

Examining relations between performance on non-verbal executive function and verbal self-regulation tasks in demographically-diverse populations

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Authors' contributions

NBD, LC, EJEM, BR, OB, and CHL conceived of the ideas presented in the paper, NBD, LC, AA, VAD, FTKF, SG, KM, EJEM, BR, RACS, LGSS managed or collected data, MN, KR, KM, LC, EJEM, BR, OB processed or coded data, LC and OB analyzed the data, NBD, LC, EJEM, BR, OB, and CHL drafted, revised, and edited the manuscript, HED, FTKF, MGN, VAD, and EMTD revised and edited the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Conflict of interest disclosure

The authors have no conflict of interest to report.

Ethics approval statement

This study was reviewed and approved by the University of Texas at Austin Institutional Review Board (approval number 2017050101). This study conforms to Federal Policy for the Protection of Human Subjects ('Common Rule').

Research Highlights

The study examines relations between performance on non-verbal executive functioning and verbal self-regulation tasks across 8–13-year-old children in 4 diverse low- and middle-income countries.

Performance on the visuospatial working memory task (Knox Cube) and the visuospatial short-term memory (Beads) task are each separately associated with performance on the self-regulation task (HTKS).

We found evidence that visuospatial working memory and visuospatial short-term memory are distinct cognitive processes which each support the development of self-regulation.

Schooling effects were not significantly associated with self-regulation and did not moderate the association of short-term and working memory with self-regulation performance.

Abstract

Self-regulation is a widely studied construct, generally assumed to be cognitively supported by executive functions (EFs). There is a lack of clarity and consensus over the roles of specific components of EFs in self-regulation. The current study examines the relations between performance on a) a self-regulation task (Heads, Toes, Knees Shoulders Task) and b) two EF tasks (Knox Cube and Beads Tasks) that measure different components of updating: working memory and short-term memory, respectively. We compared 107 8- to 13-year-old children (64 females) across demographically-diverse populations in four low and middle-income countries, including: Tanna, Vanuatu; Keningau, Malaysia; Saltpond, Ghana; and Natal, Brazil. The communities we studied vary in market integration/urbanicity as well as level of access, structure, and quality of schooling. We found that performance on the visuospatial working memory task (Knox Cube) and the visuospatial short-term memory task (Beads) are each independently associated with performance on the self-regulation task, even when controlling for schooling and location effects. These effects were robust across demographically-diverse populations of children in low-and middle-income countries. We conclude that this study found evidence supporting visuospatial working memory and visuospatial short-term memory as distinct cognitive processes which each support the development of self-regulation.

Keywords: self-regulation, short-term memory, working memory, executive functions, cross-cultural psychology

Examining relations between performance on non-verbal executive function and verbal self-regulation tasks in demographically-diverse populations

Self-regulation refers to the effortful control and management of sustained actions towards a goal and related internal states (Doebel, 2020; Inzlicht et al., 2021). It consists of cognitive, emotional, and behavioral skills that are vital for healthy adaptation to stress, appropriate expression of thoughts and feelings, and the ability to achieve goals. Performance on self-regulation tasks is often related to academic achievement (Moffitt et al., 2011). Studies predominantly conducted with children from the U.S. found that self-regulation is strongly associated with school readiness in young children and their later academic success (Cameron Ponitz et al., 2009; Malanchini et al., 2019; McClelland & Cameron, 2011).

Executive functions (EFs) are widely understood to be the cognitive processes underlying self-regulatory behaviors (Diamond, 2013; Hofmann et al., 2012; Inzlicht et al., 2021). According to the Miyake et al. (2000) model, executive functions consist of at least three correlated cognitive components: *inhibition* of prepotent responses, *shifting* attention to flexibly adapt to the demands of a situation, and *updating* relevant information (i.e., working memory). Research on self-regulation and underlying EFs is not well integrated across the disciplines of psychology, neuroscience, cognitive science, and education (Inzlicht et al., 2020). This leaves a gap in our understanding of the cognitive mechanisms that help to account for variation in self-regulatory skills. Delineating cognitive mechanisms' general impact on self-regulatory skills is further complicated by the bias towards studying highly educated populations with almost universal access to similar formal education systems (Legare, 2019; Nielsen et al., 2017; Robson et al., 2020).

The objective of this study is to fill the gap between studies of self-regulation, which focus on associations with academic success, and studies of EF in cognitive science that focus on parsing out its

components based on discrete tasks. Although there is evidence that the early development of EF is correlated with academic scores (e.g., reading and mathematics; Malanchini et al., 2021), the relationship between the two may be bidirectional, with formal education also influencing the development of EF skills (Ritchie & Tucker-Drob, 2018). Here, we tested whether EF skills pertaining to *updating* were associated with self-regulation in eight to 13-year-old children across diverse populations that vary in amount of formal schooling. The following sections are organized around two main research questions: a) Is performance on updating (working and short-term memory) tasks and self-regulation tasks related in middle and late childhood? b) How does different exposure to formal education affect EF skills and self-regulation in children from demographically-diverse communities?

Is performance on updating (working and short-term memory) tasks and self-regulation tasks related?

Working memory is a specific executive function related to the *updating* component of self-regulation and refers to the capacity to retain information while manipulating it, while short-term memory simply involves the storage of information for a limited amount of time (Cowan, 2008). Short-term memory is related to working memory (Cowan, 2008; Unsworth & Engle, 2007), but the use of ‘working memory’ and ‘short-term memory’ are inconsistent across studies, ranging from being used interchangeably to constituting two completely separate constructs (Aben et al., 2012).

Here, we take the view that working memory consists of short-term memory plus additional processes, given that working memory tasks typically require a level of attentional control and processing for storage (Cowan, 2008; Unsworth & Engle, 2007). Cowan and colleagues (2006) argue that working memory tasks are more highly associated with cognitive outcomes because they do not allow for verbal encoding and rehearsal, thus requiring greater attention and processing demands (Cowan, 2008). Whether differentiated by definition or type of task operationalization, greater consensus on whether and how these constructs are related is needed. The exigency for definitional and

relational clarity extends to other EF components. This requires studying multiple theoretically-related tasks measuring different components of executive functioning to examine how they relate to each other (Best & Miller, 2010).

There are two challenges to understanding how these components of updating and working memory operate in relation to self-regulatory skills. The first is an incongruence in ages typically studied in self-regulation literature versus ages when executive function components are distinguishable. The second is the publication bias towards samples from the U.S. and other wealthy, English-speaking, countries, which have universal and compulsory access to formal education and high rates of literacy, thus confounding potential other factors associated with cognitive development. We discuss both challenges below and outline how we address them in our study in the subsequent sections.

EFs and self-regulation skills in middle and late childhood

Many studies on the development of self-regulation and EFs focus on early childhood, especially preschool-aged children, because rapid development occurs during these years (Best & Miller, 2010; Lan et al., 2011; Legare et al., 2018). Literature on early childhood frequently links EFs and self-regulation separately to outcomes like academic achievement (Duncan et al., 2007; McClelland and Cameron, 2011; Welsh et al., 2010). This literature often also assumes the general relationship and contribution of EFs to self-regulation and overlooks the potential explanatory value of specific EFs on self-regulation as an outcome itself. The executive functions that underlie self-regulation should be systematically studied in order to distinguish their potentially independent contributions to the development of self-regulation.

Research among demographically-diverse populations suggests that beyond early childhood, there is a steady increase in working memory, inhibition, and task switching (EFs) in middle and late childhood (Best et al., 2011; Engelhardt et al., 2015; Guerra et al., 2021; Holding et al., 2018; Lee et

al., 2013). EF research across childhood and adolescence suggests that they may become increasingly differentiated from early to late childhood. Research with preschool and early elementary school children claims that executive functions are indistinguishable from one another (Fuhs & Day, 2011; Willoughby et al., 2012; Wiebe et al., 2008), forming a single general factor, whereas the evidence from later childhood and adolescence indicates that EFs are best characterized by separate, albeit correlated, factors (Engelhart et al., 2015; Hartung et al. 2020; Lee et al., 2013).

The development of visuospatial, working, and short-term memory components has shown similar trajectories among 4- to 6-year-old children (Alloway et al., 2006) and support a general-domain model of working memory (Baddeley, 2001) and "common EF factor" theories (Engelhardt et al., 2015). The evidence above supports a 'unity' model of general EF in early childhood and a 'diversity' model that distinguishes the EF factors from middle childhood until adulthood (Engelhardt et al., 2015; Malanchini et al., 2021; Miyake & Friedman, 2012). Thus, one way to distinguish these executive functioning components more clearly is to extend investigations of EFs beyond early childhood and conduct more studies during middle childhood to adolescence, when EF components are separable. Similarly, this applies to the study of EF components' relations to other constructs, like self-regulation.

Does formal education impact the relationship between self-regulation and EF tasks in children from demographically-diverse communities?

Formal education has consistently been positively correlated with EFs (Cragg, & Gilmore, 2014; Lan et al. 2011; Wolf & McCoy, 2019) and self-regulation (Gestsdottir et al., 2014; Robson et al., 2020). Updating is associated with better performance in mathematics and reading (Follmer, 2017; Friso-van den Bos et al., 2013). The relationships among self-regulation, EFs, and formal education begs the question of whether formal education may also be driving this relationship. This question is particularly difficult to answer, given that nearly all previous research on EFs and their associations

with self-regulatory behavior is conducted in high-income countries with nearly universal access to quality education and educational resources (McClelland et al., 2015).

Formal education may be related to test performance via several potential mechanisms. First, aspects of educational experience that may be particularly salient in studying performance effects include children's familiarity with features of the testing conditions, which are similar to school tasks and exams; children with less schooling experience may have minimal familiarity with performance-based testing. For example, Zuilkowski et al., (2016) reviewed research on pictorial images, showing that children with greater familiarity with paper and pencil and bidimensional images perform better on cognitive tasks relying on those mediums compared to children who do not. They also found that six-year-old children, from low SES and low school attendance in Zambia, performed better using tests with tridimensional patterns. A potential explanation for this finding was that these Zambian children were less familiar with bidimensional objects (such as books) and more familiar with the materials provided in the tridimensional patterns (wire).

Second, formal education typically directly trains language development (spoken and written). Most cognitive tests rely on tasks that require the use of verbal skills, some of which are developed only when children learn to read and write (e.g., reading numbers in a digit span memory task). Even though the non-verbal tasks proposed here rely on minimal verbal input, verbal encoding of stimuli can still occur and has been found to influence performance, albeit less strongly than in similar verbal tasks (Kearney, 1970; Vecchi & Richardson, 2001). Third, formal education may have general effects on cognitive development beyond the skills directly trained, such as attentional control and perceptual skills, which underlie verbal and non-verbal cognitive performance. Therefore, the continuous sustained engagement with challenging material spanning multiple domains (e.g., reading, writing, mathematics) may have effects on brain development and core EFs responsible for the coordination and regulation of information (Ceci, 1991; Lövdén et al., 2010; Ritchie & Tucker-Drob, 2018).

The majority of EF assessments involve skills that are influenced by access to formal education (e.g., recalling lists, tracing patterns in paper sheets, selecting cards, and tracking letters and numbers) and SES (Guerra et al., 2021; Lawson et al., 2018; Legare et al., 2018; McClelland & Wanless, 2015; Rao et al., 2019), with these assessments being positively biased towards those with greater formal education access and higher SES. However, the influence of formal education on individuals from lower SES backgrounds may be confounded with the influence of other variables, such as nutrition and exposure to stressors in early life. Nutrition is related to SES and also has an important impact on cognitive and motor development, especially in low- and middle-income countries where children face greater exposure to several risk factors, including poverty and malnutrition (DiGirolamo et al., 2002; Grantham-Mcgregor et al., 2007; Poh et al., 2019; Sánchez, 2017; Segretin et al., 2016; Teh et al. 2020).

Non-verbal tests are often considered culturally-reduced or cultural-free tests because they do not involve verbal language or literacy. However, there is evidence that non-verbal skills are influenced by culture and formal education (Rosselli & Ardila, 2003). Lozano-Ruiz et al. (2021) warn against using normative samples to assess cross-cultural differences in cognitive skills. Using the Raven's Progressive Matrices, a non-verbal test widely used in children and often deemed "culturally-free", they found that Moroccan seven-, nine-, and eleven-year-old children had lower scores than the normative samples from the United Kingdom, Spain, and Oman. The authors concluded that these differences may be due to economics or quality of education. The impact of cultural and demographic variables, as opposed to superficial comparisons of scores, are critical to consider in cross-cultural studies.

Schooling, or formal education, is an element of culture (Rosselli & Ardila, 2003), and shapes cognitive development in unique ways. Dominant measures of cognitive testing are biased towards skills that either rely on Western models of parenting and formal education, such as non-conformity

(Clegg et al., 2017), abstract thinking, and rule-switching flexibility (a type of cognitive flexibility that requires mapping arbitrary symbols; Legare et al., 2018), while also using materials and protocols similar to Western educational environments. Because most published studies are limited to universally-educated populations that largely fail to capture wider global variation in formal education and other demographic variables, EF skills are difficult to disentangle from formal education, as they relate to self-regulatory outcomes (but see Morrison et al., 2010, for school cut-off designs, natural experiments that compare children of similar age but different school entry years in the same area).

Current Study

In this study, we provided examined the relations between performance on non-verbal executive functioning (visuospatial working memory and short-term memory) and verbal self-regulation tasks in eight- to 13-year-old children in four low- and middle-income countries (Brazil, Ghana, Malaysia, and Vanuatu). Sub-components of EF skills have more distinguishable developmental trajectories starting around middle childhood (Guerra et al., 2021), and self-regulation may correlate more strongly with working memory at the early stages of middle childhood (McClelland et al., 2015), thus we tested whether children of this age range would show a similar performance across different EF tasks tapping into updating.

Our first objective was to examine child participant performance on non-verbal visuospatial working memory and short-term memory tasks, the Knox Cube and Beads tasks respectively, and a verbal self-regulation task, the Head-Toes-Knees-Shoulders task (HTKS; Cameron Ponitz, et al., 2008). We were inspired by a series of studies conducted by McClelland and collaborators on self-regulation and school readiness in young children and academic performance in older children (Cameron Ponitz, et al., 2008; Cameron Ponitz, et al., 2009; McClelland, et al., 2014). Using McClelland et al.'s (2014) task that holistically tracks the development of several EF components, we investigate the association between updating and children's performance on this self-regulatory task. To our knowledge, this is the

first time the HTKS has been studied with children older than eight years and in communities from Brazil, Ghana, Malaysia, and Vanuatu. This study was thus also an initial assessment of the suitability of the HTKS for older children. Given that our study focuses on communities from low- and middle-income countries with developing or transitioning economies, we controlled for indirect effects of SES and nutrition on cognitive performance using Body Mass Index (BMI).

Our second objective was to examine the extent to which formal education drives the relationship between visuospatial working and short-term memory and self-regulation task performance. Since self-regulation is commonly assessed in relation to educational attainment, we investigated the impact of school exposure, as years of schooling, on the relationship between children's performance on EF and self-regulation tasks. Children in the communities we investigated all had some access to schooling, though the level of access and the school environments vary. We predicted that access to formal education (measured in years of schooling) would be associated with self-regulation performance and that this may mediate the relationship between self-regulation and visuospatial memory (working and short-term memory).

Because the cognitive processes measured by self-regulation and EF tasks are complex and not always defined with clear consensus, we aimed to gain a better understanding of the relationships between constructs these tasks measure and their usefulness in cross-cultural research.

Methods

Participants

Participants included 107 8- to 13-year-old children from four populations (Tanna, Vanuatu; Keningau, Malaysia; Saltpond, Ghana; and Natal, Brazil; see Tables 1 and 2 for characteristics of each community). This data was collected as part of a larger research project investigating the influence of culture and schooling on children's social learning and cognitive development.

Table 1. Participant sample details, including age, BMI, years of schooling, and compulsory start age of school.

Characteristic	Brazil, N = 30¹	Ghana, N = 31¹	Vanuatu, N = 20¹	Malaysia, N = 26¹
Sex				
female	17 (57%)	15 (48%)	11 (55%)	12 (46%)
male	13 (43%)	16 (52%)	9 (45%)	14 (54%)
Age	10.21 (0.94) 8.60 - 12.10	10.68 (1.18) 8.40 - 12.30	10.99 (1.16) 9.30 - 12.90	10.95 (1.14) 8.90 - 12.60
BMI	19.22 (3.83) 13.87 - 26.73	15.90 (2.48) 13.73 - 27.37	13.72 (3.72) 7.95 - 19.24	17.74 (4.31) 13.44 - 34.80
Years of Schooling	6.23 (1.04) 3.00 - 8.00	8.03 (1.38) 6.00 - 10.00	3.55 (1.99) 1.00 - 7.00	6.27 (2.63) 0.00 - 9.00
Compulsory school start age	4	4	Not compulsory	7

¹n (%); Mean (SD), Minimum - Maximum

Participants were recruited in local communities and schools by researchers and/or research assistants (hereafter, experimenters) from each country. All experimenters were instructed to select participants through simple or blocked randomization. The sites selected for this study were located in low- and middle-income countries and had different levels of access to formal education. Written informed consent was provided by the children's caregivers at sites where appropriate, and verbal consent was obtained otherwise. Verbal assent was provided by child participants. All participants and guardians gave their informed consent before their inclusion in the study. Ethical and local approvals varied by country. All sites were included in the ethical approval obtained from the University of Texas at Austin IRB (see the Supplemental Information for more detail on the local ethical procedure and approvals for each site). Ten additional participants were excluded due to incomplete data. Two of these participants were missing BMI data, and eight participants were missing years of schooling data. Six missing participants were from the Brazil fieldsite, three from the Vanuatu fieldsite, and one from the Ghana fieldsite.

Table 2. Characteristics of study location communities.

Location	Keningau (Malaysia)	Natal (Brazil)	Saltpond (Ghana)	Tanna (Vanuatu)
Population size	219,100	890,480	24,689	32,260
Ethnicity	86.1% Indigenous (Majority of Kadazan Dusun and Murut), 7.9% Chinese, 3.3% Malay	49.8% Pardo (various mixed ancestries), 44.3% White, 4.7% Black, 1.1% East Asian and 0.12% Natives or Indigenous	95.4% Akans (mainly Fante people)	>95% Ni-Vanuatu (native Melanesian)
Language	Bahasa Melayu (Malay) is the national language. Mother tongue is highly valued and practiced widely in the community.	Portuguese is the official language.	Primarily Fante, English (official language), and other Ghanaian languages.	Local languages are widely spoken, alongside Bislama, English, and French (official languages)
Economic information	Unemployment rate is 5.8%. Many residents are sole traders. Other public/private sector jobs include salesperson, waiter/waitress, clerk, and driver.	Unemployment rate is high: 13.8%. Various jobs in offices (government), tourism, industry, and business.	Mostly informal sector jobs (retail, fishing, farming), schools, and offices (government and municipal). High unemployment and underemployment.	Mainly subsistence-based agriculture and household sale of crops. Small amount of government and tourism-related employment.
Political information	Local, state, and federal government. Local and state officials are democratically elected.	Local, state, and federal government. All are democratically elected.	Local, regional, and national governments supplemented by traditional rulers who settle disputes and represent the community at ceremonies.	National government supplemented by authority of village chiefs in local communities.
Educational information	94.7% attend primary school, and 91% secondary school. Many schools are available, including private institutions and after-school tutoring. Some schools operate in shifts due to limited space. School funding comes from the state, but policies are overseen by the school district board.	96.3% attend primary and secondary school (6-14 years old). There are tax-funded (public) and private schools. School funding comes from all three levels of government.	Community contains a number of primary and junior primary schools, as well as two secondary schools. Nationally, 74% of children aged 6-11 years attend primary school. 75% literacy rate is for those aged 11 years and older.	68% school attendance by children, with only half attending beyond primary school. Schools are partially funded by government and religious organizations, and still developing in many areas.

Procedure

Participant recruitment and data collection took place in the local language of the communities. Participants completed three tasks, the HTKS Task, the Knox Cube Imitation Test, and the Stanford-Binet Beads Task, as a part of a larger battery, unrelated to those employed here, that were administered over several sessions. The HTKS Task was always administered before the Knox Cube Imitation Test and the Stanford-Binet Beads Task, with typically at least one day between sessions. Participant responses were coded by experimenters during the assessment, and all sessions were video-recorded so that they could be later reviewed.

All participants completed the study in a separate area on school premises, at home, or in a community setting. Background noise differed within and across sites due to the variability across testing locations. Background noise levels were coded from testing videos to be able to account for potential influence or disruption in children's performance during cognitive tests.

Verbal self-regulation task: Head-Toes-Knees-Shoulders

We used The Head-Toes-Knees-Shoulder (HTKS; Cameron Ponitz, et al., 2008; Cameron Ponitz, et al., 2009; McClelland, et al., 2014) task to measure self-regulation, similar to the North-American *Simon Says* game. In HTKS, children must touch a different part of the body than the one instructed (e.g., the child must touch their toes when instructed to touch their head). The task is made up of three parts, each gradually increasing in cognitive load (Cameron Ponitz et al., 2008, McClelland et al., 2014). The HTKS requires several cognitive and behavioral skills for correct execution: it requires attention to verbal instructions, rule memory, inhibition of the immediate impulse to touch the instructed body part, gross motor skills to perform the actions, and flexibility when the rules change in subsequent parts of the task.

The HTKS Task has been used reliably to evaluate 4-8-year-olds in highly educated, industrialized countries (e.g., U.S.: Lan et al., 2011; McClelland et al., 2015; Taiwan, China, and South

Korea: Lan et al., 2011; Wanless et al., 2011; Iceland, France, and Germany: Gestsdottir, et al., 2014). HTKS scores were correlated with EF measures and later academic achievement in demographically diverse U.S. samples (McClelland et al., 2014, 2015). Recently, a short version of the HTKS was adopted with a population of 60-year-old adults, demonstrating that in older adulthood performance on the HTKS correlates with measures of attention and inhibitory control (Cerino et al., 2019). In a four-wave longitudinal study with three- to five-year-old children, McClelland et al. (2014) found that HTKS scores were more strongly associated with inhibitory control and cognitive flexibility in early waves, and with working memory in later waves.

The HTKS (original protocol available upon request:

<https://health.oregonstate.edu/labs/kreadiness/measure>) takes approximately 5-15 minutes to complete. This task consists of three stages, each containing an introduction, practice, and testing phase. In the introduction, the experimenter demonstrated and asked the participant to touch a body part (e.g., the experimenter said, “touch your head” and touched their head). The demonstration could be repeated twice, and the experiment ended if the participant failed to reproduce the experimenter’s actions. In the practice phase, unlike in the introduction, the experimenter instructed the participant to touch a different body part from what is instructed (e.g., “If I say touch your head, you touch your toes”). The experimenter completed six practice trials in Part I and five practice trials in Parts II and III, with corrective feedback allowed up to three times. Finally, each testing phase consisted of ten trials, during which the experimenter continued reading prompts, without correction. Part I comprised two paired body parts (head and toes), whereby the participant should touch their toes when instructed to touch their head, and vice versa. Part II comprised four paired body parts (head, shoulders, knees, and toes), whereby the participant should touch their head when instructed to touch their toes, and vice versa, and should touch their knees when asked to touch their shoulders, and vice versa. Part III is the same as Part II, but with a rule change that paired different body parts: head and knees, shoulders and toes.

Responses received scores of 0, 1, or 2: touching the correctly paired body part (2 points), touching an incorrectly paired body part (0 points), or self-correcting, defined as reaching toward an incorrect body part before ending on the correct body part (1 point). If the participant scored less than 4 after any of the test phases, they did not proceed any further in the task. Scores could reach a maximum total of 60 points, 20 per test phase.

Nonverbal EF (updating) tasks: Knox Cube and Beads tasks

Data for these tasks was collected as part of a larger nonverbal cognitive battery (the Queensland Test of General Cognitive Capacity; McElwain & Kearney, 1970) that is a conglomeration of separate cognitive performance-based tasks that can be assessed together or separately. The properties of the entire battery will be investigated in another study. Administration required minimal verbal feedback, and the tasks involved an instructional or practice period to allow the participant to do example items and understand each task objective. Items in each subtask got progressively harder, and each subtask was stopped after the designated number of incorrect responses, after which the participant moved onto the subsequent subtask. In this study, we used a measure of visuospatial working memory, the Knox Cube Imitation Task, and a measure of visuospatial short-term memory, the Beads Task¹.

The Knox Cube task (Knox, 1914; Richardson, 2005) is a visuospatial working memory measure that requires behavioral imitation of tapped sequences on four cubes. The Knox Cube task is a performance-based alternative to assessing memory of verbal sequences (i.e., the digit span test), adding an important spatial location-processing component (Berch et al., 1998). The Knox Cube Imitation Test consisted of four black cubes attached to a white base and two loose cubes, which the

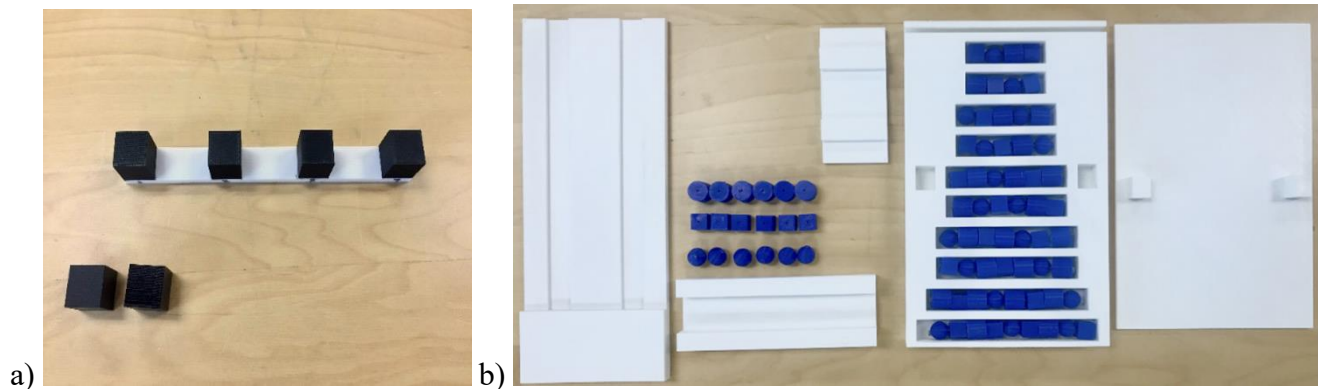
¹ The Knox Cube and the Beads tests are part of the Queensland Test (QT) of General Cognitive Capacity (McElwain & Kearney, 1970), a battery of five tasks, that were each adapted from a number of previous cognitive tasks developed in the early 1900s (see Ord, 1968, for an overview).

participant and experimenter used to tap sequences on the cube base (see Figure 1a). After the experimenter demonstrated a short sequence of taps, the participant was invited to copy the experimenter's actions. The task consisted of two practice trials at the start and in the middle of the task, along with 15 test items with sequence lengths ranging from four to seven blocks. The task was discontinued after three successive incorrect responses from the participant.

The Beads Test is based on the Bead Threading Test from the Stanford-Binet Intelligence Scales (Kearney, 1970, Pomplun & Custer, 2005). This nonverbal task relies on the re-creation of a sequence of three-dimensional beads with varying shapes. Previous literature on the Beads Test is relatively limited and somewhat outdated, but there is general consensus that the task measures visuospatial short-term memory (Drinkwater, 1976, 1978; Kearins, 1978, 1981; Kearney, 1970; though see Brown et al., 1993 and Pomplun & Custer, 2005, for more recent studies using the Beads task from Stanford-Binet). Past research revealed that increased contact with Europeans in Aboriginal Australian societies (Drinkwater 1976, 1978) and literacy skills (Kearney, 1970) both influence performance. The Beads Task improves upon previous similar tasks because it removed the problematic dexterity requirements in bead threading tasks and included provision of three-dimensional geometrical shapes instead of images, thereby reducing the apparent advantage towards Western-educated children with additional familiarity with two-dimensional images and texts.

For the Beads task (see Figure 1b), the participant was presented with a series of bead sequences, increasing in length from four to nine beads, which were viewed for five to 25 seconds (depending on the item) before the participant was asked to recreate the sequence using loose beads. After the participant indicated they were finished, the experimenter awarded a point if the sequence was accurate, then revealed the correct sequence. The participant was prompted to correct any incorrect beads in the sequence. The task consisted of two practice trials at the start of the task and 10 test items. The task was discontinued after three successive incorrect responses.

Figure 1a & 1b. Knox Cube Task (left) and Beads Task (right) stimuli.



Interview data

We collected information about schooling in short interviews with participants before or after the tasks were administered. Information collected on self-reported grade level were converted to years of formal schooling and used as a measure of education level.

Biometric Measurements

Basic biometrics measurements, including standing height and weight, were collected from participants at variable times during the study. Height and weight measurements were converted to Body Mass Indices (BMI) post-data collection, and are considered a rudimentary measure of health.

Coding and data processing

Each video task was coded to check for scoring accuracy and additional variables that may have impacted participant performance. Post-coding interrater reliability and additional information about the data checking process are reported in the Supplemental Information (Table Suppl).

Given that study settings varied between sites due to differences in accessibility, we examined whether background noise levels during the administration of the HTKS, Knox, and Beads Tasks had a significant effect on scores, and, if so, whether noise levels mediated site-level variance in scores.

Noise levels were coded as factors (0, 1, or 2) from video data post-data collection, with 0 = none, 1 =

consistent low volume noise or variable noise levels, and 2 = constant background noise (e.g., school playgrounds, animals, etc.).

Statistical analysis

Statistical analyses were done using R 4.0.4 (R Core Team, 2021) and the following packages: *car* (v3.0-10; Fox & Weisberg, 2019), *pwr* (Champely, 2020), *sjPlot* (v2.8.7; Lüdtke, 2021), and *MuMIn* (v1.43.17; Barton, 2020). One-way ANOVAs were run on demographic and cognitive measures to test for site-level differences, followed by Tukey's posthoc testing. Multiple linear regressions were used to estimate statistical relationships between Knox Cube, Beads Tasks, and additional variables on the HTKS Task. We focus on two models. The first includes all independent variables of interest: age, sex, BMI, location, years of schooling, Beads scores, and Knox Cube scores. We checked for issues of collinearity using VIFs and heteroscedasticity using the Breusch-Pagan Test (see residual graphs, Fig. Supp1). Second, we fit a fully exploratory model using a model-selection algorithm that finds the most parsimonious model defined as the fit with the lowest AICc. In addition to these two models, we fit other regressions that included different combinations of control variables, which are reported in the Supplementary Information (Table Supp 2-Supp7).

We first present descriptives of mean task scores and site-level variation in independent variables. Then, we describe correlational relationships between all study variables. Next, we compare results of multiple linear regressions and results of a fully exploratory model selection analysis, as well as results of a moderation analysis of education exposure. Finally, we present analyses exploring the potential effects of experimental variation in task environment and administration.

Sample size and effect size

A power analysis was calculated for the larger project that guided target sample sizes for each of the several fieldsites involved. This resulted in a target of about 120 children between the ages of 5 and 12 per site. However, this ideal target was often not feasible for researchers on our team due to

working in remote regions and with small populations. Additionally, in agreement with Gelman and Carlin (2014), we use power calculations with great caution (and some reluctance) because they have a flawed emphasis on statistical significance in the design of a study. That said, there needs to be an awareness that the present study is of the ‘small sample and noisy’ variety, provided we assume any measured effect sizes whereby HTKS scores as predicted by years in school or scores on the two focal tests (Knox or Beads) would be small in magnitude. For medium effect sizes, the present sample size is within the range of those recommended by conventional power analysis (arbitrary target power of 80%). However, available data is lacking from which to make an empirically informed expectation of effect sizes in this paper, except in the case of McClelland et al. (2014), which finds medium to large correlation effects between HTKS and several EF measures (i.e., Stroop, DCCS) in young children. Instead, we promote caution in interpreting the magnitude of estimated effect sizes (in this study in others), which can often be overestimated if studies have high error or small sample sizes (Gelman & Carlin, 2014).

Experimental variation across populations

We also evaluated the influence of experimental variation on the task scores. Experimental variation can be introduced by a number of issues within and outside of researcher control, particularly in the context of cross-cultural research. Those issues outside of a researcher’s control can include environmental factors and access to testing spaces, which can vary widely from site to site, and may affect things like external noise. Increased distractions such as these may be a particular concern for cognitive tasks, which require high levels of attention and mental workload. Attention levels and cognitive performance have been shown in some literature to decrease as environmental and background noise increases (Jafari et al., 2019; Klatte et al., 2013), and can cause mistakes and omission errors in short-term memory, but are also dependent on task complexity and noise type (Klatte et al., 2013). Here, we tested whether noise levels were associated with performance on both the Knox

Cube Task and Beads Task using one-way analysis of variance tests. We also accounted for potential variation in task administration for the HTKS Task, including variation in the number of practice trials prior to test sections. During the quality checking process, we discovered that for a little less than one-third of participants, experimenters repeated a practice item after a participant responded incorrectly, instead of moving onto the subsequent practice item. Although practice trials are not included in final task scoring, we also ran a linear model to determine whether a difference in the number of practice trials was associated with performance on the HTKS Task.

Results

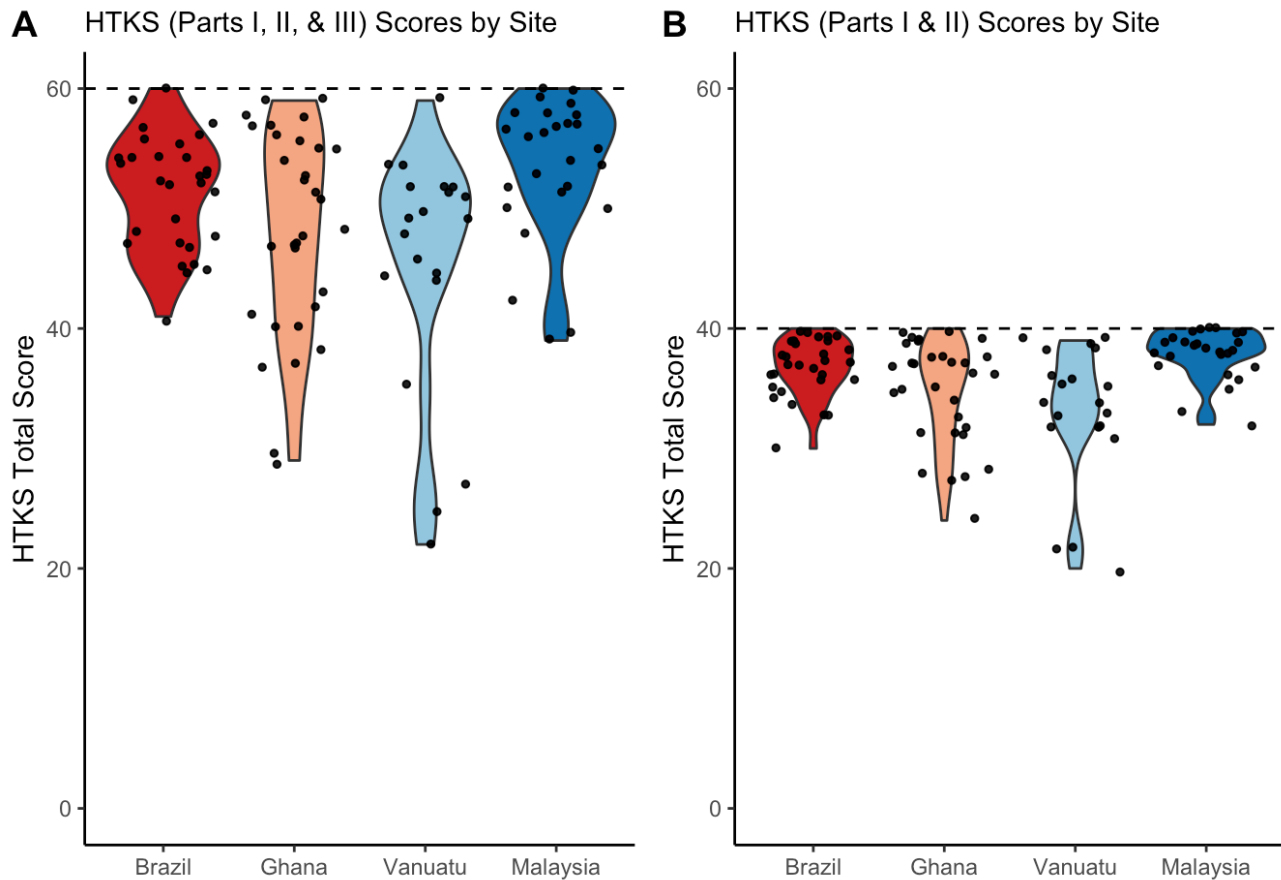
For each of our three main study tasks, we report the mean scores by site. The HTKS scores are presented as ‘HTKS I & II’, the sum of the scores from Parts I and II, and ‘HTKS all’, the sum of all three parts. The ‘HTKS all’ was used in all analyses, and the ‘HTKS I & II’ was only used for correlational analysis. Across all four sites, 8–13-year-old children scored differently across the three tasks (Table 3). Mean scores on HTKS indicated some participants may be near-ceiling (Figure 2), with an overall average score of 49.87 and a median score of 52 (out of 60).

Table 3. Scores on the HTKS, Knox Cube, and Beads Tasks by site.

Location	n	Mean HTKS all (SD)	Median HTKS all	Mean HTKS I & II (SD)	Mean Knox Cube (SD)	Mean Beads (SD)
Brazil	30	51.43(4.74)	52.5	36.80(2.35)	5.63(3.07)	3.90(2.60)
Ghana	31	48.13(8.55)	48	34.77(4.36)	6.16(2.71)	2.42(1.77)
Vanuatu	20	45.45(10.25)	49	33.00(5.64)	7.25(2.29)	2.10(2.22)
Malaysia	26	53.54(5.87)	55.5	37.92(2.10)	8.62(2.00)	4.27(2.20)
Overall	107	49.87(7.9)	52	35.78(4.1)	6.81(2.81)	3.22(2.36)

Note. The range of potential scores for each task are as follows: HTKS all, 0-60; HTKS I & II, 0-40; Knox Cube, 0-15; Beads, 0-10.

Figures 2a and 2b. Violin plots showing HTKS scores by study site. The dashed line represents the maximum possible score.



Site-level variation

We used one-way analyses of variance to describe site-level variation in each demographic and cognitive measure (Table 4). In each ANOVA, site was a categorical independent variable and posthoc Tukey's HSD tests were used to identify each significant comparison (Table 5).

Table 4. Results of five one-way ANOVAs for site-level differences in variables.

	One-way ANOVAs for site-level differences			
	<i>df</i> between	<i>df</i> within	F	<i>p</i> -value
BMI (m/kg²)	3	103	10.58	<.001

Age (years)	3	103	2.87	.039
Years of Schooling (years)	3	103	24.93	<.001
Knox Cube Score (z-scored)	3	103	7.09	<.001
Beads Score (z-scored)	3	103	5.94	<.001

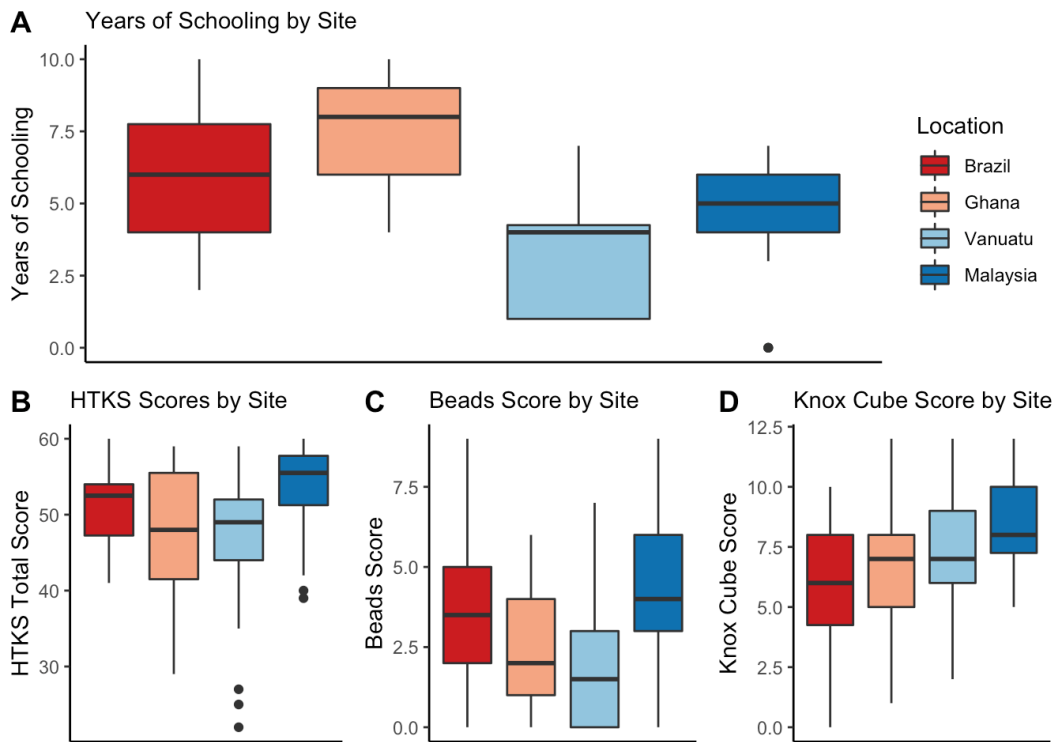
Table 5. Summary of Tukey's HSD posthoc tests for demographic and cognitive variables and location.

	Mean Differences and Significance (Tukey's HSD)				
	BMI (m/kg ²)	Age (years)	Years of Schooling (years)	Knox Cube Score (z-scored)	Beads Score (z-scored)
Ghana - Brazil	-3.32**	0.47	1.80**	0.19	-0.62
Vanuatu - Brazil	-5.49***	0.79	-2.68***	0.58	-0.76*
Malaysia - Brazil	-1.48	0.74	0.04	1.07***	-0.16
Vanuatu - Ghana	-2.18	0.31	-4.48***	0.39	0.13
Malaysia - Ghana	1.84	0.27	-1.76**	0.88**	0.78*
Malaysia - Vanuatu	4.01**	-0.05	2.72***	0.49	0.91**

Note. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Posthoc test results with Tukey's HSD revealed no significant age mean differences in demographics between sites. The difference in average BMI was significant between Ghana and Brazil, Vanuatu and Brazil, and Malaysia and Vanuatu. Posthoc testing revealed the most differences between sites for average years of schooling, which differed significantly between sites for all comparisons except Malaysia and Brazil (Table 5). Average years of schooling varied by location (Ghana: $M = 7.73$; Brazil: $M = 5.91$; Malaysia: $M = 4.38$; Vanuatu: $M = 3.55$; Figure 3a). For cognitive tests, mean Knox Cube scores in Malaysia were significantly higher than in Brazil and Ghana. Mean Beads scores were also significantly higher for Malaysia in comparison to Ghana and Vanuatu (Figure 3d). In addition, the mean difference between Brazil and Vanuatu on Beads task scores was significant (Figure 3c).

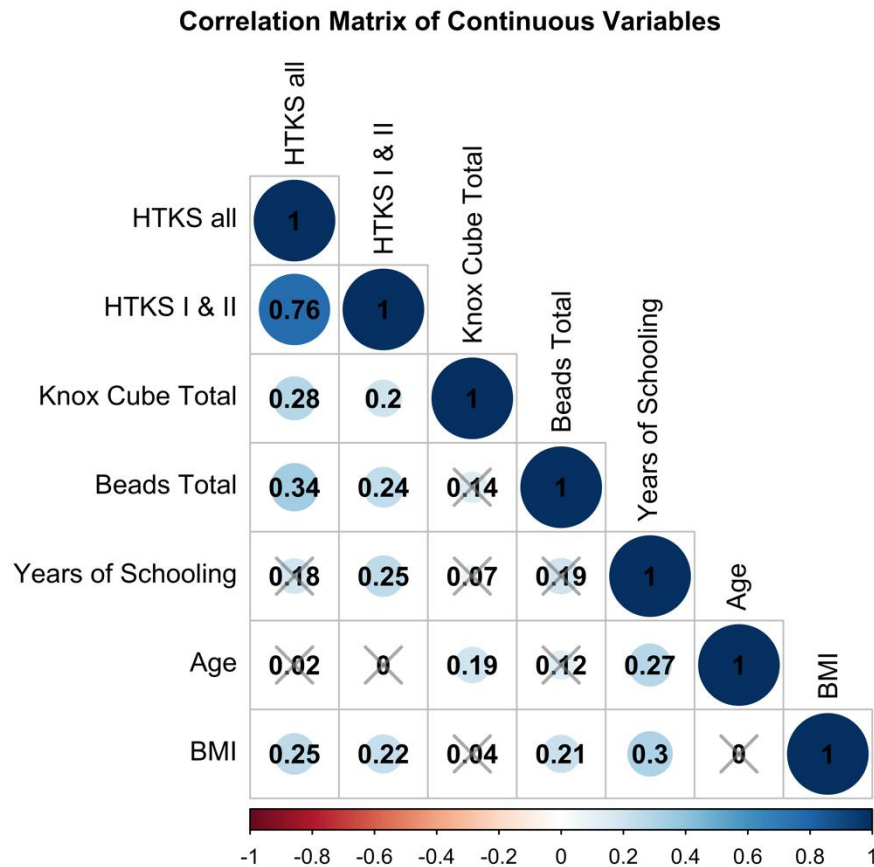
Figures 3a-d. Site-level distributions of years of schooling and task scores (HTKS, Knox Cube, and Beads).



Is there a relationship between HTKS performance and EFs (as measured by the Knox Cube and Beads Tasks) across all sites?

Figure 4 presents data on correlations between all numeric variables of interest. Both the HTKS scores were correlated with the Knox and Beads scores, though the Knox and Beads scores were more strongly correlated with all three HTKS parts. Unexpectedly, the executive function tasks (Knox Cube and Beads) were not significantly correlated together. Years of schooling correlated weakly with age, HTKS I & II, in addition to correlating moderately with BMI. Years of schooling did not correlate significantly with Knox Cube scores, Beads scores, or HTKS (three parts).

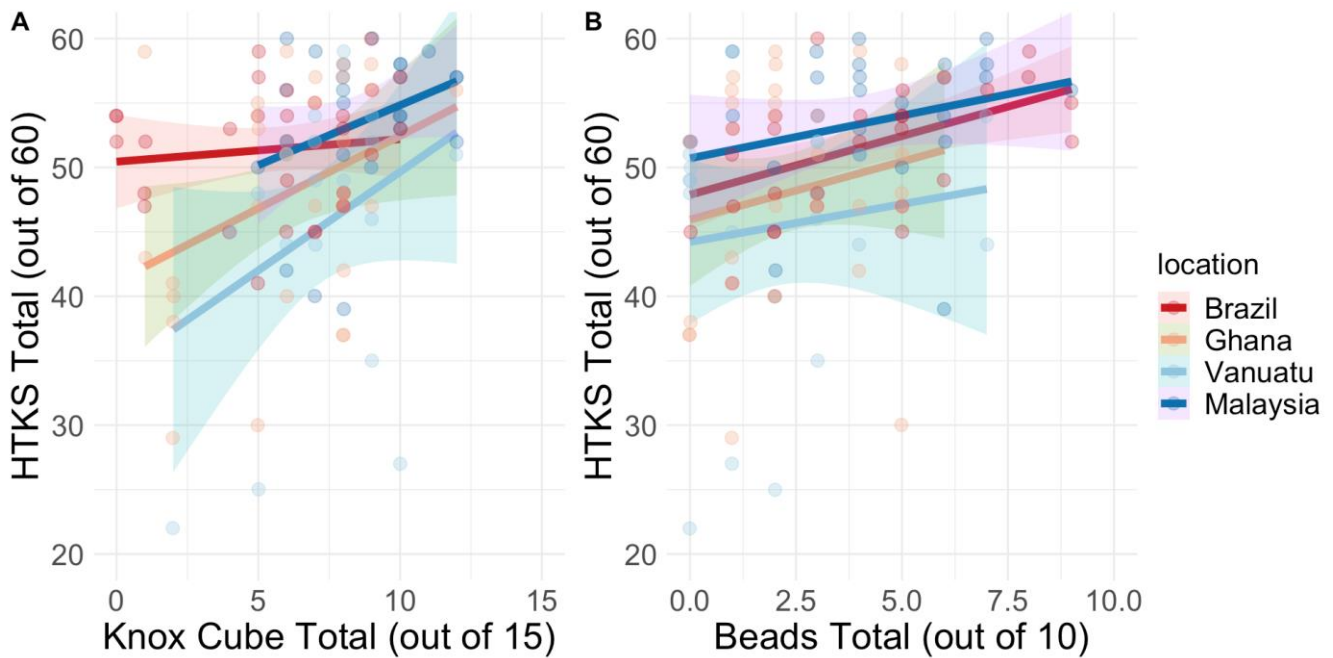
Figure 4. Pearson Correlations for HTKS, Knox Cube Task, and Beads Task scores.



Note. Non-significant correlations are indicated with ‘x’s.

The positive relationship between both the Knox Cube and Beads Tasks is also present on a site-level basis, for all locations. The plots show a clear positive trend for Knox Cube and HTKS scores, with similar slopes across sites, except for Brazil, which shows a much smaller increase in HTKS scores with improved Knox scores (Figure 5a). This positive trend is also present in the plot of Beads and HTKS scores (Figure 5b), with all sites showing very similar rates of increase.

Figures 5a and 5b. Scatterplots of Knox Cube and Beads scores against HTKS scores, respectively.



HTKS total score served as the response variable for the full regression model and included age, sex, BMI, years of schooling, location (categorical, Brazil as reference), standardized Knox Cube score, and standardized Beads score as predictors (Table 6). Model results indicated that only Knox Cube score ($\beta = 1.90, p = .03$) and Beads score ($\beta = 1.58, p = .03$) were statistically detectable sources of variation in HTKS score. For every one standard deviation increase in Knox Cube task scores, HTKS tasks scores increased by 1.88 points, on average. Every one standard deviation increase in Beads task scores was associated with an increase of 1.58 points on HTKS tasks scores, on average. Zero-order correlations and confidence intervals are included for comparison in Table 6.

The full model was checked for multicollinearity using the variance inflation factor (VIF). All VIF values were close to 1 (Table 4), so multicollinearity was determined not to be a problem. Results of a Breusch-Pagan Test indicated that heteroscedasticity was present in the model ($F(9) = 18.97, p = .03$), so standard errors, confidence intervals, and p-values are calculated using robust estimation (Table 6).

Table 6. Results of the full model of independent variables and HTKS scores.

<i>Variable</i>	HTKS				<i>VIF/ GVIF</i>	<i>Correlation with HTKS (r)</i>	<i>Correlation 95% CI</i>
	<i>Estimate</i>	<i>S.E.</i>	<i>95% CI</i>	<i>P-value</i>			
(Intercept)	51.29	1.30	48.70 – 53.88	<.001	-	-	-
Age	-0.27	0.79	-1.83 – 1.30	.733	1.17	-.02	-0.20 – 0.16
Sex: Male	0.06	1.49	-2.90 – 3.03	.966	1.01	-	-
BMI	0.15	0.23	-0.30 – 0.60	.520	1.19	.25**	0.07 – 0.42
Years of Schooling	0.20	0.45	-0.70 – 1.09	.664	1.56	.17	-0.02 – 0.35
Location: Ghana	-2.42	2.26	-6.91 – 2.08	.288	1.26 GVIF: 3.95	-	-
Location: Vanuatu	-4.34	2.75	-9.79 – 1.12	.118	-	-	-
Location: Malaysia	0.24	1.99	-3.71 – 4.19	.904	-	-	-
Beads Score (z-scored)	1.58	0.74	0.11 – 3.05	.036	1.12	.33**	0.16 – 0.49
Knox Cube Score (z-scored)	1.90	0.89	0.15 – 3.66	.034	1.13	.27***	0.09 – 0.43
Observations	107						
R² /	0.245 / 0.175						
R²adjusted							
AICc	739.59						

Note. Brazil is the reference for location. The model's S.E.s, CIs, and p-values are calculated based on robust estimation. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

We also used an exploratory model selection process to select the model with the lowest AICc across all possible model parameter combinations (MuMin package, v1.43.17; Bartoń, 2020). We started with a saturated model that includes all possible parameters among location, age, sex, BMI, Beads score, Knox Cubes score, and years of schooling, and then use a backward model selection procedure (Mantel 1970) to sequentially drops parameters as evaluated by AICc (Second-order Aikike

Information Criteria) (Burnham and Anderson 2002). It then iteratively removed model fits with the highest AICc values until converging upon the most parsimonious model with the lowest AICc. The resulting model retained only Knox Cube score, Beads score, and location ($F(5, 101) = 6.30, p < .001, R^2 = .20$, Table 7). Knox Cube score ($\beta = 1.98, p = .01$), Beads score ($\beta = 1.64, p = .03$), and location (Vanuatu; $\beta = -5.89, p = .008$) were significantly associated with HTKS scores in the model, reflecting broadly similar results to the full model. Slope estimates for Knox Cube and Beads task variables look similar to estimates in the full model, with every one standard deviation increase in Knox Cube task scores associated with an average increase on HTKS task scores by 1.98 points, and 1.64 points for the Beads task. Location (Vanuatu), was found to be significant in this model, however, despite not being a significant variable in the full model. Zero-order correlations and confidence intervals are included for comparison in Table 7. The ten most parsimonious models are included for reference in the Supplemental Information (Table Supp8).

Table 7. Best fit model of independent variables and HTKS scores.

<i>Variable</i>	HTKS						
	<i>Estimate</i>	<i>S.E.</i>	<i>95% CI</i>	<i>P-value</i>	<i>VIF</i> <i>/GVIF</i>	<i>Correlation</i> <i>(r)</i>	<i>Correlation</i> <i>95% CI</i>
(Intercept)	51.81	0.94	49.95 – 53.67	<0.001	-	-	-
Beads Score (z-scored)	1.63	0.65	0.33 – 2.93	.014	1.09	.33**	0.16 – 0.49
Knox Cube Score (z-scored)	2.00	0.84	0.34 – 3.66	.019	1.11	.27***	0.09 – 0.43
Location: Ghana	-2.66	1.82	-6.38 – 0.96	.148	1.06 GVIF: 1.41	-	-
Location: Vanuatu	-5.89	2.51	-10.86 – 0.92	.021	-	-	-
Location: Malaysia	-0.28	1.69	-3.62 – 3.07	.871	-	-	-
Observations	107						

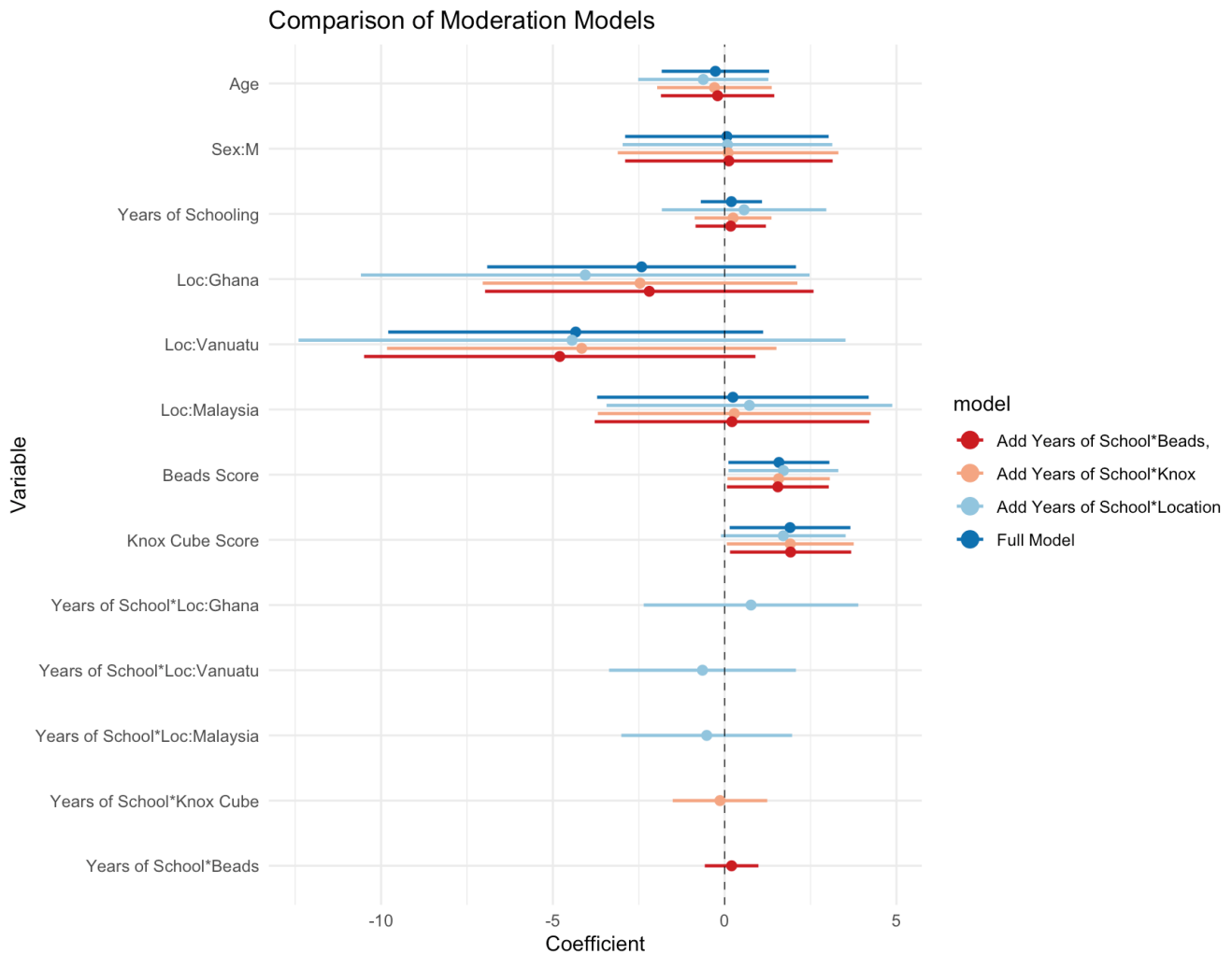
R² /	0.238 / 0.200
R²adjusted	
AICc	730.94

Note. Brazil is used as the reference for the location variable. The model's S.E.s, CIs, and p-values are calculated based on robust estimation. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Does formal education impact the relationship between HTKS and EF tasks?

A moderation analysis was conducted to assess years of schooling as a moderator of location effects as well as Knox Cube and Beads effects on HTKS performance. Years of schooling was not a significant moderator of location's effect on HTKS scores. When run on a separate model, years of schooling was also not a significant moderator of Knox Cube scores, or Beads scores (see Table Supp6 and Supp7 in Supplemental Information). In addition, change in the main effects of each location, Knox Cube, and Beads was trivial when adding the years of schooling interaction, as shown for each variable across models in Figure 6.

Figure 6. Comparison of full model and years of schooling moderation effect models.

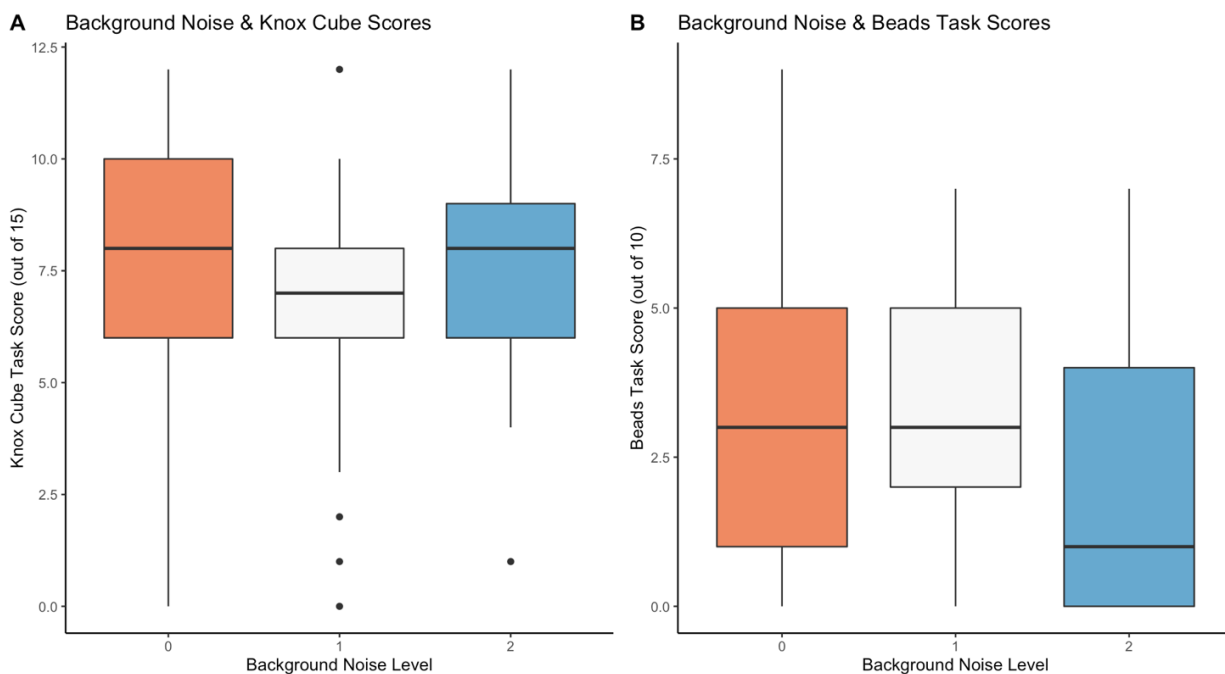


Effect of experimental variation in task environment and administration?

The number of practice trials across all three stages of the HTKS accounted for very little variance in HTKS performance ($R^2 = .00$, $F(1, 97) = .04$, $p = .837$; Table 8). One-way analysis of variance tests showed that the noise level was not significant for the Knox Cube task, ($F(2,79) = .66$, $p = .52$; Figure 7a) or for the Beads Task, ($F(2,97) = .168$, $p = .19$; Figure 7b). All participants with video data for each task were included in the analysis ($N = 74$ participants for the Knox Cube and $N = 91$ participants for the Beads task).

Table 8. Linear model results examining the number of practice trials and HTKS performance.

Number of Practice Trials and HTKS Scores (Parts I, II, and III)			
<i>Variable</i>	<i>Estimate</i>	<i>95% CI</i>	<i>P-value</i>
(Intercept)	49.12	40.79 – 57.44	<.001
HTKS Practice Trials	0.05	-0.39 – 0.49	.837
Observations	99		
R ² / R ² adjusted	0.000 / -0.010		

Figures 7a & 7b. Background noise level and EF task scores across sites.

Note. Noise levels are categorized from 0-2, with 0 representing no background noise, and 2 representing constant noise.

Discussion

The current study examined a) the association between a self-regulation task and two memory-related tasks (visuospatial working and short-term) among children from demographically-diverse

communities in low- and middle-income countries, and b) the influence of exposure to formal education on these relationships.

The relations between working and short-term memory and self-regulatory skills

Our first objective was to examine relations between non-verbal EF measures of visuospatial working memory (Knox Cube) and visuospatial short-term memory (Beads) and a verbal self-regulation measure (HTKS) in eight- to 13-year-old children across demographically-diverse communities. We found that performance on the Knox Cube and Beads Tasks were moderately correlated with performance on the HTKS. We also found that better performance on the Knox Cube Task is associated with slightly larger effects on performance on HTKS than Beads Task performance ($\beta = 1.90$ and $\beta = 1.58$, respectively). We speculate that Knox Cube may be associated with greater improvement on the HTKS task in particular because they both recruit motor skills. Conversely, the Beads Task relies more heavily on the memorization of sequences and the configuration of external objects. Nevertheless, variation on both tasks is associated with variance in HTKS performance.

Previous literature classifies these tasks as measures of overlapping constructs. Both are related to memory, specifically visual form and spatial relations memory, but are distinguished by the components of memory they measure: short-term (Beads task) and working memory (Knox Cube task). Aben et al. (2012)'s review of literature on these constructs reveals a lack of consensus on the distinction between these terms, presenting multiple models of their relationship, from completely distinct to overlapping to identical. Additionally, they argue that differences between working memory tasks and short-term memory tasks could reflect an increased complexity of tasks designed for working memory, or even that the subject's procedure for processing the information affects whether working memory or short-term memory is being measured (Aben et al., 2012). Our results do not support a model of the two constructs as identical. Notably, the Knox Cube task and the Beads task both had associations with self-regulation that were independent of each other, given the minimal and

nonsignificant correlation ($r(105) = .14, p = .14$) between the two memory tasks. These two tasks certainly seem to capture different aspects of memory and memory processing, and, if these constructs were identical, we would have expected to have found much stronger relations between them. Because the Beads task taps into the short-term memory component of working memory, this suggests that these constructs are, in fact, distinguishable in general and in children of this age and that the additional processing and attentional control components that are included in working memory but not short-term memory, as we originally defined the terms, may play a significant part in task performance on the Knox Cube task, thus explaining a lack of association between task scores. These preliminary findings point to the importance of continued clarification of these executive function terminologies.

We predicted that the Knox Cube and Beads Tasks would be correlated to HTKS performance because they both require memorizing increasingly longer sequences of detail (taps and geometrical shapes, respectively). These correlations were stronger when all three parts of the HTKS were included, compared to only the first two parts, as is with the original version of the task. This suggests that Part III may make the HTKS suitable for assessment with older children since it increases the task complexity by completely changing the previously established rules, increasing the cognitive load on the participants, and requiring utilization of cognitive flexibility to score higher.

The effect of formal education on EFs and self-regulation in children from demographically-diverse communities

Our second objective was to explore whether formal education may be driving the relationship between visuospatial EFs (short-term memory and working memory) and self-regulation. Ample research finds that access to formal education influences children's performance on self-regulation assessments and cognitive tests (Ceci, 1991; Peng & Kievit, 2020; Ritchie & Tucker-Drob, 2018), but we found that years of schooling were not associated with self-regulation outcomes, despite the variation in school exposure in our samples. Neither of the EF tasks, Knox Cube (working memory)

and Beads (short-term memory), were significantly correlated with formal education exposure either, which contradicts the relationship between EFs and formal education typically found in Western samples (Bielaczyc et al. 1995; Cornford, 2002; Heckman & Kautz, 2012; Nota et al., 2004).

We expected school exposure may be driving the relationship between nonverbal EFs (short-term and working memory) and verbal self-regulation because of the heavy emphasis school places on skills relevant to EFs (i.e. rule-following, inhibitory control), language, and exposure to unfamiliar testing environments. We found that sites with greater average years of schooling tended to perform slightly better on the self-regulation task than those with fewer average years of schooling, but did not find this for the EF tasks. In addition, educational exposure did not moderate the association of working memory and self-regulation or short-term memory and self-regulation. This is evidence for an effect of the updating (i.e., working memory) component of EFs on self-regulation and is in line with the widespread acceptance that EFs underlie self-regulation (Inzlicht et al., 2021). This is an effect not explained by educational exposure or location in our analysis, and it may point to a more general and direct effect of EFs on self-regulation. Our measure of school exposure did not capture the constellation of other factors involved in formal education, including school quality, academic achievement, attendance, curriculum, etc. As such, measures of schooling that accounted for more contextual factors may find larger effects for exposure. The challenge of developing and applying such measures is a topic for future investigation.

Our study includes samples that are under-represented in psychological research in that they are based on children from diverse backgrounds in four low- and middle-income countries. This provides an opportunity to extend and assess the robustness of tasks that are typically only used among highly educated samples from a small number of high-income countries. Our overall findings reveal similar performance across eight- to 13-year-old children from low-and middle-income countries and demographically diverse backgrounds, despite wide variability in length of formal schooling exposure

and educational infrastructure, ranging from Tanna, Vanuatu, a rural and subsistence-based population with recent introduction of formal schooling, to Natal, Brazil, an urban state capital containing multiple universities. On one hand, the lack of influence of location and school exposure on HTKS performance suggests that these tasks may be effective measures for use with diverse communities of children. On the other hand, it also points to the necessity of investigating which other contextual variables than exposure to school may influence the development of EF skills and self-regulation, and even in communities with little or no access to school (e.g., Legare et al., 2018; Pope et al., 2018).

Limitations

We found a statistically detectable relationship between visuospatial memory (working and short-term memory) tasks and a widely used measure of self-regulation. However, many factors can affect the magnitude of effect sizes and, particularly in cross-cultural studies of diverse populations with limited sample sizes, the estimated effects need to be interpreted with caution. Additionally, we note potential ceiling effects from the HTKS, (especially for the Malaysian and Brazilian samples). Some scores at these sites may have been constrained by the difficulty level of the task. Our study measured variability in HTKS performance and a relationship to working memory, but approaching ceiling effects in HTKS scores may have prevented detection of stronger relationships.

As noted by Best & Miller (2010), studying components of executive functioning is best conducted with multiple theoretically-related measures. Ideally, triangulation on each construct with more than one task is preferable, in order to increase validity and to help detect potential methodological issues. This is difficult to achieve with children, particularly in field-based studies, because of the extensive participant-time required. Nonetheless, it remains an important target to strive for. Another caveat to conclusions drawn here is the relatively small sample size. To revisit this issue, Gelman & Carlin (2014) recommend examining overestimates of magnitude instead of focusing on

power, in order to move beyond goals of statistical significance. In particular, low-powered studies may be especially likely to overestimate effect sizes, which is why we interpret our results with caution.

Future directions and implications

Our unidimensional measure of formal education may contribute to why we did not find an effect of education. Including additional measures of educational exposure, academic achievement, and other aspects of education, such as school quality and type, in future studies could better capture the complexity of the formal educational experience and the effects it may have on cognitive development. Alternate theories worth studying include educational variables such as length of schooling as an outcome of EF and self-regulatory skill, alongside other aspects of education frequently studied as outcomes, like academic achievement. In addition, self-regulatory and EF skills may impact how long children stay in school. Because education encompasses an array of complex experiences, there is likely a bidirectional influence of education on cognitive and behavioral outcomes, the specific aspects of which can be better parsed with longitudinal research.

Any effects of BMI (conceived of as a measure of health) were inconclusive, though we suggest it may have had a stronger association with self-regulation with a larger sample, given the extensive evidence for the impact of nutrition on cognitive development (Bryan et al., 2004; Freeman et al. 1980; Nyaradi et al., 2013). While we were unable to assess SES, we acknowledge its importance as a variable in cognitive assessment and that cross-cultural samples represent communities with diverse demographics in geographic location, political and educational systems, and socioeconomic conditions. We hope that future directions will include measures that capture economic, cultural, and health-related factors such as BMI and SES, to explore how these variables interact and influence the development of EFs and self-regulation. We encourage future research to continue to use these verbal and non-verbal culturally-sensitive measures with understudied populations, while holding an awareness of the potential (and likely) bias the Western-based body of literature may have on any

interpretation or conclusions, and to take into account additional educational, environmental, cultural factors to the extent possible.

Our findings suggest that the Knox Cube, Beads, and HTKS Tasks are effective measures of cognitive performance in middle to late childhood with the demographically-diverse populations we studied. Within this study, these measures capture a relationship between the improvement in the updating component of EF and self-regulation not fully explained by the effects of formal education or age. This is not surprising, given the close ties between EF and self-regulation, and the assumption that EFs underlie the cognitive processes needed for self-regulation. We suggest that the relationship between EF tasks and self-regulation points to two things: an important updating-related component of this self-regulation task in particular, and the potential for use of tasks to distinguish components of self-regulation throughout middle and later childhood.

Conclusions

This study is among the first to examine the relationship between EF skills and the HTKS self-regulation task in middle childhood with globally- and demographically-diverse populations. Our results identify relationships between updating EFs (visuospatial short-term and working memory) and self-regulation, independent of schooling and location effects. We found evidence that working and short-term memory represent distinct processes, though both are associated with higher performance on a self-regulation task. Our data highlight the need to examine and define specific associations between components of EF and self-regulation, as well as to investigate those in populations other than Western, wealthy, and highly educated ones. Our study sheds light on these potential associations and inspires further exploration of the complex relationship between demographic and educational variables and cognitive assessment in global populations.

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