task flexibility" OR "problem solving" OR "child development" OR neurocognitive OR "brain growth and development" OR cognition OR "executive function" OR "self-regulation" OR "executive flexibility" OR "child development" OR academic OR achievement OR "kindergarten readiness") NOT (autism OR adhd OR "cerebral palsy" OR preterm OR "physical disability" OR review OR microbiology).

("diet* pattern" OR "diet* quality" OR "diet quality index" OR "dietary index" OR diet OR nutrition OR "diet* intake" OR "infan* diet*" OR "infant feeding" OR "eating behavior" OR (breast AND milk)) AND ("young child" OR preschool OR "preschool child" OR preschooler OR "early childhood" OR infan*) AND ("cognitive control" OR "working memory" OR "inhibitory control" OR reasoning OR "task flexibility" OR "problem solving" OR "child development" OR neurocognit* OR "brain growth and development" OR cognit* OR "executive function" OR "self-regulation" OR "executive flexibility" OR "child development" OR academic OR achievement OR "kindergarten readiness" OR IQ OR "intelligence quotient" OR "test score*") NOT (autism OR adhd OR "cerebral palsy" OR preterm OR "physical disability" OR review OR microbiology).

Filters: publication date: last 10 years.

A.3. PsycInfo

(physical fitness OR exercis* OR physical activit* OR exertion OR play* OR active play* OR activit* OR (play & playthings) OR gross motor skills OR fundamental movement skills) AND (cognitive control OR working memory OR inhibitory control OR reasoning OR task flexibility OR problem solving OR child development OR neurocognit* OR brain growth and development OR cognit* OR executive function OR self-regulation OR executive flexibility OR child development OR academic OR achievement OR kindergarten readiness OR IQ OR intelligence quotient) NOT (autism OR adhd OR cerebral palsy OR preterm OR physical disability OR review OR microbiology).

((diet* AND pattern) OR (diet* AND quality) OR (diet AND quality AND index) OR (dietary AND index) OR diet OR nutrition OR (diet* AND intake) OR (infan* AND diet*) OR (infant AND feeding) OR (eating AND behavior) OR (breast AND milk)) AND ((cognitive AND control) OR (working AND memory) OR (inhibitory AND control) OR reasoning OR (task AND flexibility) OR (problem AND solving) OR (child AND development) OR neurocognit* OR (brain AND growth) AND development OR cognit* OR (executive AND function) OR self-regulation OR (executive AND flexibility) OR (child AND development) OR academic OR achievement OR (kindergarten AND readiness) OR IQ OR (intelligence AND quotient) OR (test AND score*)) NOT (autism OR adhd OR (cerebral AND palsy) OR preterm OR (physical AND disability) OR review OR microbiology).

Filters: human, infancy (<2 to 23 months>), preschool age (<2 to 5 yrs.>), English, last 10 years.

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