Understanding the Association between Stunting and Child Development in Low- and Middle-Income Countries: Next Steps for Research and Intervention

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Abstract

Stunting, caused by experiences of chronic nutritional deprivation, affects approximately 25% of children under age five globally (i.e., 156 million children). In this review, evidence of a relationship between stunting and child development in low- and middle-income countries is summarized, and issues for further research are discussed. We focus on studies that measured low height-for-age among children less than 5 years old as the exposure and gross/fine motor skills, psychosocial competencies, cognitive abilities, or schooling and learning milestones as the outcomes. This review highlights three key findings. First, the variability in child development tools and metrics used among studies and the differences in the timing and frequency of the assessments complicate comparisons across study findings. Second, considerable evidence from across many countries supports an association between stunting and poor child development despite methodological differences and heterogeneity in the magnitude of associations. Further, effect sizes differ by developmental domain with greater associations shown for cognitive/ schooling outcomes. How stunting influences child development, which domains of child development are more affected, and how the various domains of child development influence one another require further experimental research to test causal pathways. Finally, there is mixed evidence of the additive effect of nutrition and stimulation interventions on child development. However, understanding best methods for improving child developmental outcomes - either through nutrition programs or through integrated nutrition and psychosocial stimulation programs (or nutrition and other program interventions) - is a key area of further inquiry. Given that nearly 40% of children under age five suffer from loss of developmental potential - for which stunting is likely one of the key risk factors - reductions in stunting could have tremendous implications for child development and human capital formation, particularly in low- and middle-income countries.

Keywords: Child development, Cognition, Stunting, Undernutrition, Gross motor, Fine motor, Psychosocial skills, Cognitive ability, Height

JEL Codes: I10, J10

1. Introduction

The 2015 Sustainable Development Goals (UN, 2015) and several expert reviews on child development call for new research and interventions to prioritize solutions to the global challenge of poor child development in low- and middle-income countries (LMICs) (Black et al., 2016; Britto et al., 2016; Dua et al., 2016; Richter et al., 2016). Child development can generally be defined as the attainment of gross motor and fine motor skills, psychosocial competencies, and cognitive abilities. Although many factors may impact child development, numerous cross-sectional studies and two meta-analyses provide important initial evidence of a link between impaired linear growth and poor child development (Miller et al., 2015; Sudfeld et al., 2015; Walker et al., 2007b, 2011). The behavior of stunted children is often associated with apathy, detachment from social environments, cognitive deficits, poorer learning outcomes and lower educational attainment, as well as reduced economic prospects in the future, thus perpetuating intergenerational transfers of undernutrition and poverty (Alderman et al., 2014; Currie and Vogl, 2013; Grantham-McGregor et al., 2007; Perkins et al., 2016). If stunting causes developmental deficits, then the consequences at the population-level are immense, as there are 156 million children across the world who are stunted (UNICEF et al., 2016).

A meta-analysis of cross-sectional studies found that linear growth among children less than two years old was associated with cognitive and motor development across diverse studies from 29 LMICs (Sudfeld et al., 2015). Similarly, evidence from 15 countries participating in the Multiple Indicator Cluster Surveys showed associations between stunting and some child development domains, though the associations varied by country and other factors (Miller et al., 2015). Drawing a definitive conclusion about these relationships from meta-analyses is difficult, however, given substantial heterogeneity in how studies are conducted, the populations that are targeted, whether it is linear growth or stunting that is measured, and the tools used to measure various child development domains. Challenges with accurately measuring linear growth and stunting may also affect conclusions (Corsi et al., 2017).

In addition, a causal relationship between stunting and child development should not be assumed based on evidence from observational studies due to the potential for many factors, such as socioeconomic status and place, to confound the relationship. For example, stunted children are more likely to grow up in conditions of overall deprivation, which affect both physical growth and child development (Grantham-McGregor et al., 2007). Thus, studies need to adequately account for a variety of confounding factors at various levels of influence.

Taken together, these challenges make it difficult to determine how to use observational evidence about the stunting-child development relationship for intervention purposes, particularly for researchers and policy-makers who may be unfamiliar with this area of work. Moreover, caution is needed when using evidence from meta-analyses for decision-making about further research and intervention development (Ioannidis, 2016).

To address these challenges, several studies have used designs that permit causal assessments of the extent to which linear growth and stunting impact child development. Including these studies' conclusions alongside findings from observational studies that have been reviewed in the past would provide a stronger case for deciding how to invest in programs that target stunting reduction while supporting paths to meet global goals for improving child development. Thus, the purpose of this paper is to provide a substantive review of the association between stunting and child development in LMICs based on evidence from correlational designs, quasi-experimental studies, randomized nutrition interventions and nutrition and psychostimulation interventions. This review moves beyond presenting a quantitative summary assessment of the observational relationship between stunting and child development by discussing the current extent of literature on stunting and child development with the objective of understanding the conceptual relationships between stunting as a measure of nutritional deprivation and child development. In addition, we describe challenges associated with measures and study designs as well as with interpretation of results within and across studies.

Finally, we discuss how this area of research may evolve and inform the development of evidence-based intervention programs. Although other determinants of child development are important for policy and intervention (e.g., addressing socioeconomic conditions), we focus here on the direct relationship between stunting and child development. We are motived to offer this review given the considerable interdisciplinary attention on addressing child development and on how nutritional deprivation may play a role in impacting population human capital and wellbeing. This repository of information will be useful for policymakers, practitioners, program managers, or researchers new to this field, who seek to reduce stunting and address child development challenges, particularly in LMICs.

2. Identifying peer-reviewed evidence on stunting and child development

We conducted a comprehensive review of key databases in public health, economics, social science, and psychology (PubMed, Web of Science, PsycInfo and Embase) to identify studies on stunting and child development to include in this review. We searched for studies or reviews of studies assessing height (or length) among 0-5 year old children as an exposure for child development. Height could be measured as (a) height-for-age, which is a linear growth measure standardized into z-scores using international growth standards or (b) stunting, which is a widely used binary indicator of chronic undernutrition in infancy and early childhood (WHO, 2006). Stunting occurs when a child's height is more than two standard deviations below the median height-forage among children of a given sex according to WHO Child Growth Standards. We included papers using either or both height measures as they capture different, but related exposures.

We further required studies and reviews to have focused on at least one measure of child development as the outcome. Most child development assessment tools focus on major educational milestones, measure a specific individual developmental domain (e.g., gross motor skills, fine motor skills, or psychosocial development), or use a battery of skills tests. Web Tables 1-3 provide a list of common assessments and the typical targeted population. For a more in-depth discussion on individual child development assessment tools, there are several recent reviews (Fernald et al., 2009b; Frongillo et al., 2014; Sabanathan et al., 2015).

The following search terms were used: cognition, cognitive, awareness, consciousness, cognitive disorder, intelligence, intelligence tests, mental tests, achievement, achievement tests, school readiness, psychosocial, behavior, attitude, height, stunting, stunt, height-for-age, anthropometry, anthropometric, growth, growth disorders, infant, infancy, child, and childhood. Only studies published in English were included.

As part of this review, we first discuss the many challenges that exist when comparing studies on child development, which make comparisons between results and generalizations difficult. After acknowledging such challenges and caveats, we review evidence of the association between stunting and child development provided by cross-sectional and longitudinal observational studies, as well as from quasi-experimental studies and randomized experiments. After establishing a plausible link between stunting and child development, we then briefly review potential mechanisms through which stunting may lead to developmental impairments. Finally, we highlight gaps in knowledge and further directions for this area of research. We conclude by discussing why the potential for a causal connection between stunting and child development matters for policies, programs, and advocacy.

3. Challenges with child development assessments

Most child development assessments were designed for use with English-speaking populations in high-income countries. Thus, challenges arise when using them in LMICs (Grantham-McGregor, 1984, 1993). Although many child development metrics have been adapted for local contexts, they may not be appropriate for children living in poverty and therefore may lead to biased testing results (Isaacs and Oates, 2008; Prado and Dewey, 2014). A study on child development across eight LMICs emphasized that significant effort and time is needed to adapt child development assessment tools, develop and implement standard operating procedures, and ensure high quality data collection across places (Murray-Kolb et al., 2014). Thus it is possible to overcome these particular challenges, but doing so may be time-consuming and expensive.

Instead of using difficult to adapt tests that are also often hard to administer in low-resource settings, studies on child development often evaluate learning and schooling outcomes such as grade completion or years of schooling in lieu of cognitive tests. Although these measures would not always apply to children under age five, the quality of education, the selection of material that is taught, and the amount of learning that occurs during years of education, vary both within and between countries (Behrman and Birdsall, 1983). These factors may not be challenges if studies always selected children from within the same school, but studies often sample children from various locations. In addition, assessment implementation varies in practice. For cognitive assessments, children most often engage in the testing. In contrast, to assess motor and psychosocial development, parents, teachers, or an observer often assess a child's skills. Therefore, children's performance on these assessments is not only a measure of their abilities, but also reflects their interactions with the test administrator and the testing situation (Isaacs and Oates, 2008).

Finally, the use of varied child development tools and metrics across studies as well as differences in assessment timing and frequency complicate comparisons of results (Grantham-McGregor and Baker-Henningham, 2005; Sudfeld et al., 2015). Moreover, there are also differences in how test results are analyzed. Some studies use number of successes as measures of cognitive ability (e.g., number of objects correctly identified by children taking the Peabody Picture Vocabulary Test) while others transform the raw numbers of successes into age-standardized z-scores or percentiles (Cheung et al., 2008). Thus, these differences in testing approaches and methodology need to be considered when interpreting findings in the literature.

4. Evidence of a link between stunting and child development

4.1. Cross-sectional observational studies

A recent review found that across cross-sectional studies, height-for-age z-scores (HAZ) were positively associated with gross motor scores and odds of walking among children ≤2 years old (Sudfeld et al., 2015). Similarly, HAZ scores were positively associated with multivariate adjusted standardized mean differences in cognitive scores among children 0e23 months old, and, to a lesser extent, among children ages two and older (Sudfeld et al., 2015). Due to differences in how psychosocial developmentwas measured and the small number of studies included, generalized findings about the association between HAZ and psychosocial development could not be established. Detailed information and findings from other cross-sectional studies included in this review are presented inWeb Tables 4A-C (Abubakar et al., 2008; Avan et al., 2010; Bogale et al., 2013; Crookston et al., 2011; Fernald et al., 2006; Handal et al., 2007; Kariger et al., 2005; Ketema et al., 2003; Kordas et al., 2004; Kuklina et al., 2006; Mohd Nasir et al., 2012; Olney et al., 2007, 2009; Siegel et al., 2005; Taneja et al., 2005). Overall, these studies show a positive relationship between child height and child development. There are two critical limitations to cross-sectional studies. First, they only capture the relationship between stunting and child development at one time point. Thus, they are not able to ascertain whether changes in stunting affect changes in development status, nor can they provide any indication as to whether stunting precedes, or occurs in tandem with, poor child development. Second, a third variable may influence both stunting and child development. If such a variable is not included in the analyses, then stunting and child development may appear linked even if they do not share a causal relationship.

4.2. Longitudinal observational studies

The same recent review study described above also reported positive prospective associations between HAZ at 3 years old or younger and gross motor scores at age 5-8 years and also between HAZ at two years old or younger and cognition at age 5-11 years (Sudfeld et al., 2015). In addition, evidence across several studies suggested that stunting was associated with poor psychosocial development among children who were stunted at age 9-24 months. Associations from studies included in this review are shown in Web Tables 5A-C (Adair et al., 2013; Alberto Camargo-Figuera et al., 2014; Aubuchon-Endsley et al., 2011; Aurino and Burchi, 2014; Berkman et al., 2002; Casale et al., 2014; Chang et al., 2002, 2010; Cheung and Ashorn, 2010; Cheung et al., 2001, 2008; Crookston et al., 2013; Gardner et al., 1999; Hamadani et al., 2012, 2014; Kuklina et al., 2004, 2006; Lima et al., 2004; Mendez and Adair,1999; Nguyen et al., 2017; Niehaus et al., 2002; Pollitt et al., 1993; Sanchez, 2013; Walker et al., 2000, 2007a; Whaley et al., 1998; Yang et al., 2011). Most studies indicated an association between stunting or child height and child development across each of the developmental domains. The main limitation of these longitudinal studies is that they still cannot make claims of causality because analyses may not have adequately adjusted for critical confounding variables, such as various indicators of poverty.

4.3. Quasi-experimental studies

Quasi-experimental studies have provided some evidence that stunting causes cognitive impairments by using instrumental variables (e.g., rainfall or food price shocks) or natural experiments in the form of social welfare programs (e.g., the Protective Safety Nets Program, the National Rural Employment

Guarantee Scheme, or similar initiatives), which are not randomly implemented but are plausibly exogenous to stunting and cognitive status. Other quasi-experimental studies use data from siblings to account for unmeasured confounding at the household level. Most of these studies have found negative effects of stunting on cognitive development with varying effect sizes as seen inWeb Table 6 (Dercon and Porter, 2014; Glewwe et al., 2001; Glewwe and King, 2001; Leight et al., 2015; Outes-Leon et al., 2011; Umana-Aponte, 2011).

4.4. Experimental studies on social welfare

Some experimental studies assess how program-facilitated changes in nutritional status influence child development by studying the effects of social welfare programs that enroll participants randomly (Web Table 7). Two out of five studies included in this review found that improvements in cognitive development due to cash transfer programs were mediated by increases in height (Fernald et al., 2008, 2009a). In contrast, the other three studies indicated that cash transfers had no effect on height, but independently improved cognition (Fernald and Hidrobo, 2011; Macours et al., 2012; Paxson and Schady, 2010). Follow-up periods in these studies may not have been long enough, however, to observe changes in height or stunting status.

4.5. Experimental studies on nutrition supplementation

Four out of eight studies included in this review found improved motor development among children who received nutrition supplementation and only one out of five studies found psychosocial development benefits. In contrast, several studies included in this review found that early nutrition supplementation appeared to influence cognitive development (Web Tables 8A-C) (Chang et al., 2010; Frongillo et al., 2017; Gardner et al., 1999; Grantham- McGregor et al., 1991, 1996, 1997; Nahar et al., 2012; Pollitt et al., 1993, 1995, 1997; Prado et al., 2017; Vazir et al., 2012; Waber et al., 1981; Walker, 2006). However, a recent review of more than 20 studies of nutrition interventions in LMICs found few effects on cognitive development among children under two years (Aboud and Yousafzai, 2015; Larson and Yousafzai, 2017). Although some evidence suggests that supplementation improves developmental outcomes, there is substantial heterogeneity in the design of these studies. Moreover, the effects of supplementation may not be uniform and may instead depend on many factors which nonexperimental studies have been found to be relevant for child development, such as the timing and duration of the intervention (Martorell, 1995; Pollitt et al., 1995), child sex (Martorell, 1995; Waber et al., 1981) and socioeconomic status (Pollitt, 2009; Pollitt et al., 1993, 1995).

4.6. Interventions integrating nutrition supplementation and stimulation

As enhancing psychosocial stimulation among children impacts cognitive and language development among children under the age of 2 years in LMICs (Aboud and Yousafzai, 2015), there is a great interest in exploring the synergistic interaction between nutrition supplementation and stimulation on child development more broadly. Comprehensive summaries of existing studies on such integrated programs are provided in recent reviews (Black et al., 2015; Grantham-McGregor et al., 2014). In addition, one paper reviewed the implementation process of integrated nutrition and psychosocial stimulation (Yousafzai and Aboud, 2014) and a more recent study reviewed the benefits and challenges of implementing integrated interventions to address early childhood development and nutrition (Hurley et al., 2016). Of the ten studies reviewed here, three studies found that the combined treatment effects (i.e., nutrition supplementation and psychosocial stimulation) were significantly more effective for motor skills and cognitive development than was either treatment alone among children in Bangladesh (Nahar et al., 2012) and Jamaica (Grantham-McGregor et al., 1991). However, the additive effect of combined treatments was no longer significant four years after the end of the study in Jamaica (Grantham-McGregor et al., 1997). A more recent study in Jamaica found significant interactions between zinc supplementation and psychosocial stimulation on the development quotient (Gardner et al., 2005). Other studies found no interaction between the two interventions on stunting and child development (Web Table 9) (Aboud and Akhter, 2011; Chang et al., 2010; Gardner et al., 1999; Vazir et al., 2013; Walker et al., 2007a; Yousafzai et al., 2014).

4.7. Potential pathways

The associations between stunting and child development present in some of the papers we reviewed may be due to a variety of different processes linking the exposure and outcome. Although it is a nascent area of work, several studies suggest various mechanistic pathways, including neurological (Black, 1998; John et al., 2017; Lozoff, 2007; Vohr et al., 2017), hormonal (Berger, 2001; Le Roith, 1997; van Pareren et al., 2004), functional isolation (Grantham-McGregor et al., 2007), stress (Fernald and Grantham- McGregor, 1998; Soeters and Schols, 2009; Wachs et al., 2013), stigma (Currie and Vogl, 2013), and infectious disease related channels (Black et al., 2013; UNICEF, 2013; Walker et al., 2007b). The research to date, however, is often unclear on whether such factors act as mediators or as precursors to stunting. In addition, these pathways may dynamically interact with each other. For example, impaired motor development may mediate the relationships between stunting and cognitive development (Larson and Yousafzai, 2017). Stunted children with lower motor activity are more likely to be carried by caregivers, further handicapping motor development and inhibiting cognitive and psychosocial development attained through independent exploration of environments (Adolph et al., 2003; Kariger et al., 2005; Gardner et al., 1995; Olney et al., 2007; Siegel et al., 2005). Greater apathy as well as distress in stunted children (Grantham-McGregor,1995; Pollitt, 2000) increase the likelihood that caregivers treat stunted children as if they were younger, resulting in a lack of age-appropriate stimulation (Kuklina et al., 2004). Taking this evidence together, children's motor, psychosocial, and cognitive development occur in an interactive and dynamic manner with significant influence from their social environments (Wachs et al., 2013). The lack of study designs permitting rigorous mechanistic assessment, however, prohibits a definitive layout of a complete framework for pathways and mediators. Research on these pathways (as well as other potential mechanisms) is still in its early stages. Future work on causal pathways will be of particular interest to policy makers trying to identify and support interventions designed to improve child development.

4.8. Summary of evidence

We have reviewed findings from many types of studies examining the relationship between stunting and child development. Comparisons of findings from these studies are complicated by heterogeneity in the timing and frequency of measurement, the types of child development metrics used, and the age and composition of study populations. Moreover, the extent to which causal inference has been addressed varies significantly across studies. To provide credible insights into this relationship, future research needs to adequately adjust for any differences in socioeconomic status between stunted and non-stunted children given the strong link between poverty and stunting and between poverty and cognitive development.

5. Further questions about stunting and child development

5.1. Timing of nutrition interventions

Nutrition intervention effects on cognition may be greatest in the first two years of life (Pollitt et al., 1993). This claim is supported by findings from several observational studies (Pongcharoen et al., 2012; Sudfeld et al., 2015). However, it is difficult to draw strong conclusions on this issue, at least in respect to the pre- and postnatal periods, as some studies have found either no difference in associations between prenatal and postnatal linear growth and cognition (Yang et al., 2011), or that postnatal growth is more salient (Adair et al., 2013; Kuklina et al., 2004). Moreover, brain development continues into adulthood (Thompson and Nelson, 2001), with important periods of growth in adolescence and early adulthood (Isaacs and Oates, 2008; Wachs et al., 2013). Further, growth faltering can still happen after the first two years (Lundeen et al., 2013; Prentice et al., 2013), suggesting that children may also be vulnerable to impaired development later in later life (Crookston et al., 2011).

5.2. Long-run associations and the role of catch-up growth

Children who experience developmental impairments due to nutritional deprivation in the first 1000 days may be able to recover later on (Levitsky and Strupp, 1995; Strupp and Levitsky, 1995). A recent cross-country study suggested that sustained linear growth throughout childhood after early stunting may improve child cognition (Georgiadis et al., 2017). Another study found that linear growth after age 2 was associated with cognitive development at age 15 (partly mediated through education), but not by earlier growth (Teivaanmaki et al., 2017). However, the degree to which associations between early stunting and later cognition are mediated by later growth remains unclear. While some studies find that children who catch-up in growth are able to recover in development (Cheung and Ashorn, 2010; Crookston et al., 2010a, 2010b, 2013; Gandhi et al., 2011; Mendez and Adair, 1999), other work finds that catch-up growth does not help children recover cognitive deficits (Sokolovic et al., 2014). Moreover, there is no conclusive evidence about the best timing for catch-up growth (Cheung and Ashorn, 2010; Gandhi et al., 2011). Further research is required to resolve the ambiguity about critical windows for physical and cognitive development as well as the role of catch-up growth.

5.3. Differential effects on development domains

Many of the nutrition studies report improvements in cognitive development but no impact on gross or fine motor development or psychosocial development. Although it is possible that heterogeneous effects exist but differ by domain, current assessments for gross motor development, fine motor development and psychosocial development may not adequately reflect the positive impact of nutrition interventions. Alternatively, there may be ongoing interactions between domains not captured by analyses. Advanced statistical techniques such as structural equation models, which allow for an investigation into interactions between multiple determinants, may help illuminate the pathways by which different developmental domains influence one another and how nutritional status may directly or indirectly influence developmental outcomes. However, even these models cannot easily reveal causal links without appropriate data and strong assumptions about omitted confounders. Thus, rigorous experimental studies are needed to test how nutrition may differentially impact different domains of child development.

5.4. Integrating interventions

Child development occurs in a dynamic fashion in which children's characteristics interact with the social environment to influence their development. Therefore, the impact of integrated interventions may be stronger than any nutrition supplementation alone based on theoretical models (Alderman et al., 2014; Black et al., 2015; Christian et al., 2015; DiGirolamo et al., 2014; Fernandez-Rao et al., 2013; Grantham-McGregor et al., 2014). Although evidence on synergy between nutrition and stimulation interventions is inconsistent and inconclusive, some data support the addition of stimulation to nutrition programs to improve child growth as well as developmental outcomes (Gardner et al., 2005; Grantham-McGregor et al., 1997; Nahar et al., 2012). The absence of any major additive effect on child development outcomes in other studies (Aboud and Akhter, 2011; Chang et al., 2010; Gardner et al., 1999; Vazir et al., 2013; Walker et al., 2007a; Yousafzai et al., 2014) indicates that the scope of integrated interventions should expand beyond the current focus on combining macro- or micronutrient supplementation with psychosocial stimulation, and additionally implement other intervention components such as improved sanitation, hygiene, access to health care, and early learning programs. For example, a recent randomized study has begun to assess the combined impact of child development counseling, nutrition, and maternal mental health messaging on subsequent child development in Pakistan (Khan et al., 2017). Overall, there is a need for comprehensive evaluations of a variety of integrated programs, especially concerning long-term sustainability of benefits.

Despite inconsistent evidence on synergistic interaction between nutrition and stimulation on child development, simultaneous implementation of cross-functional policies and programs at the population level aimed at improving food security, reducing poverty and social inequalities, and improving maternal education has exhibited success in reducing undernutrition in some countries in South East Asia and Latin America (DiGirolamo et al., 2014). In addition, two recent reviews concluded that multi-sectoral approaches and integrated interventions combining nutrition, health, education, child protection, responsive parenting and social protection, are critical for building successful and sustainable interventions that will improve child development and increase human capital (Britto et al., 2016; Perez-Escamilla and Moran, 2017).

6. Discussion

Stunting and child development are major development foci, which are often studied and targeted as separate issues (Berkman et al., 2002; Casale et al., 2014; Grantham-McGregor et al., 2007). Recent reviews based on observational studies, however, have suggested that there is a positive relationship between linear growth and several domains of child development and that promoting early child nutrition will improve child development (Miller et al., 2015; Sudfeld et al., 2015). Building on that initial body of work, this review presents an updated multi-disciplinary perspective on the relationship between stunting and child development for children under five years of age in LMICs by reviewing evidence from a range of study designs and populations and integrating work across the fields of nutrition, social science and public health. We summarize the current state of the literature for researchers and organizations who are newer to this area of work, and discuss challenges in research measurement and interpretation with a focus on three salient findings.

First, our critical analysis of studies from across multiple disciplines finds that there is considerable heterogeneity in the methodology used to examine the relationship between child stunting and child development. On the one hand, such heterogeneity makes comparisons of study findings difficult. Any attempt to quantitatively pool current evidence on the association between stunting and child development must be carefully interpreted and the results critically questioned. Creating a harmonized way to measure and evaluate the relationship between stunting and child development would be a helpful solution to this issue. Initiatives such as Young Lives and the Consortium of Health-Orientated Research in Transitioning Societies (COHORTS) have attempted to do so by establishing birth cohorts in different countries (Barnett et al., 2013; Richter et al., 2012). These studies use similar measures and study designs, and assess children at similar intervals.

Findings could be used to provide global, cross-comparative evidence of the links between stunting and child development. Such harmonization, however, is nearly impossible for many of the existing studies. On the other hand, consistent results arising from different studies using heterogeneous measures help to show the relevance of stunting to child developmental domains across diverse populations.

Second, although there is evidence that stunting is plausibly linked to poor developmental outcomes among children despite variability in study design and outcome measures, critical questions remain. For example, which domains of child development are more affected and at what ages? What are the mechanisms linking stunting and development? How do the various domains of child development influence one another in the pathway between stunting and development? Can the effects of stunting be reversed? Such gaps in knowledge necessitate a level of caution before drawing general conclusions about the relationship between stunting and child development. Further research using rigorous study designs will push forward our understanding of these critical questions about the formation of human capital.

Finally, improving multiple aspects of the early life environment that are critical for child development may have synergistic or additive effects. Further research is needed on integrated nutrition programs (e.g., programs addressing nutrition and psychosocial stimulation) to evaluate how they affect child development, particularly in the long run. In addition, efforts to improve gross motor and fine motor development, cognition, and psychosocial development should not necessarily be limited to the narrow period of pre- and early-postnatal life. Much remains uncertain and unknown about what happens beyond this period, particularly surrounding the potential for, and consequences of, catch-up growth. Thus, there may be opportunities to intervene on the stunting-child development relationship at later ages. In summary, the complex relationship between stunting and different child development domains presents critical opportunities for testing and scaling up proven interventions to target multiple, interacting factors during childhood.

Questions remain about how markers of linear growth/stunting and child development are used. The literature tends to think of one (i.e., height) (Perkins et al., 2016) as an exposure and another (i.e., child development) as an outcome (Walker et al., 2011). However, child development is a process that incorporates multiple domains, which may co-occur or influence each other. Further, child development is both a function of physical inputs partially captured by anthropometry and other markers, and a function of stimulation independent of any physical factors, with the plasticity of the brain being particularly important. In addition, both linear growth and child development are influenced by a common set of factors. Thus, to a certain extent, the association between linear growth and child development could reflect co-varying variables as opposed to one being a cause of the other. Finally, if height is an exposure by itself for child development, then the mechanistic pathways remain understudied.

Across the world, international organizations, national governments and non-governmental organizations recognize the importance of reducing the global burden of stunting on child health and wellbeing. Further, the Sustainable Development Goals endorsed the World Health Assembly's target of reducing the number of stunted children globally by 40% by 2025 (UN, 2015). In addition to this focus on prevention, it is also important to think about the children who are already stunted and who may be at risk of, or are already experiencing, poor development in at least one domain. What is the modifiable quantity of interest in relation to stunting and child development if much of stunting cannot be reversed? The more than 156 million children who are already stunted should not be forgotten in research or by intervention targets. Instead, the field needs to think in terms of a variety of interventions, ranging from nutrition interventions that target improvements in cognition (and include anthropometric indicators as measurable outcomes) to direct stimulation interventions to some combination of interventions. Moreover, if interventions are able to address the etiologies of stunting and other determinants of poor child development (e.g., poor child stimulation or poverty) simultaneously, they are likely to be more effective in addressing developmental deficits in young children compared to child development interventions focusing solely on educational outcomes, for example.

7. Conclusion

Although the literature provides support for the impact of stunting on cognitive development, schooling and learning outcomes, the evidence on whether stunting leads to deficits in motor and psychosocial development is variable. The considerable heterogeneity across research studies in study design, targeted populations, assessment tools, and outcome measures, may be responsible, at least in part, for producing this variability in results. Further testing of the specific mechanisms by which stunting may influence child development and the ways in which various domains of child development influence one another is needed. Randomized controlled trials with multifactorial designs that allow for the testing of both singular and additive effects of different intervention components would help to draw more definitive conclusions about the impact of stunting and nutrition on child development. Given that nearly 40% of children under age five suffer from loss of developmental potential, for which stunting is one of the key risk factors, reductions in stunting could have tremendous implications for child development and human capital formation, particularly in LMICs. Programs targeting child development for children who are already stunted should also be a focus of ongoing research and intervention.

Web Table 1. Child development: measures of gross motor and fine motor skills.

Measure	Domains	Age of administration
Beery scale	Visual-motor integration	2-18 years
Lafayette Grooved Pegboard Test	Fine motor skills	5-18 years
Bruninks–Oseretsky Test of Motor Proficiency	Fine motor skills	4-18 years
Neurological Examination of Soft Signs	Hyperactivity, Attention Deficit Hyperactivity Disorder	5-18 years
Edinburgh Handedness Inventory	Handedness	3-12 years
Gardner Steadiness Test	Hyperactivity, attention deficits, motor persistence, motor coordination	4-18 years
Purdue Pegboard	Dexterity, bimanual coordination	5-18 years
Kilifi Developmental Inventory	Locomotor skills, eye-hand coordination	6-35 months
Movement Assessment Battery	Motor impairment	3-16 years

Web Table 2. Child development: psychosocial measures.

Measure	Domains	Age of administration	Administered to
Brazelton Neonatal Behavioral Assessment Scale	Behavior, reflex	0-2 months	Child
Rutter Teacher and Parent Scales	Conduct difficulties, emotional difficulties, hyperactivity/inattention, prosocial behavior	11-12 years	Parent, teacher
How I Think about Myself questionnaire	Self-esteem	11-12 years onwards	Child
Manifest Anxiety (What I Think and Feel) Questionnaire	Anxiety	6-19 years	Child
Mood and Feelings Questionnaire	Depressive symptoms	8-18 years	Child, parent
Behavior and Activities Checklist	Antisocial behavior		Child
Conners' Parent Rating Scale	Cognitive problems/inattention, hyperactivity, oppositional behavior	6-18 years	Parent
Conners' Teacher Rating Scale	Cognitive problems/inattention, hyperactivity, oppositional behavior	6-18 years	Teacher
Richman Child Behavior Scale	Behavioral difficulties (eating problems, sleep disturbance, soiling, hyperactivity, lack of concentration, poor relationships, tempers, and fears)	3 years	Parent
Child Behavior Checklist	Children's competencies and problem behaviors	4-16 years	Parent
Strengths and Difficulties Questionnaire	Hyperactivity, conduct problems, emotional symptoms, peer problems and prosocial behavior	3-16 years	Child
Brazelton Neonatal Behavioral Assessment Scale	Behavior, reflex	0-2 months	Child
Rutter Teacher and Parent Scales	Conduct difficulties, emotional difficulties, hyperactivity/inattention, prosocial behavior	11-12 years	Parent, teacher
How I Think about Myself questionnaire	Self-esteem	11-12 years onwards	Child
Manifest Anxiety (What I Think and Feel) Questionnaire	Anxiety	6-19 years	Child
Mood and Feelings Questionnaire	Depressive symptoms	8-18 years	Child, parent

Web Table 3. Child development: cognitive tests and measures of learning/schooling outcomes

Measure	Domains	Age of administration
Individual cognitive domains		
Peabody Picture Vocabulary Test (4th ed)	Language comprehension	2 years +
Stroop test	Processing speed, attention and executive function, working memory, and cognitive development	2 years +
Multiple cognitive domains		
NEPSY (2nd ed)	Attention and executive functions, language and communication, sensorimotor, visuospatial, learning and memory, and social perception	12-16 years
Ages and Stages Questionnaire (3rd ed)	Communication, Gross motor, Fine motor, Problem-solving and Personal-social	1-66 months
Woodcock-Johnson (3rd ed)	Fluid intelligence, knowledge and comprehension, and processing speed	2 years +
Overall ability		
Bayley Scales of Infant Development (3rd ed)	Motor (fine and gross), language (receptive and expressive), cognitive, social-emotional, and adaptive behavior	1-42 months
Griffith's Mental Development Scales	Development quotient	0-8 years
Wechsler Intelligence Scales for Children - Revised (4th ed)	Verbal comprehension, perceptual reasoning, working memory, processing speed.	6-16 years
Wechsler Preschool and Primary Scale of Intelligence	Verbal skills, cognitive performance, processing speed, and general language	3-7 years
Kaufman's Assessment Battery for Children	Simultaneous processing, sequential, planning, learning, and knowledge	3-18 years
Ravens Progressive Matrices	Visual reasoning ability	6 months-17 years
Stanford Binet	Fluid reasoning, knowledge, quantitative reasoning, visual-spatial processing, and working memory	2 years +
British Ability Scales (3rd ed)	Verbal ability, non-verbal reasoning ability, spatial ability, and diagnostic scales for other cognitive functions	3-17 years

Cognitive Abilities Test	Verbal, Quantitative and Nonverbal.	6 months-17+ years
Tests for learning outcomes		
Test of Early Mathematical Ability (3rd ed)	Mathematics	3-18 years
Suffolk Reading Scales	Reading comprehension	6 months-17 years
Early Grade Reading Assessment	Basic skills for literacy acquisition in early grades including prereading skills such as listening comprehension	6-9 years
Wide Range Achievement Test	Arithmetic, spelling, and word reading	5+ years

Web Table 4A. Cross-Sectional Studies on Stunting and Gross Motor and Fine Motor Child Development

Citation	Country	Findings	Age of assessment	Measures	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?
(Abubakar et al., 2008)	Kenya	Correlation between HAZ and psychomotor scores was 0.29 (p-value <0.01).	24-35 months	Kilifi Developmental Inventory	No	No	Yes (maternal education)
(Kariger et al., 2005)	Zanzibar	1-SD increase in HAZ was associated with an odds ratio of 1.31 (95% CI: 0.90, 1.90; p=0.127) for crawling alone and 2.10 (95% CI: 1.68, 2.63; p<0.001) for walking alone	1-18 months	Crawling (for 1-6 moths); Walking (for 6-18 months); Milestone attainment (14 motor activities) for all	No	No	Yes (parental education)
(Olney et al., 2009)	Zanzibar	Correlations between LAZ and motor development: At 5-9 months - 0.12 (p=0.026); At 10-14 months - 0.30 (p<0.001); At 15-19 months - 0.41 (p<0.001). Correlations between LAZ and motor activity: At 5-9 months - 0.28 (p<0.001); At 10-14 months - 0.26 (p<0.001); At 15-19 months - 0.43 (p<0.001).	5-19 months	20 motor activities and 14 motor milestones	No	No	No
(Olney et al., 2007)	Zanzibar	1-SD change in LAZ was associated with a 0.034 increase in total motor activity score (p<0.001) and 0.65 percentage point increase in the percent of time spent in locomotion (p=0.003).	5-19 months	20 motor activities and 14 motor milestones	No	No	Yes (parental education)
(Siegel et al., 2005)	Nepal	1-SD increase in LAZ was associated with a 1.69 higher odds (p<0.01) of walking.	8-17 months	Walking	No	No	No
(Taneja et al., 2005)	India	1-SD increase in HAZ was associated with a 4.09 unit (95% CI: 3.02, 5.14; p<0.001) increase in PDI score.	12-18 months	BSID II (PDI)	No	No	Yes (maternal education)

Abbreviations: BSID: Bayley Scales of Infant Development. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. LAZ: length for age z-score. PDI: psychomotor development index. SD: Standard deviation. SE: Standard error.

Web Table 4B. Cross-Sectional Studies on Stunting and Psychosocial Child Development

Citation	Country	Findings	Age of assessment	Measures	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?
(Avan et al., 2010)	South Africa	Stunted children had a mean Richman score of 3.23 (SD: 2.11) while non-stunted children had a mean score of 2.80 (1.99) (p=0.039). (High = Better)	2 years	Richman Child Behavior Scale	No	No	Yes (maternal education)
(Handal et al., 2007)	Ecuador	At age 3-23 months, there were no significant differences in mean ASQ scores. At age 24-61 months, the mean ASQ problem-solving score among stunted children was 30.7 (SD: 13.3) and among non-stunted children was 34.1 (SD: 14.4).	3-61 months	ASQ	Yes (low birth weight)	No	Yes (parental education)

Abbreviations: ASQ: Ages and Stages Questionnaire. ADHD-DSM-IIIR-B: Attention-deficit hyperactivity disorder-Diagnosis and Statistical Manual-IIIR-B. BSID: Bayley Scales of Infant Development. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. LAZ: length for age z-score. PDI: psychomotor development index. SD: Standard deviation. SE: Standard error.

Web Table 4C. Cross-Sectional Studies on Stunting and Cognitive Child Development or Learning/Schooling Milestones

Citation	Country	Findings	Age of assessment	Measure	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?
(Ketema et al., 2003)	Ethiopia	1-unit increase in HAZ was significantly associated with increases cognitive z score by 0.296 (p<0.001).	6-42 months	BSID-II	No	No	No
(Kuklina et al., 2006)	Guatemala	1-SD increase in HAZ was associated with 1.71 unit (95% CI: 1.00 to 2.43) increase in MDI for 6 months, 2.82 unit (95% CI: 1.67 to 3.98) increase for 24 months, and 1.82 unit (95% CI, 0.88 to 2.75) increase for 36 months	6, 24, 36 months	BSID-II	Yes (gestational age)	No	Yes (maternal education)
(Taneja et al., 2005)	India	1-SD increase in HAZ was associated with a 1.82 unit (95% CI: 1.01 to 2.63) increase in MDI score.	12-18 months	BSID-II	No	No	Yes (maternal education)
(Bogale et al., 2013)	Ethiopia	Correlation between HAZ and working memory was 0.426 (p < 0.001) and for visual processing it was 0.422 (p<0.001).	5 years	KABC-III	No	No	Yes (maternal education only for visual processing)
(Crookston et al., 2011)	Peru	1-SD increase in HAZ was associated with 0.03 point (95% CI: -0.09 to 0.14) increase in CDA score for 6-18 months, and 0.15 point (95% CI: 0.02 to 0.28) increase in CDA for 4-5 years. For PPVT, 1-SD increase in HAZ associated with 0.20 point (95% CI: -0.59 to 0.99) and 2.23 point (95% CI: 1.29 to 3.17) increases in cognition at ages 6-18 months and 4-5 years, respectively.	6-18 months, 4-5 years	PPVT, Cognitive Development Assessment	No	No	Yes (maternal education)
(Mohd Nasir et al., 2012)	Malaysia	1-SD increase in HAZ was associated with 1.43 increase in RCPM score (p <0.001).	4-6 years (72.5% were 4-5 years)	RCPM	No	No	Yes (maternal and paternal education)
(Fernald et al., 2006)	Mexico	Both HAZ and age-adjusted MDI score declined across the second year of life. Scores were also lower than US standards for older children, even after controlling for socio-economic status and parental characteristics. At 13–14 months, 3% of children received less than 2 SD below median MDI scores. By 19–20 months, nearly 17% of children were 2 SD or more below. The association between HAZ and MDI was not tested.	1-2 years	BSID-II	No	No	Yes (maternal and paternal education)

Abbreviations: BSID: Bayley Scales of Infant Development (2nd version). CAT: Cognitive Abilities Test. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. KABC-III: Kaufman Assessment Battery for Children (3rd version). LAZ: length for age z-score. NEPSY: A Developmental NEuroPSYchological Assessment. PPVT: Peabody Picture Vocabulary Test. RPM: Raven's Progressive Matrices. RCPM: Raven's Colored Progressive Matrices. SD: Standard deviation. SE: Standard error. MDI: Mental development index

Web Table 5A. Longitudinal Studies on Stunting and Gross Motor and Fine Motor Child Development

Citation	Country	Findings	Age stunting assessed	Age outcome assessed	Measures	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?
(Susan M Chang et al., 2010)	Jamaica	RSCM scores were lower in the stunted group than in the non-stunted group (p=0.01), but differences in dexterity were not significant (p=0.18) after adjusting for social background. Among stunted children, the RSCM score was significantly associated with IQ (p=0.04) and school achievement (all p<0.05).	9-24 months	11-12 years	Grooved Pegboard, Bruininks–Oseretsky Test of Motor Proficiency, Neurological Examination of Soft Signs, Finger tap	No	No	Yes (maternal education and IQ using PPVT)
(Cheung et al., 2001)	Pakistan	Correlation between HAZ and age at walking was -0.12 (p <0.05). Stunting was inversely associated with age at which independent walking started (Time ratio=0.96; p<0.05)	At birth	0-6 months	Denver Developmental Screening	Yes (birth weight/ length)	No	Yes (maternal education)
(Cheung et al., 2008)	Malawi	1-SD increase in HAZ was associated with 0.28 z-score increase in both gross motor and fine motor (p<0.01).	36 months	3-6 years	Test of developmental milestones	No	No	No
(Hamadani et al., 2012)	Bangladesh	Correlation between HAZ at 15 months and: Sits alone: -0.18 (p <0.01); Pulls self to stand: -0.15 (p <0.01); Stands assisted: -0.18 (p<0.01); Walks assisted: -0.22 (p<0.01); Stands alone: -0.25 (p<0.01); Walks alone: -0.27 (p<0.01).	3-15 months	18, 64 months	BSID-II (PDI)	Yes (gestational age)	No	Yes (parental education)
(Kuklina et al., 2004)	Guatemala	1-SD increase in HAZ during the first year of life was associated with a 0.57 year (SE: 0.27) earlier age of walking (p<0.05).	1-15 months	10-24 months	17-milestone Gross Motor Development Scale, Walking	Yes (birth size)	No	Yes (maternal education)
(Kuklina et al., 2006)	Guatemala	1-SD increase in HAZ was associated with a 2.94 unit (95% CI: 1.12, 4.76) increase in PDI for 0-6 months; 5.5 (95% CI: 3.13, 6.97) for 0-24 months; and 5.04 (95% CI: 2.52, 7.57) for 6-24 months.	6-36 months	6-36 months	BSID-II (PDI)	Yes (gestational age)	No	Yes (maternal education)
(Lima et al., 2004)	Brazil	Children with HAZ < -1 had mean PDI score of 101.1 while those with HAZ ≥ -1 had mean PDI score of 106.2 (p<0.001).	From birth	12 months	BSID-I (PDI)	Yes (birth weight)	No	Yes (maternal education)

Abbreviations: BSID: Bayley Scales of Infant Development. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. PDI: psychomotor development index. RSCM: rapid sequential continuous movements. SD: Standard deviation. SE: Standard error. PPVT: Peabody Picture Vocabulary Test.

Web Table 5B. Longitudinal Studies on Stunting and Psychosocial Child Development

Citation	Country	Findings	Age stunting assessed	Age outcome assessed	Development Measures	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?	Household stimulation?
(Casale et al., 2014)	South Africa	No significant association was found between stunting and social maturity.	2 years	4 years	Vineland Social Maturity Scale	Yes (birth weight)	Yes (maternal height)	Yes (maternal education)	Yes
(Aubuchon-Endsley et al., 2011)	Ethiopia	At 6 months, LAZ was inversely correlated with both total duration of inattention (r=-0.21, p<0.05) and mean inattention (r=-0.25, p<0.05). At 9 months, there was no significant association between LAZ and inattention.	6 months	9 months	Laboratory Temperament Assessment Battery	No	No	Yes (maternal education)	No
(Cheung et al., 2008)	Malawi	1-SD increase in HAZ was associated with 0.20-SD (p<0.01) increase in social development z-score.	36 months	3-6 years	Test of developmental milestones	No	No	No	No
(Whaley et al., 1998)	Kenya	Correlation between HAZ between 0-6 months and sociability behavior was 0.26 (p-value<0.01).	0-6 months	6-30 months	BSID (MDI)	No	No	No	Yes
(Yang et al., 2011)	Belarus	Associations between length gain and psychosocial behavior were not significant after adjusting for potential confounders.	0-5 years	0-6.5 years	Strengths and Difficulties Questionnaire	Yes (birth weight)	Yes (maternal and paternal height and BMI)	Yes (parental education)	No
(Walker et al., 2007)	Jamaica	Stunted children reported significantly more anxiety (regression coefficient: 3.03; 95% CI: 0.99, 5.08) and depressive symptoms (0.37; 95% CI: 0.01, 0.72) and lower self-esteem (21.67; 95% CI: 20.38, 22.97) than non-stunted children and were reported by their parents to be more hyperactive (1.29; 95% CI: 0.12, 2.46).	9-24 months	17-18 years	How I Think About Myself Questionnaire, Manifest Anxiety Questionnaire, Short Mood and Feelings Questionnaire, Behavior and Activities Checklist, Conners' Parent Rating Scale	Yes (birth weight)	No	Yes (Maternal verbal intelligence by PPVT)	Yes

(S M Chang et al., 2002)	Jamaica	Stunted children had more conduct difficulties (beta= -0.087, p<0.05) than non-stunted children, but there were no other significant differences in behavior (i.e. emotional difficulties, hyperactivity/inattention, or prosocial behavior reported by either parent or teacher) between them.	9-24 months	11-12 years	Rutter Teacher and Parent Scales	No	No	Yes (maternal education and IQ using PPVT)	Yes
(Meeks Gardner et al., 1999)	Jamaica	Stunted children were less enthusiastic when exploring their environment (p<0.05) and showed happiness less frequently (p<0.05) than non-stunted children. The Child behavior factor score was significantly lower in the stunted children (p<0.01), which was also significantly associated with a mental age measure.	12-24 months	18-30 months	Griffiths' Mental Development Scales	Yes (birth weight)	No	Yes (maternal verbal intelligence by PPVT)	Yes

Abbreviations: BSID: Bayley Scales of Infant Development. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. LAZ: length for age z-score. MDI: Mental development index. PDI: psychomotor development index. PPVT: Peabody Picture Vocabulary Test. SD: Standard deviation. SE: Standard error. BMI: body mass index.

Web Table 5C. Longitudinal Studies on Stunting and Cognitive Child Development or Learning/Schooling Milestones

Citation	Country	Findings	Age stunting assessed	Age outcome assessed	Development Measures	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?
(S M Chang et al., 2002)	Jamaica	Stunted children had significantly lower scores in arithmetic (Beta: 4.79, p<0.001), spelling (Beta: 0.10, p<0.01), word reading (Beta: 0.84, p<0.001), and reading comprehension (Beta: 4.57, p<0.01) compared to the non-stunted children.	9 to 24 months	11-12 years	WRAT, Suffolk Reading Scales	No	No	Yes (maternal education and IQ using PPVT)
(Susan M Chang et al., 2010)	Jamaica	Stunted children had worse motor skills (RSCM), which were significantly related to arithmetic (Beta=-1.50; p=0.039), spelling (Beta:-0.06; p=0.006), word reading (Beta=-0.36, p=0.009), reading comprehension (-2.70; p=0.014), and IQ (Beta=-2.49; p=0.036)	9-24 months	11-12 years	WISC-R	No	No	Yes (maternal education and IQ using PPVT)
(Walker et al., 2000)	Jamaica	Stunting was associated with lower scores on several cognitive tests: (1) WISC-R/Full-Scale: 7.48 (SE: 2.08, p<0.001); (2) WISC-R/Performance: 7.17 (SE: 2.44, p<0.01); (3) WISC-R/Verbal: 6.93 (SE: 1.87, p<0.001); (4) RPM: 3.05 (SE: 0.91, p<0.001); (5) PPVT: 7.88 (SE: 2.78, p<0.01); (6) Analogies: 1.25 (SE: 0.53, p<0.05); and (7) Vocabulary: 3.94 (SE: 1.26, p<0.01).	9-24 months	11-12 years	WISC-R, RPM, PPVT, Stanford Binet, auditory working memory, digit span forwards, digit span backwards, visual-spatial memory, Corsi blocks, visual information processing, sustained attention, Stroop Test	No	No	Yes (maternal education and IQ using PPVT)
(Berkman et al., 2002)	Peru	Children severely stunted at age two scored 10 points lower on the WISC-R test (95% CI: -2.4, 17.5, p=0.011) compared to non- or not severely-stunted children.	Birth to 2 years	9 years	WISC-R	No	No	Yes (maternal and paternal education)
(Cheung & Ashorn, 2010)	Philippines	1-SD increase in HAZ was associated with a 0.24 unit (CI: 0.17-0.31, p<0.001) increase in cognition.	6-24 months	11 years	PNIT	No	No	Yes (maternal education)
(Hamadani et al., 2012)	Bangladesh	1-SD increase in HAZ was associated with 0.27 SD (SE: 0.082) increase in WPPSI IQ and 0.17 (p <0.001) increase in Bayley score.	15 months	18, 24 months	BSID-II; WPPSI, Movement Assessment Battery for Children	Yes (gestation al age)	No	Yes (parental education)
(Hamadani et al., 2014)	Bangladesh	1-SD increase in LAZ score between birth and 12 months and 12-24 months was associated with 0.13-SD (CI: 0.09- 0.17, p<0.001) and 0.11-SD (CI: 0.07- 0.14, p<0.001) increase in z scores for WPPSI, respectively. From 24-64 months, a 1-SD	Birth to 64 months	7, 18, 64 months	BSID-II; WPPSI	Yes (birth length)	Yes (maternal BMI)	Yes (maternal and paternal education)

		increase in LAZ was associated with 0.06-SD (CI: 0.02-0.1, p=0.002) increase in WPPSI score.						
(Niehaus et al., 2002)	Brazil	There was no significant association between HAZ and TONI-III score (R^2=0.27, p=0.13)	2 years	6-10 years	TONI-III, WISC-III, WRAT	Yes (birth weight)	No	Yes (maternal education)
(Pollitt et al., 1993)	Guatemala	1-SD increase in LAZ is associated with a standardized mean difference of 0.17-SD (SE: 0.06) in cognition.	2 years	4 years	Brazelton Neonatal Assessment, Composite Infant Scale and Preschool Battery	No	No	Yes (maternal education)
(Adair et al., 2013)	Brazil, Guatemala, India, Philippines, South Africa	1-SD increase in conditional height at 2 years was associated with 0.47 (95% CI: 0.39-0.56) more years of schooling. Faster linear growth at age 2 years was strongly associated with the risk of not completing secondary school (0.74; 95% CI: 0.67-0.78).	2 years	18-31 years	Years of schooling; Completing secondary school	Yes (gestation al age)	Yes (maternal height)	Yes (maternal education)
(Alberto Camargo-Figuera et al., 2014)	Brazil	Stunting at age one year was associated with double the odds of low IQ (less than 1 SD from the median standardized IQ) (95% CI: 1.6-2.5, p<0.0001). In the fully adjusted logistic model, HA deficit was associated with 1.3 (95% CI: 1.0-1.7, p=0.05) higher odds of low IQ	3months, 1 year, 6 years	6 years	WISC-III	Yes (low birth weight)	No	Yes (maternal education)
(Aurino & Burchi, 2014)	Ethiopia, India, Peru, Vietnam	1 SD increase in HAZ was associated with an increment of between 3 and 8 per cent of an SD in PPVT, and with an increase of between 5 and 10 percent and between 4 and 8 percent of a SD in CDA and Math scores, respectively.	6-18 months, 4-5 years	4-5 years, 7-8 years	PPVT, Cognitive Development Assessment, Mathematics test	No	No	Yes (household head education)
(Casale et al., 2014)	South Africa	Being stunted was associated with 2.41 (SE: 0.37, p<0.01) lower score on the R-DPDQ in unadjusted models and 0.18 lower score (SE: 0.36, p<0.01) in fully adjusted models.	2 years	5 years	Revised-Denver Prescreening Developmental Questionnaire (R-DPDQ)	Yes (birth weight)	Yes (maternal height)	Yes (maternal education)
(Crookston et al., 2013)	Ethiopia, India, Peru, Vietnam	Across all four countries, compared with never stunted children, • persistently stunted children had higher odds of being overage for grade (ORs ranging from 1.71-2.79); those who became stunted at age 8 had ORs of 1.35-2.40; and those who recovered from stunting by age 8 had ORs of 0.85-2.20 • persistently stunted children had 0.22-0.48 lower mathematics scores; those who recovered from stunting had 0.12-0.21lower scores; there was no	1 year, 7-8 years	7-8 years	Mathematics, reading comprehension, PPVT, overage for grade	No	No	Yes (maternal and paternal education)

		difference for children who became stunted at age 8. • persistently stunted children had 0.13–0.31 lower PPVT scores; those who became stunted had 0.07–0.24 lower scores; and those who recovered from stunting had 0.01-0.25 lower scores in PPVT. • persistently stunted children had 0.24–0.38 lower reading comprehension scores; those who became stunted had 0.05–0.37 lower scores; and those who recovered from stunting had 0.10-0.23 lower scores.						
(Mendez & Adair, 1999)	Philippines	At age 8 years, children with severe early stunting had mean cognitive scores 0.61 SD below the mean for non-stunted children (P <0.000). This was more than twice the shortfall in children with moderate stunting, whose mean scores were 0.25 SD lower than those of non-stunted children (P <0.001).	0-2 years	8-11 years	PNIT, English (reading comprehension) and Mathematics achievement tests (at age 11)	Yes (birth weight)	maternal height	Yes (maternal and paternal education)
(Sanchez, 2013)	Ethiopia, India, Peru, Vietnam	1-SD improvement in HAZ at 4 to 5 years tends to increase cognitive ability at 7 to 8 years by 9%, 15%, 11% and 11%, and increase cognitive ability during adolescence (14-15 years) by 6%, 9%, 17% and 7% in Peru, India, Vietnam and Ethiopia, respectively.	1-2, 4-5, and 7-8 years	7-8, 11-12, 14-15 years	PPVT, numeracy, math, reading comprehension	No	No	Yes (maternal education)

Abbreviations: BSID: Bayley Scales of Infant Development (2nd version). CAT: Cognitive Abilities Test. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. KABC-III: Kaufman Assessment Battery for Children (3rd version). LAZ: length for age z-score. NEPSY: A Developmental NEuroPSYchological Assessment. PPVT: Peabody Picture Vocabulary Test. PNIT: Philippines Non-Verbal IQ Test. RPM: Raven's Progressive Matrices. RCPM: Raven's Colored Progressive Matrices. RAVLT: Rey Auditory-Verbal Learning Test. SD: Standard deviation. SE: Standard error. WAIS: Wechsler Adult Intelligence Scale. WISC: Wechsler Intelligence Scale for Children. WISC-R: Wechsler Intelligence Scale for Children Revised. WPPSI: Wechsler Preschool and Primary Scale of Intelligence. WRAT: Wide Range Achievement Test. RSCM: rapid sequential continuous movements

Web Table 6. Quasi-experimental Studies on Stunting and Cognitive Child Development or Learning/Schooling Milestones

Citation	Country	Findings	Age stunting assessed	Age outcome assessed	Development Measures	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?	Method used
(Dercon & Porter, 2014)	Ethiopia	Children who were in utero during a famine or exposed to a famine within the first 36 months were 3.9 cm shorter. Exposure between 2-3 years of life was associated with a 2% lower likelihood of finishing primary school.	12-36 months	19-22 years	Completion of primary school	No	No	No	DD, IV, household fixed effects
(Umana-Aponte, 2011)	Uganda	Cohort exposed to famine in utero earned 0.364 fewer years of schooling, was 4.2% less likely to complete primary school, and was 3.1% less likely to be literate. With family fixed effects, children exposed to famine in utero were 7-10% less likely to ever attend school.	In utero to 5 years	10-14 years	Ever attending school, currently attending school, primary school completion, literacy	No	No	No	IV, family-fixed effects, sibling design
(Leight et al., 2015)	China	1-SD increase in rainfall in two periods in utero and in the first year led to 0.1–0.2 SD lower achievement in test scores at 9-12 years. There was little evidence of a significant impact of rainfall in the second year of life, when the coefficients varied in sign. There was also evidence that, over time, children exposed to adverse shocks catch up with their peers who did not experience any shocks. By the second wave of the survey, at which point the children were between 13 and 16 years old, the effect of shocks on cognitive skills was attenuated.	In utero to 16 years	9-12 years, 12-16 years, 17-21 years	General cognitive ability test, grade-specific Chinese and mathematics achievement tests, literacy or "life skills" tests	No	No	No	IV
(Outes-Leon et al., 2011)	Peru	1-SD increase in HAZ was associated with a 17.2 (SE: 7.9) to 20.7 (SE: 5.9) percent SD increase in PPVT score, depending on model specification.	6-18 months, 4-5 years, 7-8 years	6-18 months, 4-5 years, 7-8 years	PPVT	No	No	No	IV, Household fixed effects, sibling design

(Glewwe et al., 2001)	Philippines	1-SD increase in height was associated with improvement in the achievement test score by 5.0 (SE: 2.2) points.	4-5 years	8-11 years	Academic production function which is a sum of age of enrollment, time spent in school, and time not in school.	No	No	Yes (maternal education)	IV, Household fixed effects, sibling design
(Glewwe & King, 2001)	Philippines	From OLS models controlling for growth in various periods, one cm increase in height between age 0-12 months would increase IQ by 0.50 points (SE: 0.10) while growth from 12-24 months would increase IQ by 0.93 points (SE: 0.12). After using IVs, only growth during 12-24 months was significantly associated with IQ.	0-12 months, 12-24 months, 2-8 years	8 years	Philippines Non-Verbal Intelligence Test	Yes (birth weight)	Yes (maternal height)	Yes (maternal and paternal education)	IV

Abbreviations: BSID: Bayley Scales of Infant Development (2nd version). CAT: Cognitive Abilities Test. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. KABC-III: Kaufman Assessment Battery for Children (3rd version). LAZ: length for age z-score. NEPSY: A Developmental NEuroPSYchological Assessment. PPVT: Peabody Picture Vocabulary Test. PNIT: Philippines Non-Verbal IQ Test. RPM: Raven's Progressive Matrices. RCPM: Raven's Colored Progressive Matrices. RAVLT: Rey Auditory-Verbal Learning Test. SD: Standard deviation. SE: Standard error. WAIS: Wechsler Adult Intelligence Scale. WISC: Wechsler Intelligence Scale for Children. WISC-R: Wechsler Intelligence Scale for Children Revised. WPPSI: Wechsler Preschool and Primary Scale of Intelligence. WRAT: Wide Range Achievement Test.; OLS: Ordinary Least Square regression; DD: Difference in Difference; IV: Instrumental Variable

Web Table 7. Randomized Experimental Cash Transfer Programs and Cognitive Child Development or Learning/Schooling Milestones

Citation	Country	Findings	Age stunting assessed	Age outcome assessed	Development Measures	Adjusted for birth weight?	Adjusted for parental height?	Adjusted for parental education/IQ?
(Fernald et al., 2008)	Mexico	Receiving cash transfers led to a 0.20-SD (95% CI: 0.09-0.30) increase in HAZ, and 0.12 (95% CI: 0.04-0.19), 0.13 (95% CI: 0.07-0.19), 0.08 (95% CI: 0.01-0.14), and 0.18 (95% CI: 0.08-0.27) SD increases in long-term memory, short-term memory, visual integration, and receptive vocabulary respectively.	0-68 months	24-68 months	Woodcock-Munoz (Spanish version), PPVT (Spanish version),	No	No	Yes (maternal and paternal education)
(Fernald et al., 2009)	Mexico	Almost 10 years after the programme began, children who received cash transfers had a 0.03-SD (95% CI: 0.01-0.05) increase in HAZ and 0.73 (95% CI: 0.48-0.99) and 0.47 (95% CI: 0.19-0.74) SD increases in verbal and cognitive assessments, respectively.	0-2 years	8-10 years	WISC-R	No	No	Yes (maternal and paternal education)
(Fernald & Hidrobo, 2011)	Ecuador	Program receipt associated with 5.24 (CI: 1.28-9.20) increase in language skills score for rural children. There were no significant differences in height.	0-36 months	36 months or younger	Fundación MacArthur Inventorio del Desarrollo de Habilidades Comunicativas - Breve (IDHC-B), MacArthur-Bates Communicative Development Inventory (CDI) (Spanish/Short versions)	No	No	Yes (maternal education)
(Macours et al., 2012)	Nicaragua	Cash transfer program receipt (joint treatment) was associated with: 0.13 (SE: 0.06) and 0.17 (SE: 0.06) SD increases in the social and language components of the Denver test and a 0.22 SD (SE: 0.08) increase in PPVT score. There were no significant differences in height.	0-6 years	3-9 years	Denver Developmental Screening Test, PPVT (Spanish), short-term memory test	No	No	Yes (maternal and paternal education)
(Paxson & Schady, 2010)	Ecuador	Cash transfer program was on average associated with 5% SD increase in cognitive measures (vocabulary recognition, long-term memory, short-term memory, visual integration), with SE of 7%. There were no significant differences in height.	3-7 years (average age <5 yrs)	3-7 years	PPVT (Spanish), Woodcock-Johnson-Munoz	No	No	Yes (maternal education and PPVT)

Abbreviations: BSID: Bayley Scales of Infant Development (2nd version). CAT: Cognitive Abilities Test. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. KABC-III: Kaufman Assessment Battery for Children (3rd version). LAZ: length for age z-score. NEPSY: A Developmental NEuroPSYchological Assessment. PPVT: Peabody Picture Vocabulary Test. PNIT: Philippines Non-Verbal IQ Test. RPM: Raven's Progressive Matrices. RCPM: Raven's Colored Progressive Matrices. RAVLT: Rey Auditory-Verbal Learning Test. SD: Standard deviation. SE: Standard error. WAIS: Wechsler Adult Intelligence Scale. WISC: Wechsler Intelligence Scale for Children. WISC-R: Wechsler Intelligence Scale for Children Revised. WPPSI: Wechsler Preschool and Primary Scale of Intelligence. WRAT: Wide Range Achievement Test.

Web Table 8A. Nutrition Supplementation Intervention Studies on Stunting and Gross Motor and Fine Motor Child Development

Citation	Country	Findings	Age of enrollment	Age of assessment	Development measures
(Grantham-McGregor et al., 1991)	Jamaica	Supplementation (1 kg milk-based formula per week) was associated with a 6.6 unit (95% CI: 2.3; 10.9) increase in locomotor skills from enrollment to age 12 months and 12.4 units (5.4; 19.5) units from enrollment to 24 months.	9-24 months	12 months, 24 months	Griffith's Mental development Scale
(Grantham-McGregor et al., 1997)	Jamaica	Four years after the end of the two-year supplementation intervention (1 kg milk-based formula per week), there was only a very small global benefit of supplementation detected.	9-24 months	7-8 years	Digit span, Corsi blocks. Lafayette Grooved Pegboard Test
(Susan M Chang et al., 2010)	Jamaica	No significant differences in fine motor skills were observed due to supplementation (effect sizes in SDs: 0.08 for RSCM and 0.04 for dexterity).	9-24 months	11-12 years	Grooved Pegboard, Bruininks–Oseretsky Test of Motor Proficiency, Neurological Examination of Soft Signs, Finger tap
(Nahar et al., 2012)	Bangladesh	Food supplementation (distribution of cereal-based food packets (150–300 kcal/day) for 3 months) alone did not show a significant benefit in motor development or growth.	6-24 months	9-30 months	BSID-II (PDI)
(Waber et al., 1981)	Colombia	Food supplementation significantly improved locomotor skills ($F=15.9$, $p<0.001$) and hand-eye coordination ($F=7.25$, $p=0.008$).	3rd trimester-3years	3 years	Griffith's Mental development Scale
(Vazir et al., 2012)	India	There were no significant differences in the Motor Development Index among the three intervention groups, before and after adjusting for important covariates.	3 months	6, 9, 2, 15 months	BSID-II

Abbreviations: BSID: Bayley Scales of Infant Development. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. LAZ: length for age z-score. MDI: Mental development index. PDI: psychomotor development index. SD: Standard deviation. SE: Standard error.

Web Table 8B. Nutrition Supplementation Intervention Studies on Stunting and Psychosocial Child Development

Citation	Country	Findings	Age of enrollment	Age of assessment	Development measures
(Meeks Gardner et al., 1999)	Jamaica	Supplementation predicted mental age at 12 and 24 months after intervention enrollment, but had no significant effect on behavior.	12-24 months	18-30 months	Griffiths' Mental Development Scales
(Walker, 2006)	Jamaica	Sixteen years after the end of the two-year supplementation intervention (1 kg milk-based formula per week), there was no significant effect (F = 1.505, P = 0.17) on psychosocial functioning of stunted children.	9-24 months	17-18 years	How I Think About Myself Questionnaire, Short Mood and Feelings Questionnaire, Manifest Anxiety Questionnaire, Behavior and Activities Checklist, Conners' Parent Rating Scale
(Nahar et al., 2012)	Bangladesh	Food supplementation (distribution of cereal-based food packets (150–300 kcal/day) for 3 months) alone did not show a significant benefit in development or growth.	6-24 months	9-30 months	BSID-II (PDI)
(Waber et al., 1981)	Colombia	Nutritional supplementation improved behavior in the short-term but waned over time.	3rd trimester-3years	3 years	Griffith's Mental development Scale

Abbreviations: BSID: Bayley Scales of Infant Development. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. LAZ: length for age z-score. MDI: Mental development index. PDI: psychomotor development index. PPVT: Peabody Picture Vocabulary Test. SD: Standard deviation. SE: Standard error.

Web Table 8C. Nutrition Supplementation Intervention Studies on Stunting and Child Cognitive Development or Learning/Schooling Milestones

Citation	Country	Findings	Age of enrollment	Age of assessment	Development measures
(Grantham-McGregor et al., 1991)	Jamaica	Supplementation (1 kg milk-based formula per week) was associated with 3.4 unit (95% CI: 0.5, 6.3) increase in DQ from enrollment to 12 months and 6.1 units (95% CI: 2.9, 9.4) increase in DQ from enrollment to 24 months.	9-24 months	2 years	Griffith's Mental development Scale
(Grantham-McGregor et al., 1996)	Jamaica	Supplementation (1 kg of full cream milk per week), conditional on height gain in the first year, was associated with 1.91 unit increase in DQ ($p<0.01$) and significantly affected change in mental age ($p<0.001$).	9-24 months	2-4 years	Mental age, Development Quotient (DQ)
(Grantham-McGregor et al., 1997)	Jamaica	Four years after the end of the two-year supplementation intervention (1 kg milk-based formula per week), there was only a very small global benefit of supplementation detected.	9-24 months	7-8 years	WRAT, Stanford Binet, PPVT, RPM, Categorical fluency, Verbal analogies, Free recall, French learning test, Digit span, Corsi blocks. Lafayette Grooved Pegboard Test
(Walker, 2006)	Jamaica	Sixteen years after the end of the two-year supplementation intervention (1 kg milk-based formula per week), there was no significant effect on cognitive development outcomes.	9-24 months	17-18 years	WAIS, RPM, Corsi Blocks, Auditory working memory, PPVT, verbal analogies, reading tests, WRAT, school drop out
(Waber et al., 1981)	Colombia	Nutritional supplementation increased locomotor, personal-social, speech and language, hand-eye coordination, and performance skills as well as general IQ.	3rd trimester-3years	4-36 months	Griffith's Mental Development Tests, Corman-Escalona Einstein scale
(Pollitt et al., 1997)	Indonesia	Children who received three-month supplementation in the first 18 months performed better on working memory tests, but other cognitive outcomes were not significantly different from the control groups.	6-60 months	8 years	PPVT, information processing, word fluency, arithmetic test, working memory
(Pollitt et al., 1993)	Guatemala	Children who received Atole supplement had 4.58 higher scores on the motor component of the Composite Infant Scale at 24 months of age ($p<0.001$). They also had higher scores on the preschool battery between 4-5 years.	In utero to 3 years	2-6 years	Brazelton Neonatal Assessment, Composite Infant Scale and Preschool Battery
(Pollitt et al., 1995)	Guatemala	Children who received Atole supplement had: (1) Vocabulary: 22.35 ($p<0.001$); (2) Numeracy: 7.75 ($p<0.01$); (3) 8.57 ($p<0.01$); and (4) 20.05 ($p<0.001$) higher scores.	In utero to 3 years	13-19 years	Age of starting school, highest grade in primary school, tests of numeracy, literacy, general knowledge, two standardized educational achievement tests, RPM, tests of information processing

Abbreviations: BSID: Bayley Scales of Infant Development (2nd version). CAT: Cognitive Abilities Test. HAZ: height for age z-score. CI: confidence interval. DQ: Development quotient. IQ: Intelligence quotient. KABC-III: Kaufman Assessment Battery for Children (3rd version). LAZ: length for age z-score. NEPSY: A Developmental NEuroPSYchological Assessment. PPVT: Peabody Picture Vocabulary Test. PNIT: Philippines Non-Verbal IQ Test. RPM: Raven's Progressive Matrices. RCPM: Raven's Colored Progressive Matrices. RAVLT: Rey Auditory-Verbal Learning Test. SD: Standard deviation. SE: Standard error. WAIS: Wechsler Adult Intelligence Scale. WISC: Wechsler Intelligence Scale for Children. WISC-R: Wechsler Intelligence Scale for Children Revised. WPPSI: Wechsler Preschool and Primary Scale of Intelligence. WRAT: Wide Range Achievement Test.

Web Table 9. Synergistic Nutrition + Psychosocial Intervention Studies on Stunting and Child Development

Citation	Country	Findings	Age of enrollment	Age of assessment	Development measures
(Susan M Chang et al., 2010)	Jamaica	No significant interaction between the two interventions was observed for fine motor skills (effect sizes in SDs: 0.08 for RSCM and 0.04 for dexterity).	9-24 months	11-12 years	Grooved Pegboard, Bruininks–Oseretsky Test of Motor Proficiency, Neurological Examination of Soft Signs, Finger tap
(Nahar et al., 2012)	Bangladesh	- The combined intervention group had higher MDI compared to hospital control (mean difference=4.5; p=0.022) and clinic control groups (3.4; p=0.092). - The combined intervention group had higher PDI compared to hospital control (mean difference=4.8; p=0.031),clinic control groups (4.6; p=0.047) and food supplementation only group (6.3; p=0.003). - The combined intervention group had a 0.3 unit higher WAZ (p=0.011) and LAZ (p=0.048) compared with hospital control group.	6-24 months	9-30 months	BSID-II (PDI)
(Grantham-McGregor et al., 1991)	Jamaica	The treatment effects were additive, and combined interventions were significantly more effective than either alone. - The combined intervention group had 13.4 (95% CI: 8.8, 17.9) increase in DQ compared to the control group; 5.5 (95% CI: 0.8, 10.2) increase compared to stimulation only group; and 6.9 (95% CI: 2.3, 11.4) increase compared to supplementation only group. - The combined intervention group had 21.3 (95% CI: 11.9, 30.7) increase in locomotor skills compared to the control group; 9.6 (95% CI: 0.1, 19.3) increase compared to stimulation only group; and 9.0 (95% CI: 0.4, 18.5) increase compared to supplementation only group.	9-24 months	12 months, 24 months	Griffith's Mental development Scale
(Grantham-McGregor et al., 1997)	Jamaica	Four years after the end of the two-year program, there was no longer an additive effect of combined treatments.	9-24 months	7-8 years	Digit span, Corsi blocks. Lafayette Grooved Pegboard Test
(Walker et al., 2007)	Jamaica	Stimulation, but not supplementation, had significant benefits on psychological functioning. Hence, the supplement only group was combined with the control group.	9-24 months	17-18 years	How I Think About Myself Questionnaire, Manifest Anxiety Questionnaire, Short Mood and Feelings Questionnaire, Behavior and Activities Checklist, Conners' Parent Rating Scale
(Meeks Gardner et al., 1999)	Jamaica	The presence of intervention was not significant in either set of analyses. Hence the supplement only group, stimulation only group, and combined intervention group was grouped into a single stunted group.	12-24 months	18-30 months	Griffiths' Mental Development Scales

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