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Self-Regulation and Academic Measures Across the Early Elementary School Grades: Examining Longitudinal and Bidirectional Associations

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Abstract

This study evaluated the association between children's (N = 301) self-regulation and math and reading achievement in kindergarten, first grade, and second grade. Children's self-regulation was assessed using the Head-Toes-Knees-Shoulders (HTKS) task (involving control of gross body movements) and a computerized continuous performance task (CPT; assessing primarily inhibitory control) in kindergarten, first grade, and second grade. *Research findings*: Based on cross-lagged structural equation panel models, HTKS task performance positively predicted later math and reading achievement. Math achievement significantly and positively predicted later HTKS and CPT scores. Earlier math and reading achievement moderated the association between CPT scores and later math and reading achievement; inhibitory control-based self-regulation assessed with the CPT predicted higher math or reading achievement in subsequent grades for children with lower math or reading achievement in prior grades. Performance on the CPT moderated the paths from HTKS scores to later reading achievement; behavioral self-regulation assessed with the HTKS task predicted higher reading achievement in subsequent grades for children with low or average CPT performance in prior grades. *Practice*: Results from this study have the potential to inform targeted academic interventions focused on enhancing self-regulation in school contexts. The findings highlight the utility of assessing multiple measures of self-regulation.

Keywords

academic achievement; behavioral self-regulation; continuous performance task; elementary school; Head-Toes-Knees-Shoulders task; inhibitory control-based self-regulation; math achievement; reading achievement

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In the transition to elementary school, academic demands evolve from learning basic skills, such as identifying letters and numbers, to employing these newly-learned skills to engage in higher cognitive tasks, such as reading and solving math problems. Children's top-down (i.e., effortful; see Nigg, 2017) self-regulatory abilities (henceforth labeled self-regulation) are expected to facilitate cognitive reasoning at school (Kim, Duran, Cameron, & Grissmer, 2018) and competent performance on everyday school tasks (Blair & Raver, 2015; Rothbart & Jones, 1998), as well as social competence with teachers and schoolmates (Eisenberg, Eggum, Sallquist, & Edwards, 2010; Hernández et al., 2017). As discussed by McClelland and Cameron (2012), behavioral self-regulation involves the everyday application of executive functioning skills (e.g., attention regulation, working memory, inhibitory control). We describe self-regulation as a top-down process (see Nigg, 2017), although it has been proposed that bottom-up processes (such as emotion feedback) may modify self-regulation thresholds and therefore also be regulating (e.g., excitement may alter attention used during behavioral self-regulation; Blair, 2016; Nigg, 2017). During the transition into formal schooling, children's top-down self-regulation abilities continue to develop (Eisenberg, Valiente, & Eggum, 2010) and children encounter increased expectations for self-regulation in their environment (Li-Grining, 2007; Rothbart & Jones, 1998). Given the sustained effects of early academic achievement on various outcomes (Duncan et al., 2007), research is needed to clarify the types of self-regulation related to academic outcomes and the moderating mechanisms over time.

In many studies on the relation between self-regulation and math or reading achievement, measures of self-regulation tap primarily attentional skills (e.g., flanker tasks), the ability to manipulate multiple dimensions in the mind simultaneously (e.g., dimensional sorting tasks), and/or the abilities to effortfully inhibit and activate behavior as needed. Self-regulation may be particularly important for appropriate classroom behavior, which is believed to affect interactions with peers and teachers, sustained engagement in academic activities, and, consequently, learning outcomes (e.g., Hernández et al., 2017). This study was designed to examine the extent to which two measures of children's self-regulation varying in degree of motor involvement, the Head-Toes-Knees-Shoulders (HTKS) task and a continuous performance task (CPT), uniquely predicted higher math and reading achievement across kindergarten (K), first grade (G1), and second grade (G2). Math achievement was measured with an applied problems assessment requiring children to perform "math calculations in reponse to orally presented problems" (Woodcock, McGrew, & Mather, 2001, p. 53). Reading achievement was measured with a passage comprehension assessment requiring children to "identify a missing key word that makes sense in the context of a written passage" (Woodcock et al., 2001, p. 53). We examined possible bidirectional associations between self-regulation (both behavioral and inhibitory control-based) and academic achievement using cross-lagged panel models. We also examined potential moderators (e.g., prior achievement, self-regulation) of the association between two different measures of self-regulation and academic achievement.

Measures of Self-regulation

Self-regulation is broadly defined as the integrative "capability of controlling or directing one's attention, thoughts, emotions, and actions" (McClelland & Cameron, 2012, p. 136).

Children’s self-regulation is typically measured with a variety of assessments that require different degrees of executive functioning and gross motor behaviors to successfully complete (Eisenberg & Zhou, 2015; Kim & Cameron, 2016), and the HTKS and CPT measures involve varying demands (McClelland & Cameron, 2012; Nigg, 2017). For instance, successful performance of the HTKS task, which is often referred to as assessing broad behavioral self-regulation, requires working memory, inhibitory control, activation of appropriate behavior, attention focusing, and coordinating gross body movements. It also involves increasing cognitive demands because the task rules become more complex in some versions of the task (see the method for more details; Allan, Hume, Allan, Farrington, & Lonigan, 2014; McClelland et al., 2007). On every trial, the child is required to make a gross motor movement; what is scored is whether the movement is correct or incorrect, or whether the child initiates an incorrect option and self-corrects. Thus, successful performance on the HTKS task requires adequately incorporating gross motor responses given increasingly complex demands.

The computerized CPT requires working memory, attentional focus, and sustained attention (Sulik et al., 2010), with a large inhibitory control component during non-target stimuli trials. The CPT is completed while the child is sitting in front of a computer. Children are told to touch a computer key when certain stimuli appear and to inhibit touching the key when other stimuli appear on the screen. One CPT index typically assesses inhibiting the dominant tendency to tap the computer key, which involves primarily inhibition of impulsive movement.

Success on both the HTKS and the CPT requires self-regulatory skills based on top-down cognitive processes to successfully complete (Eisenberg & Zhou, 2015). However, it may be useful to differentiate between a task that assesses gross motor skills when inhibiting and activating behavior (as in the HTKS task) and a task that primarily requires the inhibition of movement in situations likely to tap impulsive tendencies (as in one CPT index) because they resemble different aspects of behavioral demands in classroom environments (McClelland & Cameron, 2012). Moreover, the HTKS requires regulation of some movement on every trial, whereas the CPT inhibitory control index requires merely not touching the computer key (i.e., no movement). In addition, as previously noted, the rules become more complicated across some versions of the HTKS, testing the child’s ability to successfully assimilate and adapt to a more complex set of rules, which closely resembles classroom-based behavioral demands or everyday application of executive functioning (McClelland & Cameron, 2012). Perhaps the varying demands these tasks involve helps explain why performance on such tasks often is not highly correlated (Nigg, 2017), even when measures connect to a broader construct of self-regulation (Sulik et al., 2010). Thus, we were interested in closely examining unique and moderating relations between two self-regulation measures to help clarify the underlying regulatory processes associated with math and reading achievement.

Relations between Self-Regulation and Academic Achievement in Childhood

Top-down self-regulation can be viewed as involving inhibitory control ("Capacity to plan and to surpress inappropriate approach responses under instructions or in novel or uncertain situations," Rothbart, Ahadi, Hershey, & Fisher, 2001, p. 1406), and sometimes activation control ("The capacity to perform an action when there is a strong tendency to avoid it"; Ellis, 2002, p. 57), as well as the ability to effortfully manage attention. Children who efficaciously regulate their behavior and attention should be relatively adept at curbing potential distress during challenging situations, inhibiting distractions that otherwise overburden cognitive resources during learning, and attending to and participating in classroom activities (Blair, 2002). Self-regulation also promotes planning and problem solving (Blair & Raver, 2015; Kim & Cameron, 2016), which have positive implications for academic performance (Eisenberg, Valiente, et al., 2010; Kim et al., 2017).

The association between various measures of self-regulation and academic achievement is generally robust (see a meta-analysis of concurrent studies by Allan et al., 2014, and a review by Clements et al., 2016; see Appendix 1 for a summary research literature included hereinafter). Behavioral self-regulation has predicted children's math (e.g., Blair & Razza, 2007; Blair, Ursache, Greenberg, Vernon-Feagans, & Family Life Project Investigators, 2015; Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; Clark, Pritchard, & Woodward, 2010; McClelland et al., 2007; Ponitz, McClelland, Matthews, & Morrison, 2009; Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017) and reading skills (e.g., Becker, McClelland, Loprinzi, & Trost, 2014; Bohlmann, Maier, & Palacios, 2015; Fuhs, Nesbitt, Farran, & Dong, 2014; Lonigan, Allan, & Phillips, 2017; Matthews, Ponitz, & Morrison, 2009; McClelland et al., 2007; Schmitt et al., 2017), concurrently as well as across time. However, some studies, particularly longitudinal studies, have obtained null or less robust findings (e.g., Blair et al., 2015; Brock et al., 2009; Clark et al., 2010; Connor et al., 2016; Duncan et al., 2007; Liew, Chen, & Hughes, 2010). For example, behavioral self-regulation (which included HTKS) did not predict reading comprehension from G1 to G2 (only concurrently; Connor et al., 2016). Similarly, behavioral self-regulation in the fall of preschool did not predict overall academic achievement in the spring of preschool (McClelland et al., 2007; although behavioral regulation in the spring predicted concurrent academic skills controlling for academic skills in the fall; and, *gains* in behavioral regulation significantly predicted *gains* in math and reading across preschool). In addition, in some studies, behavioral self-regulation has predicted higher concurrent levels of, but not longitudinal growth in, reading abilities (Blair et al., 2015; Schmitt et al., 2017). Although HTKS scores predicted growth in two literacy measures based on elision (requiring the child to indicate what word results from omitting a word, syllable, or phoneme) and alphabet tests within the preschool year (Lonigan et al., 2017), HTKS scores did not predict growth in eight of ten literacy and language outcomes. One study even found an opposite pattern, such that high self-regulation was negatively associated with growth in math achievement (e.g., Blair et al., 2015, children with high self-regulation showed slower growth in math). Thus, it is critical that studies use longitudinal designs to rigorously test whether the well-established concurrent associations between self-regulation and academic achievement persist across time (Allan et al., 2014), and particularly across school grades (many of the longitudinal studies have examined data from within the same school year, e.g., from fall to spring of preschool).

Few studies test the association of direct measures of children's inhibitory control-based self-regulation to academic achievement and these studies demonstrate mixed findings (Spira & Fischel, 2005). Children with inhibitory regulation difficulties are thought to more likely struggle with appropriate behavior in the classroom and during academic instruction. Some investigators have found a negative association between impulsivity and math or reading achievement (NICHD Early Child Care Research Network, 2003; Romano, Babchishin, Pagani, & Kohen, 2010) and a positive association between inhibitory control (or lack of impulsivity) and reading and math achievement in childhood (Lonigan et al., 2017; NICHD Early Child Care Research Network, 2003; Razza, Martin, & Brooks-Gunn, 2010). Indicators of attention-deficit/hyperactivity disorder (ADHD), which include symptoms of impulsivity and difficulties with inhibitory control, have also been associated with lower academic skills in childhood (Diamantopoulou, Rydell, Thorell, & Bohlin, 2007; Friedman-Weieneth, Harvey, Youngwirth, & Goldstein, 2007), although there is some evidence that inattention indicators, rather than hyperactivity/impulsivity indicators of ADHD, are most consistently associated with academic outcomes (Rabiner, Coie, & The Conduct Problems Prevention Research Group, 2000). In addition, inhibition of impulsive responding has been less consistently associated with academic achievement compared to attention skills in the ADHD research literature (Rabiner et al., 2000). The aforementioned mixed findings suggest that the HTKS, because it is a more encompassing measure of self-regulation, may be a more consistent predictor of academic achievement compared to the inhibitory control-based index of the CPT.

Math and Reading Achievement

Some studies suggest that the associations between self-regulation and academic achievement are stronger for math than for literacy outcomes (Allan et al., 2014; Blair & Razza, 2007; Blair et al., 2015; Brock et al., 2009; Clements et al., 2016; Ponitz et al., 2009; Schmitt et al., 2017). These findings support prior theorizing that executive functioning, a process involved in behavioral self-regulation, is closely tied to functioning in the prefrontal cortex (Blair, 2016), which is also closely associated with math skill development (Blair, Gamson, Thorne, & Baker, 2005). It has also been argued that executive functioning skills are most employed when information is novel, before automaticity is achieved (Blair, Protzko, & Ursache, 2011; Blair & Razza, 2007; Cameron, 2018). For literacy development, some aspects of executive functioning may be more relevant when children are acquiring basic literacy decoding skills (i.e., decoding groups of letters into sounds; e.g., letter-word knowledge, phonological awareness; Purpura, Schmitt, & Ganley, 2017). Once children have acquired fluency in basic literacy decoding skills, which would become more automatic (Blair & Razza, 2007; Cameron, 2018) and also predict more complex literacy tasks (Lai, George Benjamin, Schwanenflugel, & Kuhn, 2014), executive functioning skills would be employed for more complex literacy tasks (e.g., reading comprehension). Executive functioning skills (i.e., domain-general skills), on the other hand, have uniquely predicted math achievement development, controlling for domain-specific abilities (Fuchs et al., 2010), from learning basic numeracy skills to solving word problems and understanding that symbols represent mathematical concepts (Cameron, 2018).Thus, we examined math and reading achievement measures separately to test whether self-regulation assessed with the HTKS task and CPT would be uniquely and consistently associated with math and reading achievement over time.

Bidirectional Associations

There is some evidence that the association between self-regulation and academic achievement is bidirectional within the pre-kindergarten (pre-K) year (Fuhs et al., 2014; Schmitt et al., 2017), from pre-K to K (Schmitt et al., 2017), and within the G1 year (Connor et al., 2016). For instance, Welsh, Nix, Blair, Bierman, and Nelson (2010) found that self-regulation and executive functioning (including measures of attention, inhibitory control, and working memory) in the beginning of pre-K predicted numeracy and literacy skills in the end of pre-K, and numeracy skills in the beginning of pre-K also significantly predicted self-regulation skills in the end of pre-K. In another study, self-regulation predicted later expressive vocabulary, and vice versa, from the spring of pre-K to the fall of the following pre-K or K year (Bohlmann et al., 2015). However, few researchers, if any, have examined bidirectional associations between self-regulation and math or reading achievement across the early elementary school years. To add to this growing research area, we tested bidirectional associations between behavioral or inhibitory control-based self-regulation and math and reading achievement in the transition from K to G2.

Moderating Mechanisms

The association between self-regulation and academic achievement has strong theoretical and empirical foundations (Blair & Raver, 2015; Rothbart & Jones, 1998). However, researchers have raised concerns about the strength of the association (e.g., Jacob & Parkinson, 2015) and the presence of some null findings (e.g., Brennan, Shaw, Dishion, & Wilson, 2012; Clements et al., 2016; Liew et al., 2010; McClelland et al., 2007). Thus, we sought to examine the conditions under which the association between self-regulation and academic achievement is present during the transitions between early grades in elementary school.

Some research suggests that self-regulation has a compensatory effect on academic achievement, particularly for children who have prior regulatory or academic difficulties (Cameron et al., 2015; Cameron, Cottone, Murrah, & Grissmer, 2016; Ribner, Willoughby, & Blair, 2017). Relatedly, behavioral self-regulation may be especially predictive of academic achievement at the stage of acquiring basic academic skills before automaticity (Purpura et al., 2017). Thus, we might expect that self-regulation would be most predictive of academic achievement for children who have difficulties with basic academic skills and are still acquiring these academic skills; for children who are performing well and whose skills have become more automatic (Blair & Razza, 2007), self-regulation is expected to be less predictive of basic academic skills. Consistent with this compensatory mechanism hypothesis, Cameron et al. (2015) found that having high levels of visuomotor integration (a hand-eye coordination measure involving children reproducing a set of figures with a pencil, requiring some level of behavioral regulation) compensated for the effect of otherwise low levels of inhibitory control (measured with the pencil tap task) on literacy outcomes in pre-K. That is, when inhibitory control was low, literacy outcomes were high with strong visuomotor integration. Furthermore, when visuomotor integration was low, literacy outcomes were relatively high with strong inhibitory control. In another study, executive functioning compensated for low levels of preschool math achievement in predicting both math and reading achievement in fifth grade (Ribner et al., 2017). Specifically, children who had low levels of math in preschool but high levels of executive functioning skills performed at high math and reading achievement levels in fifth grade. This study's prospective findings (Ribner et al., 2017), which support an underlying compensatory effect on math and reading achievement, support the present study's proposal that prior achievement and self-regulation may jointly predict math and reading through a compensatory mechanism. Other studies also point to the association between effortful control and math and reading being moderated by school difficulties (Liew et al., 2010). Liew et al. (2010) found that the positive association between effortful control (accuracy in a task involving fine motor skills) and achievement from first to second grade was strongest for those who had difficulties with teachers (Liew et al., 2010). Together, these findings suggest that baseline or prior levels of academic or regulatory difficulties might moderate the association between self-regulation and academic achievement. We hypothesize a broad index of self-regulation including not only inhibitory control but also control of gross motor behavior more generally to predict higher academic achievement especially for children who had lower academic achievement at prior time-points. We also expected the broader measure of behavioral self-regulation (HTKS) to predict higher academic achievement especially for children with lower inhibitory control-based self-regulation (inhibitory control measured with the CPT) because when children are less competent in attentional regulation, they need greater behavioral self-regulation for academic achievement.

The Present Study

In the present study, we examined whether self-regulation, assessed with both the HTKS and CPT, uniquely predicted academic achievement, and vice versa, from K to G2. Based on the argument that self-regulation assessed with the HTKS is more aligned with classroom behavioral demands (McClelland & Cameron, 2012) and is a broader, more inclusive index of motor self-regulation compared to the CPT inhibitory control index, we tentatively predicted that behavioral self-regulation assessed with the HTKS would be most consistently associated with academic achievement. We tested possible bidirectional associations across time, given the possibility that academic and self-regulation skills develop and strengthen each other simultaneously (Bohlmann et al., 2015) and likely both stem from greater cortical functioning (Blair et al., 2005), as well as whether the associations were equivalent in magnitude in the K to G1 transition compared to the G1 to G2 transition. Results from these tests of equivalence are informative given that bidirectional associations between self-regulation and academic achievement in the K to G2 transition have previously not been tested (see Kim et al., 2017 for an exception). Because of concerns about insufficient inclusion of covariates in prior studies (Jacob & Parkinson, 2015), we controlled for socioeconomic status, prior math and reading achievement, gender, ethnicity, and age given prior associations with self-regulation (e.g., Li-Grining, 2007; Matthews et al., 2009) or achievement (e.g., Clark et al., 2010; Duncan et al., 2007). This study also contributes to this research area by examining moderators (i.e., prior achievement or self-regulation) of the association between self-regulation and achievement within a longitudinal design.

Method

Participants

At the beginning of the academic year in K, two cohorts (one year apart) of participants were recruited ($N = 301$; 52% girls; $M_{age} = 5.48$ years, $SD_{age} = 0.35$ years) from 26 classrooms in five schools in a southwestern metropolitan area in the United States (Hernández et al., 2016). On average, there were 21 students in each K classroom (range: 14–26). Parents provided consent for their child to participate in the study. Children provided assent to participate. The recruitment rate (301 children comprising 56% of the potential pool of participants) is typical of similar community studies of young children (e.g., McClelland et al., 2007).

Participating children were from various ethnic backgrounds (53% Hispanic, 34% White non-Hispanic, 3% Asian, 2% American Indian/Alaska Native backgrounds, 2% Black, 1% Other, 6% Unknown [percentages are rounded]). Parents had varied education levels (30% of mothers and 39% of fathers completed high school or less, 31% of mothers and 24% of fathers attended some college, and 39% of mothers and 37% of fathers graduated from college) and family income (average: $50,000 to $69,999; range: < $9,999 to $100,000+). Participants were generally representative of the recruitment schools' student ethnic background composition (the schools had 47% Hispanic, 37% White non-Hispanic, 3% Asian, 2% American Indian/Alaska Native backgrounds, 8% Black, 3% two or more races [percentages are rounded]). In the recruitment schools, 56% of students qualified for free or reduced lunch at the beginning of the study, meeting 130% poverty level [free meal equivalent to ≤ $36,283 annual income for a family of five in 2014–2015] or 185% poverty level [reduced price equivalent to ≤ $51,634 annual income for a family of five in 2014–2015]). This rate was similar to the state's rate (57%) of students qualifying for free or reduced lunch.

For the variables used in this study, at least some data were collected from 301, 264 (88%), and 242 (80%) children in K, G1, and G2, respectively. Compared to children with data in G1, children missing data in G1 did not differ on other study variables, including demographic characteristic covariates. Similarly, compared to children with data in G2, children missing data in G2 did not differ on other study variables.

Procedure

Study measures assessed in the K, G1, and G2 included standardized assessments of academic achievement and self-regulation using a computerized assessment of the CPT and a behavioral assessment of the HTKS task. Parents were compensated $30 for each survey in K and children received two small toys for their participation at each assessment. Prior to administering assessments of achievement and self-regulation, research assistants attended two 2.5-hour trainings per week for five weeks before data collection started. During these training sessions, research assistants received instruction on how to administer the standardized assessments of achievement as described in the Woodcock-Johnson III Examiner's Manual (Mather & Woodcock, 2001), and the regulation tasks as described by McClelland et al. (2014) and the NICHD Early Child Care Research Network (2003). Research assistants administered standardized assessments of achievement and direct measures of self-regulation in designated school rooms (to minimize distraction), on separate days, in the latter part of the spring semesters of K, G1, and G2.

Measures

Academic achievement.—Academic achievement was assessed with the Woodcock-Johnson III Tests of Achievement (Woodcock et al., 2001), in the spring semesters of K, G1, and G2. The passage comprehension (i.e., reading) and applied problems (i.e., math) subtests were administered in either English (for most children) or Spanish. In K, one child completed both assessments in Spanish. In G1, one child completed the passage comprehension assessment in Spanish. Raw test scores were converted to *W* scores representing equal-interval units in a Rasch scale. Passage comprehension and applied problems scores were used as separate manifest variables of reading and math achievement, respectively.

Head-Toes-Knees-Shoulders (HTKS) task.—The Head-Toes-Knees-Shoulders (HTKS) task was used as an indicator of behavioral self-regulation in K, G1, and G2 (McClelland et al., 2007; McClelland et al., 2014). There were a total of 30 possible test trials, separated in three 10 test trial segments. For each trial, an experimenter in a videotape requested a given behavior and the child was asked to perform a different (i.e., opposite) behavior. For example, if the experimenter requested that the child touch their shoulder, the child was expected to touch their knees instead (and vice versa). Prior to each set, four practice trials were administered before the test trials were scored. For the first 10 test trial items, the experimenter's requests in the videotape involved only shoulders and knees. For the second set of 10 test trials, the experimenter's requests involved only shoulders and knees as opposite behaviors, as well as head and toes as opposite behaviors. For the third and last set of 10 test trials, the experimenter changed the rules, and the child was asked to touch their shoulders when the experimenter said toes and to touch their knees if the experimenter said head. For each segment, at least four correct test trials were necessary for the experimenter to conduct the next segment of test trials. Responses were coded as *0* (child performs wrong behavior and does not self-correct), *1* (child initiates wrong behavior but self-corrects), or *2* (child immediately performs correct behavior). The scores across test trials were summed and divided by 60 (the maximum possible score), representing a proportion of correct trials across 30 possible test trials.

CPT.—A computer-administered CPT (similar to in NICHD Early Child Care Research Network, 2003; Sulik et al., 2010) was used to obtain a measure of primarily the inhibitory control aspect of self-regulation. For this task, children sat in front of a computer and were asked to press the keyboard space bar as soon as the target stimulus appeared on the screen. Using eight pictures of different non-target objects (e.g., boat, flower) and one picture of the target object (i.e., fish), 44 presentations of the target stimulus and 176 presentations of non-target stimuli were randomly presented on the screen. Stimuli appeared on the screen for 0.5 s with 1.5 s intervals between stimuli. All students performed enough trials (75% of trials) to be included in analyses. For each trial where non-target stimuli appeared, a score of 1 was assigned for a correct rejection (i.e., no space bar press) or 0 for a false alarm (i.e., pressed space bar). The proportion of correct rejections for trials with non-target stimuli was computed. This score, which represents how well children discriminate between target stimuli and non-target stimuli trials and inhibit the impulse to react (i.e., press the space bar) to non-target stimuli during the sustained task, was used as an indicator of inhibitory control in K, G1, and G2.

Covariates.—Parents reported children's age, ethnic minority status (1 = *ethnic minority* (*Hispanic, Asian, American Indian/Alaska Native, Black, two or more races*), 0 = *non-Hispanic, white*), and gender (1 = *boy*; 0 = *girl*), which were used as control variables. Parents also reported children's maternal and paternal education levels (1 = *less than a high school diploma*, 2 = *high school degree or equivalent*, 3 = *some college*, 4 = *college graduate or higher*), as well as family income (range: < $9,999 to $100,000+). To create a socioeconomic status control variable, standardized *z*-scores were calculated for family income and the average of maternal and paternal education levels, which were subsequently averaged.

Results

Table 1 provides the descriptive statistics and correlations among the variables used in the present study. Variables did not display marked skew (above |2|) or kurtosis (above |7|) except four out of twelve main study variables: HTKS at G2 (skew: −2.14, kurtosis: 8.19), and CPT at K (skew: −2.51, kurtosis: 7.37), G1 (skew: −3.04, kurtosis: 11.56), and G2 (skew: −4.20, kurtosis: 25.24). The percent of cases at the floor or ceiling ranged from 0 to 8%. For HTKS, 21 (7%) cases in K, 7 (2.3%) cases in G1, and 2 (.7%) cases in G2 scored at the floor (i.e., lowest possible score), whereas, 3 (1%) cases in K, 2 (.7%) cases in G1, and 6 (2%) cases in G2 scored at the ceiling (i.e., highest possible score). For CPT, 0 cases scored at the floor in K, G1, and G2, whereas, 24 (8%) cases in K, and 7 (2.3%) cases in G1 and G2 scored at the ceiling. The HTKS task scores were positively correlated with all math and reading achievement measures (across K, G1, and G2). However, CPT correct rejection scores were not significantly correlated with academic achievement measures, with one exception; CPT in K was positively correlated with passage comprehension academic achievement in K.

Preliminary Analyses and Analysis Plan

We tested our proposed models with a structural equation model (SEM) framework using M*plus* v8 (Muthén & Muthén, 1998–2017). The TYPE = COMPLEX command was used to account for the clustering of data by K classroom (K classroom was used as a cluster because there were more students per classroom in K). Full information maximum likelihood estimation with robust standard errors (MLR) was used to account for missing data (Satorra & Bentler, 1994) and non-normal distributions (i.e., the presence of skew and kurtosis) on some of the variables (Curran, West, & Finch, 1996), as suggested by (Finney & DiStefano, 2008). To test bidirectional associations between self-regulation, math, and reading achievement, we ran a cross-lagged panel SEM. In this model (see Figure 1), autoregressive paths were included (e.g., a path from HTKS in K to HTKS in G1, and a path from HTKS in G1 to HTKS in G2). We regressed the academic achievement measures (passage comprehension and applied problems) on both HTKS and CPT scores, and vice versa. We regressed the HTKS scores on the CPT scores, and vice versa. We regressed the passage comprehension scores on the applied problems scores, and vice versa. Socioeconomic status, ethnic minority status, male, and age (covariates) were used as predictors of HTKS scores, CPT scores, passage comprehension, and applied problems achievement in G1 and G2, and were correlated with HTKS scores, CPT scores, passage comprehension, and applied problems achievement in K. Cohort did not relate to the study variables and thus, was not included as a covariate. All SEM regression paths were tested for equality across time by constraining paths to be equal over time. If the fit with constrained paths did not significantly worsen compared to the fit of a model with unconstrained paths (based on scaled chi-square change tests; Satorra & Bentler, 2001), the more parsimonious constrained paths were kept (Bollen & Curran, 2006).

To test the hypothesized interactions, in six separate models, we centered the predictor variables in K and in G1 and used the products of the two interacting variables (within each time point) as predictors of the academic achievement outcomes at G1 or G2, respectively. First, four models with interactions between HTKS or CPT and prior achievement were tested for predicting applied problems or passage comprehension, separately (e.g., one model tested the interactions between HTKS and prior math achievement for predicting later math achievement). Second, two models (predicting math or passage comprehension) with interactions between HTKS and CPT were tested. For example, to test the hypothesized interaction between HTKS and CPT, we centered these two variables and multiplied them with each other within K and G1 to be used as a predictor of G1 and G2 passage comprehension. Models with significant interactions were compared with models with the interactions estimated to be null (i.e., models with interactions effects fixed to be zero). The scaled chi-square change in fit was tested (Satorra & Bentler, 2001). If a model with the interactions estimated was significantly better than the model with the interactions set to zero, the interactions were interpreted. For models with significant interactions, the associations between self-regulation (HTKS or CPT) and later academic achievement variables were tested at one *SD* below the mean, at the mean, and one *SD* above the mean of the moderating variable.

Self-Regulation and Academic Achievement Stabilities, Cross-Lags and Interactions

The following sections describe stabilities, cross-lagged associations, and interactions tested in the study.

Stabilities and covariates.—Table 2 displays standardized estimates in the SEM for the stabilities and cross-lagged associations between HTKS, CPT, scores on the applied problems test, and scores on the passage comprehension test from K to G2, controlling for covariates. This model showed adequate fit, MLR χ^2 (16) = 46.21, $p < .001$, CFI = .98, RMSEA = .08, 90% CI [.05, .10], but adding a stability path from K to G2 for applied problems achievement resulted in superior fit, $\Delta\ \chi^2$ (1) = 11.43, $p < .001$. Stability and cross-lagged paths across time were tested for equality and all showed equal magnitude, $\Delta\ \chi^2$ (14) = 8.48, $p = .86$, except for the HTKS stability paths. HTKS from K to G1 ($b*$ [standardized beta] = .37, $p < .001$) was significantly more stable than HTKS from G1 to G2 ($b* = .24$, $p = .007$), based on an equality test, $\Delta\ \chi^2$ (1) = 4.14, $p = .04$. This final model showed adequate fit: MLR χ^2 (29) = 42.19, $p = .05$, CFI = .99, RMSEA = .04, 90% CI [.00, .06]. The stabilities for HTKS, CPT, applied problems scores, and passage comprehension scores were all in the expected direction.

Socioeconomic status predicted higher passage comprehension achievement in G1 ($b* = .10$, $p = .01$) and higher applied problems achievement in G2 ($b* = .12$, $p = .01$). Children from ethnic minority backgrounds (compared to non-Hispanic, white backgrounds) had higher performance on the HTKS task ($b* = .15$, $p = .01$), lower applied problems achievement in G1 ($b* = -.13$, $p = .01$), and lower passage comprehension achievement in G1 ($b* = -.10$, $p = .004$). Boys had lower CPT scores in G1 ($b* = -.25$, $p < .001$) and G2 ($b* = -.23$, $p < .001$), and higher applied problems achievement in G1 ($b* = .15$, $p < .001$) and G2 ($b* = .10$, $p = .003$). Age predicted higher CPT scores in G2 ($b* = .11$, $p = .01$).

Cross-lagged associations.

Self-regulation and passage comprehension achievement cross-lagged associations.: HTKS uniquely predicted passage comprehension from K to G1 ($b* = .09$, $p = .03$) and from G1 to G2 ($b* = .09$, $p = .03$), at equal magnitudes (see Table 2). Passage comprehension did not significantly predict HTKS from K to G1 ($b* = .02$, $p = .75$) or from G1 to G2 ($b* = .02$, $p = .75$). There were no significant cross-lagged paths between CPT and passage comprehension from K to G2.

Self-regulation and applied problems achievement cross-lagged associations.: HTKS uniquely predicted applied math problems achievement from K to G1 ($b* = .18$, $p < .001$) and from G1 to G2 ($b* = .12$, $p < .001$; see Table 2), at equal magnitudes. Applied problems achievement also predicted HTKS from K to G1 ($b* = .18$, $p < .001$) and from G1 to G2 ($b* = .26$, $p < .001$). In addition, applied problems achievement predicted CPT scores from K to G1 ($b* = .16$, $p = .01$) and from G1 to G2 ($b* = .24$, $p < .001$). CPT did not significantly predict applied problems achievement.

Interactions between self-regulation and prior achievement.

Self-regulation and passage comprehension achievement interactions.: The interactions between HTKS and passage comprehension did not significantly predict passage comprehension from K to G1 and from G1 to G2 (*b*s [unstandardized betas] = .12, *p*s = .25) within the first interaction model (see Table 3, Model 1A for null interaction model, and Model 1B for estimated interaction model). Within the second interaction model (Model 2B), estimating the interactions between CPT in K and passage comprehension in K and between CPT in G1 and passage comprehension in G1 at equal magnitudes resulted in significantly improved model fit, $\Delta\ \chi^2$ (1) = 5.26, $p = .02$ (compared with Model 2A). The interactions between CPT and passage comprehension significantly predicted passage comprehension from K to G1 and from G1 to G2 (*b*s = −.95, *p*s = .02; Figure 2). The path from CPT in K to passage comprehension in G1 was significant at low levels of passage comprehension in K (b = 28.72, p = .05; see Figure 2A) and not significant at average (b = 8.88, p = .21) and high levels of passage comprehension in K (b = −10.96, p = .10). Similarly, the path from CPT in G1 to passage comprehension in G2 was significant at low (b = 26.35, p = .05; see Figure 2B) levels of G1 passage comprehension and not significant at average (b = 8.88, p = .21) and high levels of G1 passage comprehension (b = −8.59, p = .16).

Interactions between CPT and HTKS were tested as predictors of passage comprehension in G1 and G2 in a third interaction model (Table 3, Model 3B). Estimating the interactions between CPT in K and HTKS in K and between CPT in G1 and HTKS in G1 at equal magnitudes resulted in a significantly improved model fit, $\Delta \chi^2 (1) = 15.78$, $p < .001$ (compared with Model 3A). These interactions significantly predicted passage comprehension in G1 and G2 (*b*s = −.87, *p*s < .001; see Figure 3). The path from HTKS in K to passage comprehension in G1 was significant at low (b = 10.88, p = .001; see Figure 3A) and average (b = 6.1, p = .02) levels of CPT in K and was not significant at high levels of CPT in K (b = 1.32, p = .63). Similarly, the path from HTKS in G1 to passage comprehension in G2 was significant at low (b = 13.91, p < .001; see Figure 3B) and average levels of G1 HTKS (b = 6.1, p = .02) and not significant at high levels of G1 HTKS (b = −1.71, p = .59).

Self-regulation and applied problems achievement interactions.: Within a fourth interaction model (Model 5B), the interactions between CPT and applied problems achievement in K and G1, significantly predicted applied problems achievement in G1 and G2 (*b*s = −1.06, *p*s = .003), respectively, and significantly improved model fit, $\Delta \chi^2 (1) = 9.81$, p = .002 (compared to Model 5A). The path from CPT in K to applied problems achievement in G1 was significant at low levels of applied problems achievement in K (b = 24.65, p = .01; see Figure 4A) and not significant at average (b = 7.96, p = .19) and high levels of applied problems achievement in K (b = −8.73, p = .20). The path from CPT in G1 to applied problems achievement in G2 was significant at low levels of applied problems achievement in G1 (b = 25.15 p = .01; see Figure 4B) and not significant at average (b = 7.96, p = .19) and high levels of applied problems achievement in G1 (b = −9.23, p = .18). The interactions between HTKS and applied problems achievement (Model 4B), and the interactions between CPT and HTKS (Model 6B), did not significantly predict applied problems achievement from K to G1 or from G1 to G2.

Discussion

The present study used a longitudinal design to test whether the association of self-regulation with academic achievement was uniquely unidirectional or bidirectional across K, G1, and G2. We used two different measures of self-regulation that varied in the breadth of behavioral and motor control required; one tapped solely inhibitory control (CPT inhibition of impulsive responding index) whereas the other assessed the abilities to inhibit and activate desired behaviors and required regulation of sizable gross motor movements (HTKS). Self-regulation capacities assessed with the HTKS and with the CPT were not strongly associated in our sample of kindergarten and emerging elementary school students: They were weakly associated only in K and G2 in bivariate correlations and analytical models, but were not correlated in G1 (or in K in the passage comprehension model). These weak relations suggest that the two measures of self-regulation in this study differ in their regulatory demands and might relate differently to academic achievement.

Self-Regulation and Academic Adjustment from K to G2

The study's findings suggest that behavioral self-regulation assessed with the HTKS task and academic achievement were consistently related (even when controlling for prediction by the CPT index). The bidirectional findings for behavioral self-regulation and math are similar to prior findings within the pre-K year (Fuhs et al., 2014; Schmitt et al., 2017; Welsh et al., 2010) or from pre-K to K (Blair & Razza, 2007). Researchers have proposed that self-regulation is closely tied to math skill development (Blair et al., 2005) and the present study's bidirectional findings between self-regulation (for HTKS, and for CPT under conditions of low prior math achievement) and math achievement suggest that these skills co-develop in the transition from K to G2. These findings support a dynamic strengthening between math and self-regulation skills, perhaps because prefrontal cortex functioning is closely tied to the development of both math and self-regulation skills (Blair, 2016). We did not find bidirectional associations for reading, contrary to some prior research findings within pre-K (Bohlmann et al., 2015) and within G1 (Connor et al., 2016). Rather, the association from behavioral self-regulation (based on the HTKS) to reading achievement was unidirectional, consistent with most prior research findings (e.g., Lonigan et al., 2017; Matthews et al., 2009; Welsh et al., 2010). Our passage comprehension language measure was knowledge-based and did not primarily assess expressive language, which is thought to help children self-regulate via self-regulation speech (Bohlmann et al., 2015); the knowledge-based focus of the passage comprehension test may explain why the association between behavioral self-regulation and reading achievement was only unidirectional. Additionally, these associations were equal in magnitude from K to G1 and from G1 to G2, suggesting the importance of behavioral self-regulation does not diminish or intensify across these early elementary grade transitions.

The direct paths from self-regulation (based on the HTKS and, conditionally, on the CPT) to both reading and math add to a growing body of research literature examining self-regulation and school outcomes (Allan et al., 2014), as well as understanding unique aspects of self-regulation as predictors of academic achievement in the early elementary grades (Cameron et al., 2016). As mentioned earlier, the HTKS task demands may be more aligned to classroom-based demands compared to the CPT, given that the HTKS task in our study required a child to assimilate and adapt to an increasingly complex set of rules (McClelland & Cameron, 2012). The increasing complexity embedded in the HTKS task may be why HTKS scores more consistently predicted main effects for math and reading outcomes, given the complex regulatory requirements of math and reading development. The findings have implications for compensatory mechanisms involving self-regulation of gross motor activity and inhibitory control as it relates to academic achievement.

Rather than examine domain-general academic achievement, we examined math and reading separately. Prior findings suggest that self-regulation is more strongly associated with math compared to reading achievement (Allan et al., 2014; Clements et al., 2016), and our findings are somewhat consistent with prior findings given that there were more direct effects for math. Perhaps prefrontal cortex functioning more strongly underlies the association between behavioral self-regulation (measured with the HTKS) and math, which was bidirectional, than the association between behavioral self-regulation and reading, which was unidirectional, supporting prior arguments on the strong link between math and self-regulation (Blair, 2016). Also, learning math may require executive functioning beyond decoding skills and executive functioning is less relevant for literacy skills that have become automatic (Blair & Razza, 2007).

Prior Achievement and Self-Regulation as Moderators

Although most research suggests that self-regulation predicts academic achievement (Allan et al., 2014; Hernández et al., 2017; Jacob & Parkinson, 2015), identifying the moderating mechanisms underlying this association within a longitudinal framework can help researchers to tailor the design of interventions based on improving self-regulation to maximize effects (Clements et al., 2016). The study's findings suggest that CPT and HTKS self-regulation measures and prior academic achievement levels interact to jointly predict later math or reading achievement.

As hypothesized, inhibition-based self-regulation assessed with the CPT in G1 predicted higher math achievement in G2 for children who had lower G1 math achievement. Similarly, CPT scores in G1 predicted higher G2 reading achievement for children who had lower G1 reading achievement. This same moderation pattern was present from K to G1 for reading and math achievement. Thus, children who show lower levels of math or reading in K or G1 (because they have room for improvement with proper support) may better attend to and benefit from math or reading instruction across time when they have higher inhibitory regulation assessed with the CPT (while controlling for behavioral self-regulation assessed with the HTKS and other key background covariates). These findings imply that children's math and reading development may be supported by environments that promote inhibitory control, particularly for those with difficulties in math or reading in K or G1, consistent with prior research (Ribner et al., 2017). Furthermore, the findings suggest that inhibitory control-based self-regulation may be especially predictive of academic achievement before basic academic skills, such as decoding words, become automatic (Purpura et al., 2017). Children who are experiencing difficulties in math or reading are at an earlier stage of acquisition and their academic skills are not yet automatic; hence, inhibitory control-based self-regulation, such as ignoring irrelevant information and focusing on a specific task, might be especially predictive of later academic achievement for these children. Although further research is necessary, the findings suggest that variation in prior academic achievement may help explain the otherwise null main effect from CPT measures of self-regulation to reading or math across K to G2 found in this study, as well as other studies in other grades (Brennan et al., 2012; Liew et al., 2010; Romano et al., 2010).

Behavioral self-regulation assessed with the HTKS task predicted higher math and reading achievement regardless of prior academic achievement. Only main effects of HTKS task scores were present, consistent with prior evidence of robust associations between behavioral self-regulation and academic achievement (Allan et al., 2014; Clements et al., 2016), regardless of prior achievement level. Perhaps the interaction between prior academic achievement and HTKS task scores is not predictive of later academic achievement until children have accumulated social and academic experiences in school, setting a cumulative advantage for children with high behavioral self-regulation; for example, the study by Ribner et al. (2017) found that a similar interaction between achievement and executive functioning in preschool significantly predicted academic achievement in fifth grade.

As hypothesized and consistent with prior research (Cameron et al., 2015), behavioral self-regulation as assessed with the HTKS task in K and G1 predicted higher reading achievement in G1 and G2, respectively, especially for children with low or average inhibitory control as assessed with the CPT. This finding supports the proposition that the ability to inhibit impulsive responses may compensate for otherwise weak behavioral or motor integration, or vice versa (Cameron et al., 2015), suggesting compensatory mechanisms involving behavioral self-regulation as they pertain to academic achievement. That is, the benefit of having strong behavioral self-regulation is most helpful to learning to read for children who struggle with inhibitory control-based self-regulation, such as focusing on decoding words and ignoring irrelevant rules or information. Interventions designed to bolster children's self-regulation skills could target children who have low behavioral self-regulation, given that children who had low regulation assessed with both the CPT and HTKS had lower reading comprehension.

Study Strengths and Limitations

A strength of the present study is that it used two measures of self-regulation rather than relying solely on parent or teacher reports and assessed their unique prediction of academic functioning. We examined the associations of interest from K to G2, testing possible bidirectional associations across time using a cross-lagged longitudinal panel design. Given recent critiques of the cross-lagged panel model framework (Berry & Willoughby, 2017), future work will clarify the extent to which the tested associations account for bidirectional associations at the individual level. The use of standardized and behavioral measures and the inclusion of controls for stabilities and key background variables (e.g., socioeconomic status, gender, ethnicity) provided a strong test of the associations of interest. However, it is possible that unmeasured variables, such as school quality or school readiness skills, could have confounded the associations we tested; thus, future research examining possible confounding variables will clarify the conditions under which the association between self-regulation and academic achievement is present.

Limitations of the study include the inability to clearly quantify differences between our two measures of self-regulation (e.g., the degree to which they differentially tapped inhibitory control). Furthermore, although our study design was longitudinal, it was not experimental, which limits our ability to test casual effects (Jacob & Parkinson, 2015).

Future Research Directions

We chose to focus on two measures of self-regulation. Because different measures assess various aspects of self-regulation, research might further examine how different facets of self-regulation build on each other and relate to achievement in additive and non-additive ways. Although we examined the association between self-regulation and academic achievement from K to G2, nonlinear trajectories of this association should be examined across more time points. A closer analysis of children's self-regulation development, as well as modifiable factors that promote self-regulation, might reveal more nuanced associations with school outcomes. For example, physical coordination and movement likely promote children's self-regulation, such as motor inhibition (Stein, Auerswald, & Ebersbach, 2017), which would be expected to promote positive schooling outcomes (Becker et al., 2014). Interventions that promote children's sociodramatic play also may help improve self-regulation (Bierman & Torres, 2016).

Examining possible mediating factors, such as self-regulated learning skills (Zumbrunn, Tadlock, & Roberts, 2011) or specific academic skills (Fuhs, Hornburg, & McNeil, 2016), would be useful for assessing additional mechanisms by which self-regulation and academic achievement relate, particularly as children are increasingly expected to assume academic tasks independently. For instance, Fuhs et al. (2016) found that executive functioning skills predicted higher math achievement from K to G1 via number sets identification – a skill where children identify sets of objects and numbers that equal a target value. In the future, researchers could identify mediators that account for prediction by different self-regulation measures.

Conclusion

Results from this study suggest a complex association between self-regulation and reading and math achievement in the transition to elementary school. Although there was some direct prediction from self-regulation to academic achievement, bidirectional and interacting effects also emerged. These findings suggest that to improve children's math and reading levels in this transition, interventions could target both self-regulation and academic readiness. The results depended partly on the type of self-regulation measures included, suggesting the utility of assessing multiple measures of self-regulation and testing their unique and interacting associations with academic achievement in future research.

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Appendix 1: Summary of research literature on the association between self-regulation and academic achievement

Citation	Grade or age range; design	Self-regulation measures	Math or reading achievement associations
Allan et al. (2014)	preschool, kindergarten; meta-analysis	Inhibitory control based on parent, teacher, observer reports; behavior tasks (e.g., grass/snow Stroop, peg-tapping)	Inhibitory control was positively associated with math and literacy (prediction was stronger for math than literacy).
Becker et al. (2014)	preschool; cross-sectional	Head–Toes–Knees–Shoulders task	Behavioral self-regulation was positively associated with math and literacy scores.
Blair and Razza (2007)	preschool, kindergarten; longitudinal	Inhibitory control based on a peg-tapping task, attention shifting based on an item-selection task	Inhibitory control in preschool and kindergarten uniquely predicted higher kindergarten math scores. Inhibitory control in kindergarten also uniquely predicted higher levels of kindergarten phonemic awareness and letter knowledge.
Blair et al. (2015)	preschool, first grade, second grade; longitudinal	Various measures of self-regulation: Executive functioning, which included inhibitory control, working memory, and attention shifting tasks. Effortful control included the Dinky Toys task, and parent and teacher reports of attentional focusing and inhibitory control.	Self-regulation measures primarily predicted higher math and reading levels in preschool. Self-regulation based on teacher-reports of effortful control predicted steeper growth in math from preschool to second grade, whereas self-regulation based on direct behavioral measures of executive functioning predicted slower growth in math from preschool to second grade.
Bohlmann et al. (2015)	preschool, kindergarten; longitudinal	Pencil-tap, toy sort latency composite Executive Control/compliance score	Self-regulation positively predicted later expressive vocabulary. Expressive vocabulary positively predicted later self-regulation.
Brock et al. (2009)	kindergarten; longitudinal	Cool executive functioning (Balance beam, pencil-tap), Hot executive functioning (toy sort task, gift wrap task)	Cool executive functioning measures predicted higher math achievement but did not predict reading achievement.
Clements et al. (2016)	childhood; research literature review	Variety of EF skills, involving attention shifting, cognitive flexibility, and working memory	The research review supported bidirectional associations between executive functioning and math.
Connor et al. (2016)	first grade, second grade; longitudinal	Self-regulation with Head–Toes–Knees–Shoulders task, and an attention and hyperactivity scale	Self-regulation predicted concurrent reading comprehension in first grade. Reading comprehension in kindergarten predicted subsequent self-regulation in first grade.
Diamantopoulou et al. (2007)	ages 8 to 9.5; longitudinal	Various measures indicating executive functioning deficits	Executive functioning deficits predicted lower general academic functioning.
Friedman-Weieneth et al. (2007)	preschool, age 3; cross-sectional	Various measures of ADHD hyperactivity	ADHD hyperactivity symptoms predicted lower pre-academic language and math skills.
Fuhs et al. (2016)	kindergarten, second grade; longitudinal	Executive functioning measure composite included Day/Night Stroop and Dimensional Change Card Sort tasks.	Executive functioning in kindergarten predicted higher math achievement in second grade.
Fuhs et al. (2014)	prekindergarten, kindergarten; longitudinal	Executive functioning measure composite included backward digit span, copy design, Dimensional Change Card Sort, Head–Toes–Knees–Shoulders, reflection-impulsivity, and peg-tapping tasks.	Math and oral comprehension at the start of prekindergarten predicted executive functioning at the end of prekindergarten. Executive functioning predicted math and oral comprehension across prekindergarten and from prekindergarten to kindergarten. Executive functioning at the start of prekindergarten predicted letter-word identification at the end of prekindergarten, but not in kindergarten.
Kim et al. (2017)	kindergarten, first grade; longitudinal	Design copy task measuring visuomotor integration, visual attention with a task assessing accuracy identifying a target picture in a set of pictures, visuomotor coordination with a task assessing speed and accuracy of eye-hand coordination of a line drawing	Attention and visuomotor integration generally predicted higher math scores across the kindergarten year, first grade, and from first to second grade. Visuomotor integration predicted higher math scores, and vice versa, within kindergarten, from kindergarten to first grade, and within first grade.

Citation	Grade or age range; design	Self-regulation measures	Math or reading achievement associations
Liew et al. (2010)	first grade, second grade; longitudinal	Effortful control included inhibitory control and task accuracy measures from Walk-a-Line, Star, Telephone Poles, and Circle tasks.	Effortful control (accuracy in a task involving fine motor skills) in first grade predicted higher math and reading achievement in second grade, especially for those who had difficulties with teachers.
Lonigan et al. (2017)	preschool; longitudinal	Head–Toes–Knees–Shoulders task, teacher-reported inattention	Self-regulation predicted initial literacy levels in preschool. Inattention predicted growth in literacy skills across preschool.
Matthews et al. (2009)	kindergarten; longitudinal	Head–Toes–Knees–Shoulders task, teacher-reported self-regulation	Self-regulation predicted higher math scores and sound awareness gain scores, and did not predict academic knowledge, letter-word identification, and picture vocabulary gain scores.
McClelland et al. (2007)	pre-kindergarten; longitudinal	Head–Toes–Knees–Shoulders task	Behavioral self-regulation in the spring of preschool predicted concurrent math, emergent literacy, and vocabulary skill levels, controlling for skills in the fall. Behavioral self-regulation in the fall of preschool did not predict math, emergent literacy, and vocabulary skills in the spring of preschool when controlling for skills in the fall. Gains in behavioral self-regulation predicted gains in math, emergent literacy, and vocabulary.
NICHD Early Child Care Research Network (2003)	54-month-olds; cross-sectional	Lack of sustained attention and impulsivity measures calculated from the Continuous Performance Task	Lack of sustained attention and higher impulsivity were associated with lower math and reading achievement.
Ponitz et al. (2009)	kindergarten; longitudinal	Head–Toes–Knees–Shoulders task	Behavioral regulation in the fall of kindergarten predicted higher math, literacy, and vocabulary skills in the spring of kindergarten. Once fall skill level scores were included, behavioral regulation in the fall of kindergarten only predicted math in the spring of kindergarten.
Rabiner et al. (2000)	kindergarten, first grade, fifth grade; longitudinal	teacher-reported inattention and hyperactivity	Inattention in second grade predicted lower reading levels in fifth grade.
Razza et al. (2010)	five-year-olds; cross-sectional	Focused attention and lack of impulsivity based on the Leiter International Performance Scale—Revised	Focused attention and lack of impulsivity predicted higher levels of receptive vocabulary.
Romano et al. (2010)	kindergarten, third grade; longitudinal	Mother-reported attention and hyperactivity/impulsivity	Attention skills in kindergarten predicted higher math and reading achievement in third grade. Hyperactivity/impulsivity in kindergarten predicted lower reading skills and did not predict math skills in third grade.
Schmitt et al. (2017)	preschool, kindergarten; longitudinal	Executive functioning measured with Head–Toes–Knees–Shoulders task, Card Sort task, Auditory Working Memory subtest, and Simon Says task	Executive functioning predicted higher math across prekindergarten and kindergarten, and higher literacy across kindergarten. Math also predicted higher executive functioning across prekindergarten and from prekindergarten to kindergarten. Growth in executive functioning was positively associated with growth in math, but not in literacy.
Welsh et al. (2010)	prekindergarten, kindergarten; longitudinal	Working memory and attentional control aspects of executive functioning measured with the Backward Word Span, Peg Tapping task, and the Dimensional Change Card Sort.	Executive functioning predicted higher emergent literacy across prekindergarten and reading in kindergarten. The association between executive functioning and numeracy skills was bidirectional in prekindergarten. Executive functioning predicted higher math scores in kindergarten.

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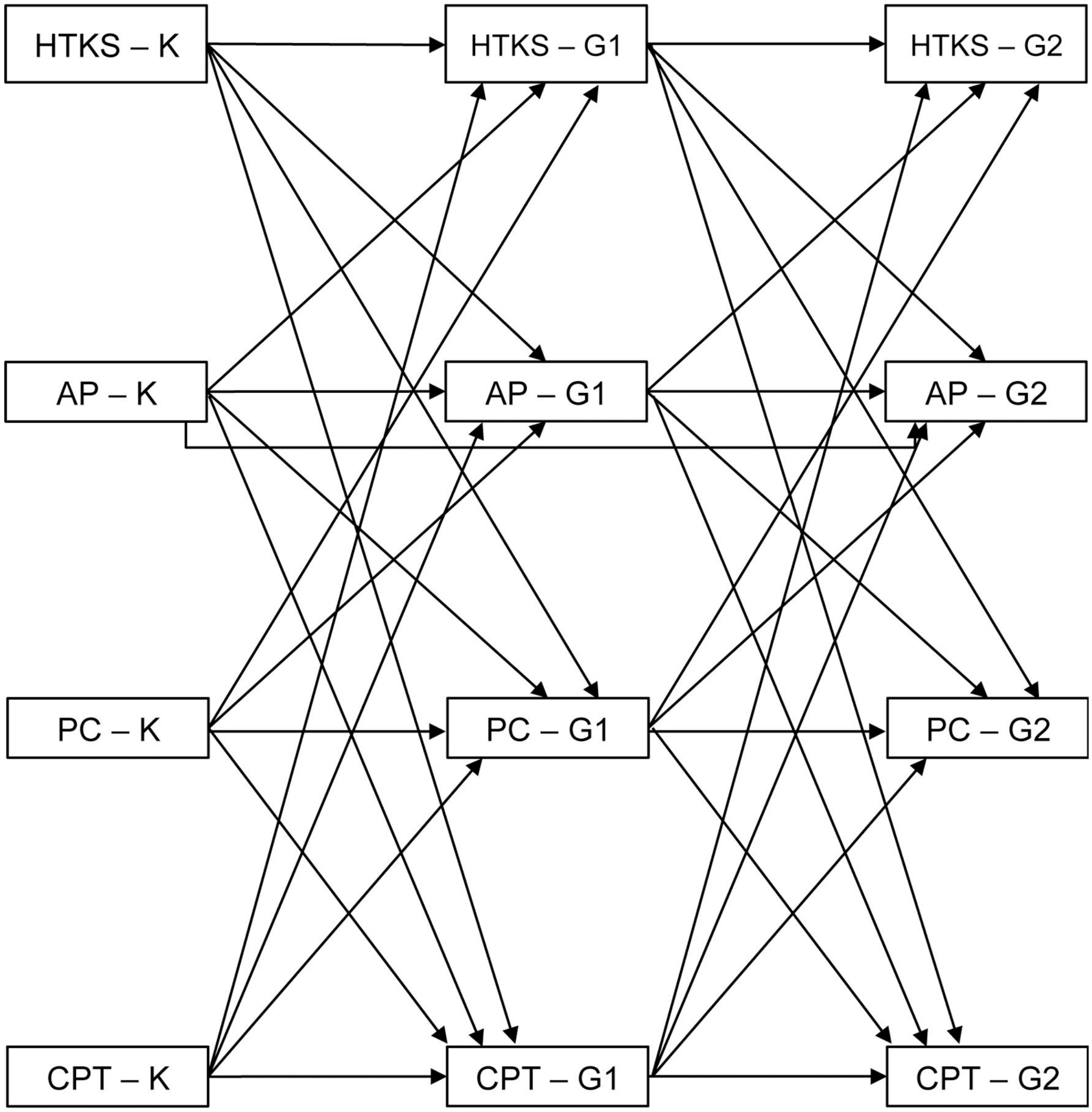

Figure 1.

Longitudinal and bidirectional associations tested between self-regulation (Head-Toes-Knees-Shoulders [HTKS] task score or Continuous Performance Task Correct Rejection [CPT CR] score) and passage comprehension (PC) academic achievement in K, G1, and G2, controlling for covariates (i.e., socioeconomic status, ethnic minority status, male, age; not shown in this figure). Within-grade correlations and covariate control paths were estimated but are not shown in this figure.

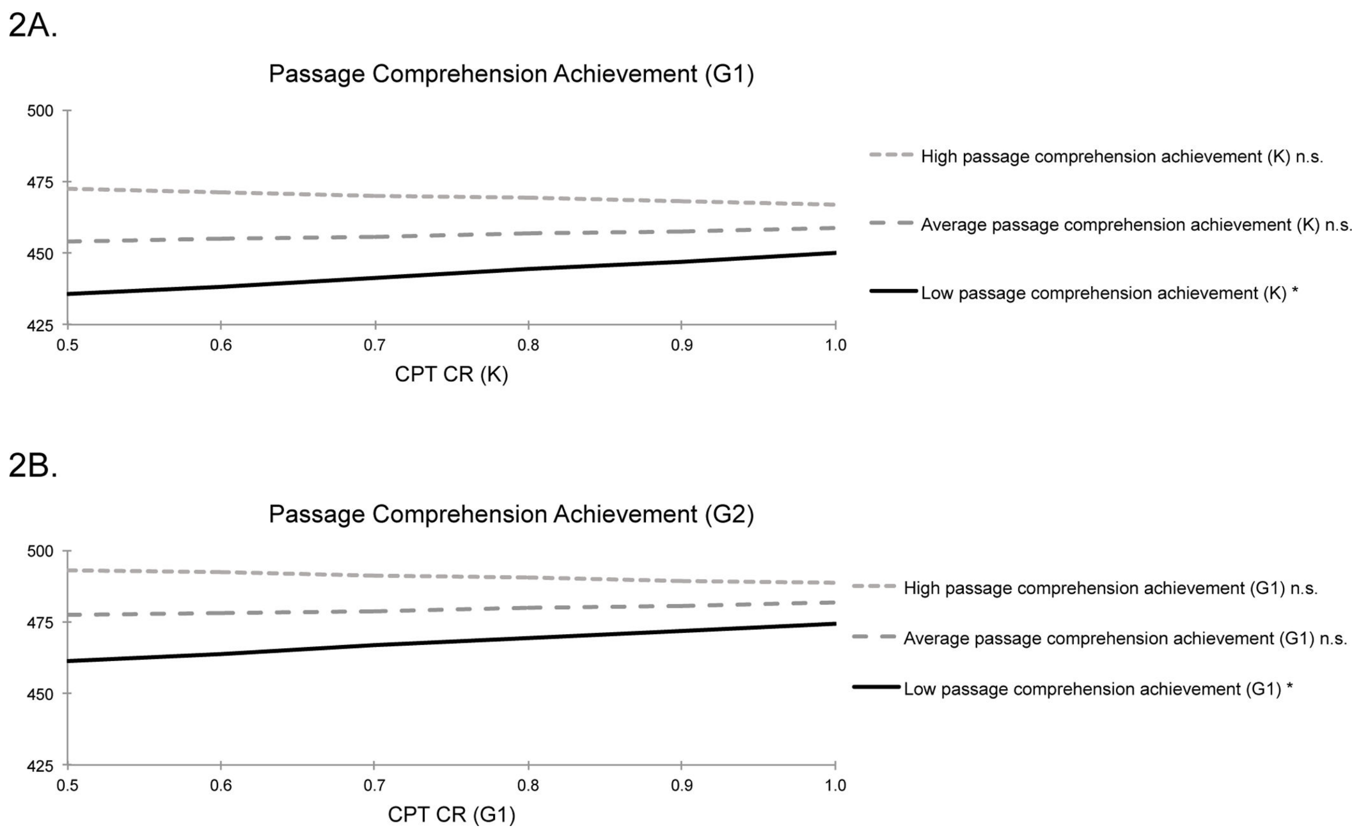

Figure 2.

Interactions between Continuous Performance Task Correct Rejection (CPT CR) score and passage comprehension achievement predicting later passage comprehension achievement, (A) from kindergarten to first grade and (B) from first grade to second grade.

* $p < .05$.

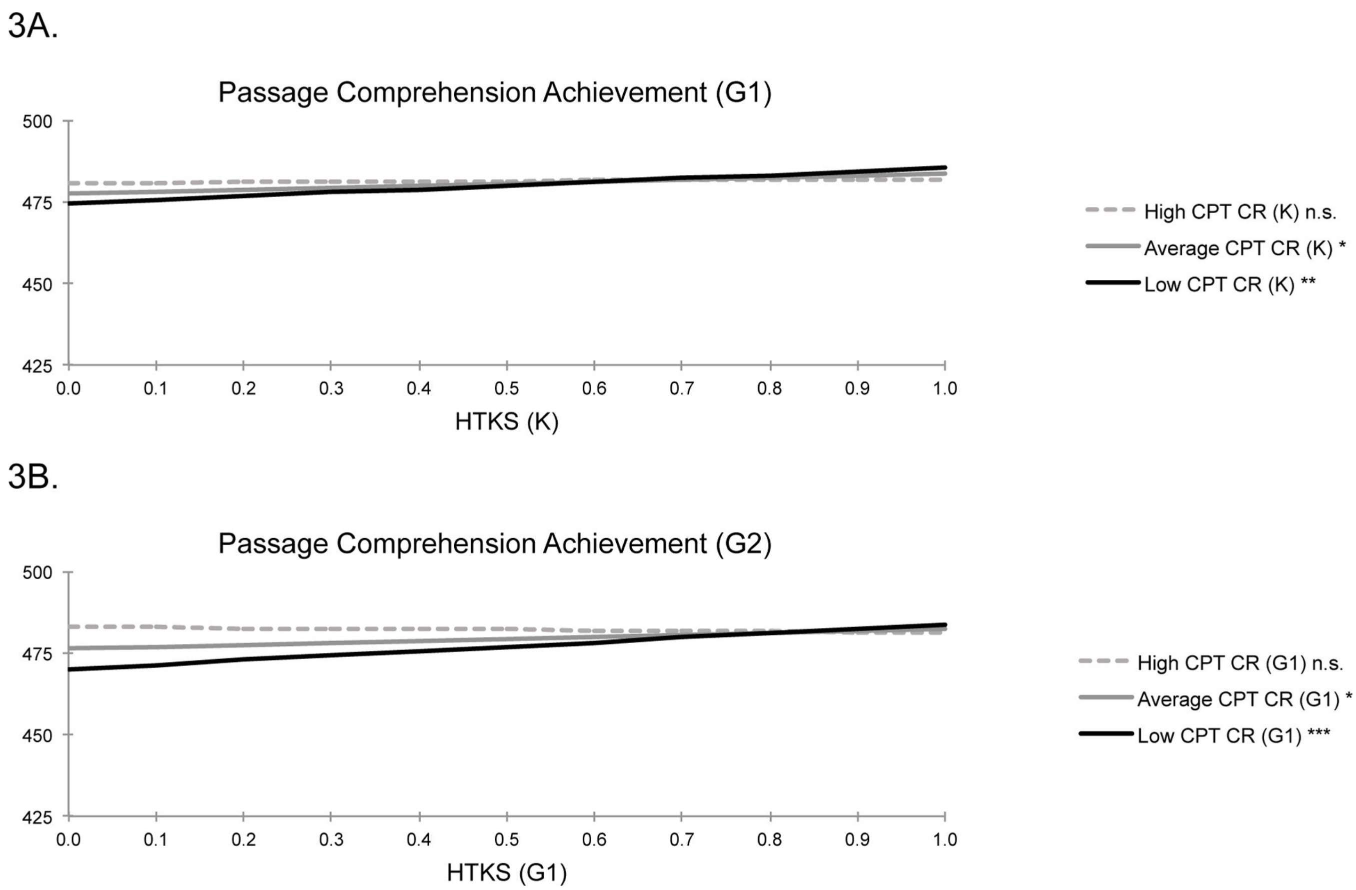

Figure 3.

Interactions between Head-Toes-Knees-Shoulders (HTKS) task score and Continuous Performance Task Correct Rejection (CPT CR) score predicting passage comprehension achievement (A) from kindergarten to first grade and (B) from first grade to second grade. * $p < .05$. ** $p < .01$. *** $p < .001$.

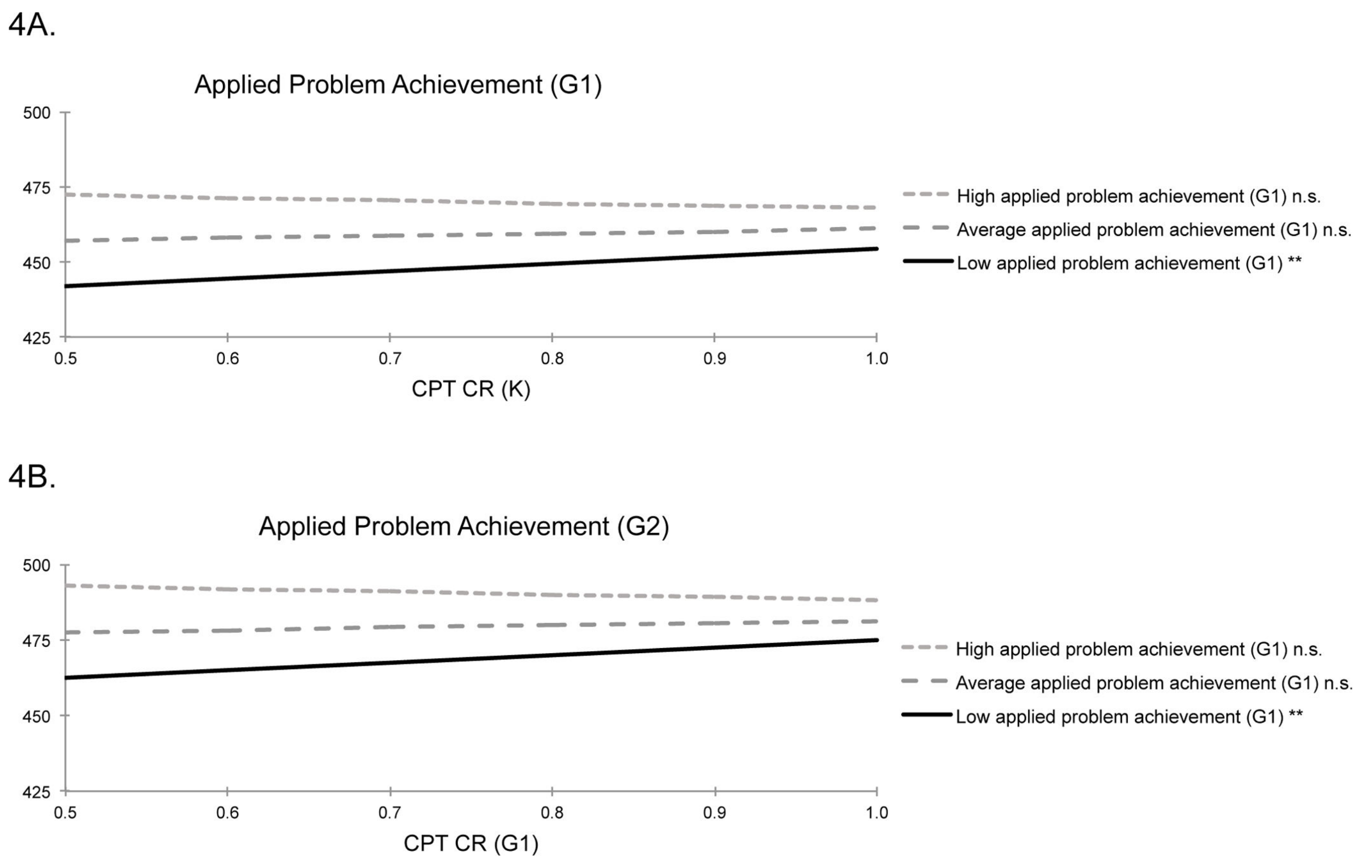

Figure 4.

Interactions between Continuous Performance Task Correct Rejection (CPT CR) score and applied problems achievement predicting later applied problems achievement, (A) from kindergarten to first grade and (B) from first grade to second grade.

** $p < .01$.

Table 1:

Descriptive statistics and correlations among study variables (*N* = 301)

			1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
1.	HTKS	K	---															
2.	HTKS	G1	.51***	---														
3.	HTKS	G2	.41***	.34***	---													
4.	CPT CR	K	.11†	−.02	.10	---												
5.	CPT CR	G1	−.04	.00	.00	.26***	---											
6.	CPT CR	G2	.08	.02	.20**	.15*	.37***	---										
7.	WJPC	K	.36***	.25***	.16*	.13*	−.02	.01	---									
8.	WJPC	G1	.43***	.35***	.28***	.03	−.05	.01	.62***	---								
9.	WJPC	G2	.44***	.36***	.30***	.11†	−.02	−.03	.53***	.78***	---							
10.	WJAP	K	.51***	.41***	.36***	.06	.05	.10	.53****	.54***	.60***	---						
11.	WJAP	G1	.50***	.35***	.33***	.03	−.03	.08	.52***	.58***	.60***	.69***	---					
12.	WJAP	G2	.54***	.43***	.37***	.03	−.04	.04	.55***	.60***	.66***	.70***	.75***	---				
13.	SES	K	.36***	.34***	.22***	.04	−.05	.03	.38***	.39***	.45***	.45***	.37***	.47***	---			
14.	EMS	K	−.12*	−.10	.00	.08	.13*	.09	−.17**	−.23***	−.29***	−.25***	−.29***	−.25***	−.34***	---		
15.	Male	K	.08	.06	.08	−.24***	−.27***	−.27***	.03	.01	.09	.16**	.23***	.24***	.10†	−.07	---	
16.	Age	K	−.08	−.04	−.10	−.10	−.05	.09	.02	−.09	−.11†	.03	−.02	−.05	−.10†	−.10†	.12*	---
	M		0.56	0.74	0.83	0.95	0.93	0.95	428.53	464.67	481.05	442.84	461.72	481.51	-0.05	0.64	0.49	5.48
	SD		0.26	0.20	0.15	0.06	0.09	0.06	20.96	18.47	14.56	15.83	16.31	19.91	-1.83	0.48	0.50	0.35
	Min.		0.00	0.00	0.00	0.65	0.37	0.44	368	391	430	388	403	427	1.16	0	0	4.27
	Max.		1.00	1.00	1.00	0.99	0.99	0.99	503	525	528	504	528	539	0.91	1	1	6.81

Note. HTKS = Head-Toes-Knees-Shoulders task score; CPT CR = Continuous Performance Task Correct Rejection score; WJPC = Woodcock-Johnson Tests of Achievement passage comprehension score; WJAP = Woodcock-Johnson Tests of Achievement applied problems score; EMS = ethnic minority status (1 = *ethnic minority*, 0 = *white, non-Hispanic*); SES = socioeconomic status; Male (1 = *boy*, 0 = *girl*); K = kindergarten; G1 = first grade; G2 = second grade.

† $p < .10$

* $p < .05$

** $p < .01$

*** $p < .001$.

Table 2:

Cross-lagged panel model results

	Estimates from K to G1			**Estimates from G1 to G2**					
	b*	**S.E.**	***p*-value**	***b****	**S.E.**	***p*-value**			
Stabilities									
HTKS	**.37*****	**.07**	**< .001**	**.24****	**.09**	**.007**			
CPT CR	**.13*****	**.04**	**< .001**	**.30*****	**.07**	**< .001**			
WJAP	**.45*****	**.04**	**< .001**	**.40*****	**.04**	**< .001**			
WJPC	**.48*****	**.05**	**< .001**	**.56*****	**.04**	**< .001**			
Cross-lagged paths									
HTKS ➔ CPT CR	−.04	.04	.34	−.05	.05	.33			
CPT CR ➔ HTKS	−.01	.02	.74	−.02	.05	.74			
WJPC ➔ WJAP	**.22*****	**.04**	**< .001**	**.16*****	**.03**	**< .001**			
WJAP ➔ WJPC	**.16*****	**.03**	**< .001**	**.22*****	**.04**	**< .001**			
HTKS ➔ WJPC	**.09***	**.04**	**.03**	**.09***	**.04**	**.03**			
WJPC ➔ HTKS	.02	.05	.75	.02	.06	.75			
CPT CR ➔ WJPC	.02	.02	.39	.03	.04	.39			
WJPC ➔ CPT CR	−.08	.05	.11	−.09†	.05	.07			
HTKS ➔ WJAP	**.18*****	**.03**	**< .001**	**.12*****	**.02**	**< .001**			
WJAP ➔ HTKS	**.18*****	**.04**	**< .001**	**.26*****	**.06**	**< .001**			
CPT CR ➔ WJAP	.02	.02	.32	.03	.03	.30			
WJAP ➔ CPT CR	**.16***	**.06**	**.01**	**.24****	**.07**	**< .001**			
	Estimates in K			Estimates in G1			Estimates in G2		
	*b**	S.E.	*p*-value	*b**	S.E.	*p*-value	*b**	S.E.	*p*-value
Correlations									
HTKS & WJAP	**.52*****	**.05**	**< .001**	.03	.05	.52	.06	.08	.48
HTKS & WJPC	**.37*****	**.06**	**< .001**	.11	.07	.12	.06	.06	.32
HTKS & CPT CR	.11	.07	.10	.02	.03	.45	**.21***	**.09**	**.02**
CPT CR & WJAP	.09	.07	.21	.03	.05	.63	.01	.08	.94
CPT CR & WJPC	**.16****	**.06**	**.004**	−.06	.06	.34	−.10	.06	.10
WJAP & WJPC	**.53*****	**.06**	**< .001**	**.22*****	**.06**	**< .001**	**.15***	**.07**	**.02**

Note. Longitudinal associations among Head-Toes-Knees-Shoulders (HTKS) task score, Continuous Performance Task Correct Rejection (CPT CR) score, passage comprehension (WJPC) achievement, and applied problems (WJAP) achievement in kindergarten (K), first grade (G1), and second grade (G2), controlling for covariates: socioeconomic status, ethnic minority, male, age. Significant standardized coefficients (*b**) are in **bold**. MLR χ^2 (29) = 42.19, p = .05, CFI = .99, RMSEA = .04, 90% CI [.00, .06].

$^{\dagger}p < .10$

$^{*}p < .05$

** $p < .01$

*** $p < .001$.

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Table 3:

Models testing interactions as predictors of passage comprehension (PC) and applied problems (AP) achievement

	Model 1A: PC			Model 1B: PC				Model 4A: AP			Model 4B: AP		
G1 PC	B	S.E.	*p*	B	S.E.	*p*	**G1 AP**	B	S.E.	*p*	B	S.E.	*p*
HTKS (K)	**6.25** *	**2.74**	**.02**	**7.06** *	**2.77**	**.01**	HTKS (K)	**11.87** ***	**19.7**	**< .001**	**12.01** ***	**.19**	**< .001**
PC (K)	**.43** ***	**.03**	**< .001**	**.43** ***	**.03**	**< .001**	AP (K)	**.48** ***	**.05**	**< .001**	**.48** **	**.05**	**< .001**
HTKS x PC (K)	.00	.00	--	.12	.11	.25	HTKS x AP (K)	.00	.00	--	.03	.10	.77
G2 PC							**G2 AP**						
HTKS (G1)	**6.25** *	**2.74**	**.02**	**7.06***	**2.77**	**.01**	HTKS (G1)	**11.87** ***	**19.7**	**< .001**	**12.01** ***	**.19**	**< .001**
PC (G1)	**.43** ***	**.03**	**< .001**	**.43** ***	**.03**	**< .001**	AP (G1)	**.48** ***	**.05**	**< .001**	**.48** **	**.05**	**< .001**
HTKS x PC (G1)	.00	.00	--	.12	.11	.25	HTKS x AP (G1)	.00	.00	--	.03	.10	.77
Model fit change:				$\Delta\ \chi^2$ (1) = 1.5, p = .22							$\Delta\ \chi^2$ (1) = .08, p = .77		
	Model 2A: PC			Model 2B: PC				Model 5A: AP			Model 5B: AP		
G1 PC	B	S.E.	*p*	B	S.E.	*p*	**G1 AP**	B	S.E.	*p*	B	S.E.	*p*
CPT CR (K)	5.33	6.42	.41	8.88	7.06	.21	CPT CR (K)	6.62	6.63	.32	7.96	6.04	.19
PC (K)	**.43** ***	**.03**	**< .001**	**.45** ***	**.03**	**< .001**	AP (K)	**.48** ***	**.05**	**< .001**	**.48** ***	**.05**	**< .001**
CPT x PC (K)	.00	.00	--	−.95 *	.42	.02	CPT x AP (K)	.00	.00	--	**−1.06** **	**.35**	**.003**
G2 PC							**G2 AP**						
CPT CR (G1)	5.33	6.42	.41	8.88	7.06	.21	CPT CR (G1)	6.62	6.63	.32	7.96	6.04	.19
PC (G1)	**.43** ***	**.03**	**< .001**	**.45** ***	**.03**	**< .001**	AP (G1)	**.48** ***	**.05**	**< .001**	**.48** ***	**.05**	**< .001**
CPT x PC (G1)	.00	.00	--	−.95 *	.42	.02	CPT x AP (G1)	.00	.00	--	**−1.06** **	**.35**	**.003**
Model fit change:				$\Delta\ \chi^2$ (1) = 5.26, p = .02							$\Delta\ \chi^2$ (1) = 9.81, p = .002		
	Model 3A: PC			Model 3B: PC				Model 6A: AP			Model 6B: AP		
G1 PC	B	S.E.	*p*	B	S.E.	*p*	**G1 AP**	B	S.E.	*p*	B	S.E.	*p*
HTKS (K)	**6.3** *	**2.7**	**.02**	**6.1** *	**2.7**	**.02**	HTKS (K)	**11.9** ***	**2.0**	**< .001**	**11.8** ***	**2.0**	**< .001**
CPT CR (K)	5.4	6.4	.40	7.7	6.0	.20	CPT CR (K)	6.7	6.6	.31	6.8	6.5	.29
CPT x HTKS (K)	.00	.00	--	**−87.3** ***	**26.6**	**< .001**	CPT x HTKS (K)	.00	.00	--	−33.4	33.8	.32
G2 PC							**G2 AP**						
HTKS (G1)	**6.3** *	**2.7**	**.02**	**6.1** *	**2.7**	**.02**	HTKS (G1)	**11.9** ***	**2.0**	**< .001**	**11.8** ***	**2.0**	**< .001**

CPT CR (G1)	5.4	6.4	.40	7.7	6.0	.20	CPT CR (G1)	6.7	6.6	.31	6.8	6.5	.29
CPT x HTKS (G1)	.00	.00	--	**−87.3** ***	**26.6**	**< .001**	CPT x HTKS (G1)	.00	.00	--	−33.4	33.8	.32
Model fit change:				$\Delta\ \chi^2$ (1) = 15.78, $p < .001$							$\Delta\ \chi^2$ (1) = 1.10, $p = .29$		

Note. The models presented in this table were estimated as in Table 1, along with added interaction estimates. The first columns (e.g., Model 1A) represent models with interactions estimated at zero as predictors of PC or AP, and the adjacent columns (e.g., Model 1B) represent models with interactions estimated as predictors of PC or AP. For simplicity, only the interactions and associated main effect estimates predicting either PC or AP achievement within the cross-lagged models are presented. K = kindergarten; G1 = first grade; G2 = second grade. Coefficients are unstandardized. Significant unstandardized coefficients (B) are in bold.

* $p < .05$

** $p < .01$

*** $p < .001$.