

How executive control predicts early reading development

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Attentional and action control are two levels of executive control that are essential to early reading development. Together these levels enable the construction and monitoring of cognitive representations and of efficient task-behavior, which are both necessary to benefit from reading instruction. The longitudinal and unique contributions of this internal and external level of executive control to early reading are still unclear. We therefore examined how these control capacities facilitate reading development from kindergarten to second-grade. Attentional and action control and multiple early reading skills were assessed at all three time points. Structural Equation Modeling showed a mediation effect for attentional control and an indirect effect for action control to subsequent reading skills via the contributions to the precursor of phonological awareness. From these results it can be concluded that both types uniquely allowed for the emergence of kindergarten preliteracy skills, which in turn provided children with a better starting point for reading development in first- and second-grade.

Keywords: executive control, attentional control, action control, early reading development

1. Introduction

Reading comprehension is a primary educational goal but a very complex ability to master. While reading texts, bottom-up as well as top-down processes are necessary, because the reader has to decode words and simultaneously integrate the meaning that is conveyed (Perfetti, 2007). These higher-level processes rely upon the control system, with two main types of executive control in particular: attentional control at an internal level, and action control at an external level (Cain, 2006; Cartwright, 2012; Christopher et al., 2012; Diamond, 2013). *Attentional control* helps to monitor the cognitive representations of the text that is read (Arrington,

Kulesz, Francis, Fletcher, & Barnes, 2014; Conners, 2009). *Action control* prevents acting out impulsively in class and is thus crucial to sustain goal-directed behavior and benefit from reading instruction (Altemeier, Abbott, & Berninger, 2008; Diamond, Barnett, Thomas, & Munro, 2007). The importance of both types of executive control for reading development are established, but longitudinal studies in which both executive control and literacy skills are assessed at all time points are severely lacking (McClelland, Acock, & Morrison, 2006; Willoughby, Kupersmidt, & Voegler-Lee, 2012). Moreover, most studies considered executive contributions with subjective teacher-ratings of either attentional *or* action control. Finally, studies that included different types of executive control generally related these to a composite score of reading skills, while it has been shown that executive control contributes differently to different aspects of literacy development (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014; Segers, Damhuis, Van de Sande, & Verhoeven, 2016). The aim of the present study therefore was to longitudinally examine the unique direct and indirect contributions of objective and domain-general measures of attentional and action control to decoding and reading comprehension in second-grade via advancements in prior executive control and reading skills in kindergarten and first-grade.

1.1 Direct contributions of attentional and action control to early reading development

Children start to develop the blueprint for reading comprehension at an early age, when they are read to, and instructed by, their parents and teachers. This way, they acquire key underlying skills such as phonologic awareness and decoding (Bus & van IJzendoorn, 1999; Perfetti, 2011; Stanovich, 2000, Torgesen, 2000). *Phonological awareness* begins to develop around four years of age, and progresses rapidly from a syllable and onset-rime level to an experienced phoneme level at six years of age (Bradley & Bryant, 1983; Castles & Coltheart, 2004; Goswami, 2000). From children's phonological awareness grows their understanding that a phonological form corresponds to an orthographic form and that, just as with phonemes, graphemes can be connected to form a written word (Melby-Lervåg, Lyster, & Hulme, 2012; Verhoeven, Reitsma & Siegel, 2011). The ability to *decode* words then gradually develops with increased accuracy and speed to an automatized recognition of written words (Adams, 1990; Ehri, 2005; Verhoeven & Van Leeuwe, 2009). Children also acquire further phonological abilities alongside the development of decoding skills. Soon after the ability to decode words (around six years of age) follows the reading of sentences and text passages. Children then also start to acquire the understanding of the meaning of the text at the lexical, semantic, syntactic, and pragmatic level (Perfetti, 1992; Perfetti, Landi, & Oakhill, 2005).

In addition to bottom-up phonological and decoding skills, reading comprehension recruits the executive control system (Hagoort, 2013). This cognitive system is necessary to relate language processing with children's cognitive and behavioral processes during reading and reading instruction. On a cognitive (i.e., *attentional*) level, executive control is crucial for suppressing irrelevant information retrieval, updating the mental model of a text and flexibly switching between orthographic, semantic and spoken representations (e.g., Arrington et al., 2014; Henderson, Snowling, & Clarke, 2013; Sesma, Mahone, Levine, Eason, & Cutting, 2009). On an external (i.e., *action*) level, executive control is associated with inhibiting inappropriate behavior, holding the task in mind and adapt to changing task demands, and is thus necessary to stay focused to a text and to benefit from reading-related classroom activities (e.g., Best, Miller, & Naglieri, 2011; Diamond, 2013; Kegel & Bus, 2014). These control processes are driven by an interaction of the core executive functions inhibition, working memory, and cognitive flexibility. For example, inhibition is necessary to automatically resist irrelevant information retrieval from memory on an attentional level and to withhold from impulsive actions in a tempting kindergarten environment on a behavioral level (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Diamond, 2013). Working memory relates to attentional control for the simultaneous processing and storage of information, and relates to action control in avoiding task failures caused by lengthy instructions (Alloway, Gathercole, Kirkwood, & Elliot, 2009; McClelland, Cameron, Wanless, & Murray, 2007). And cognitive flexibility is necessary to flexibly shift attention between different sounds and graphemes and to adapt to changing task demands in the classroom (Altemeier et al., 2008, Dally, 2006; Foy & Mann, 2013; Walcott, Scheemaker, & Bielski, 2010).

Longitudinal insights about attentional benefits to reading development early in life are still quite limited (Garon, Bryson, & Smith, 2008). Dally (2006) established a relation between inattention in kindergarten and reading comprehension in second-grade, and Rabiner et al. (2000) showed that kindergarten attentional control contributed to first-grade decoding. Moreover, they showed that the number of children with reading difficulties due to inattentiveness doubled from kindergarten to first-grade, suggesting that it is difficult to catch up once attentional control interferes with early reading development. However, as in many studies examining attention to reading, the subjective assessment of attentional control by teachers in the studies above inevitably included some assessment of external (i.e., *action*) control as well, because teachers perceive children's attention through their learning behavior that is visible. A focus on more cognitive, direct measures of attentional control is thus called for.

As with attentional control, only few studies longitudinally investigated benefits of action control to beginning reading development, and used subjective

assessments. As a case in point, Hirvonen et al. (2010) established that kindergartners reduced their task-focused behavior, which is driven by action control, and gave up more quickly when the reading tasks were difficult. Likewise, Lepola, Niemi, Kuikka, and Hannula (2005) established contributions of kindergarten task-focused behavior to decoding and reading comprehension in second-grade, even when controlling for prior reading skills. McClelland, Acock, and Morrison (2006) evidenced that kindergartners with low abilities to regulate their actions in the classroom remained behind on their peers on reading comprehension, resulting in a widening gap in this skill from kindergarten to second-grade. Furthermore, Spira, Bracken, and Fischel (2005) showed that kindergarten reading deficits could be overcome by behavioral factors, and helped to provide a better basis for the development of reading comprehension in fourth-grade.

Converging evidence thus suggests that poor attentional and action control in kindergarten could hamper the development of later reading development. However, more fine-grained insights are called for. That is, most studies concerned the influence of only one type of executive control, while in fact both types might contribute uniquely to early reading development (see Foy & Mann, 2013; Van de Sande, Segers, & Verhoeven, 2013). Blair and Razza (2007), for example, evidenced that preschool attentional control benefitted to letter-sound knowledge in kindergarten while action control did not. Furthermore, most studies on this topic did not collect measures of executive control at each time-point of their longitudinal design but only at the beginning of the examined trajectory of reading development. Exemplarily, in a recent study we found a predictive role for attentional and action control in kindergarten to reading comprehension in second-grade, but that sample did not provide the opportunity to examine the direct ongoing contributions of executive control over these three years of time (Segers et al., 2016). Such information is necessary given that early executive control seems to lay the basis of precursors for academic achievements already before formal education begins, which might indicate a changing role of executive control in the transition from informal to formal literacy education (Wass, Sceriff, & Johnson, 2012). Lepola et al. (2005), for example, showed that task-focused behavior both before formal education and concurrently did contribute to second-grade decoding and reading comprehension, while task-orientation in first-grade did not. Related to this, it has been found that classroom behavior in first-grade did not contribute to consecutive reading skills when kindergarten action inhibition was included in the model, despite initial significant correlations (von Suchodoletz, Trommsdorf, Heikamp, Wieber, & Gollwitzer, 2009).

Furthermore, the role of executive control to different reading skills might differ given the variation in complexity and automation in these reading skills, but previous studies mostly used a composite reading score that taps multiple reading

abilities. Only a recent study by Arrington et al. (2014) disentangled effects of attentional control to multiple reading skills, albeit in adolescents. They showed that attentional inhibition predicted reading comprehension, but not decoding. Moreover, whereas reading comprehension continues to demand attentional control in order to update the mental model of the texts, reading abilities such as decoding might rapidly progress to an automatized process in the early grades, which leads to diminished attentional demands over time (see Adams, 1990; Ehri, 2005; Verhoeven & van Leeuwe 2009).

That is, when phonological and decoding abilities are not yet automatized and hence still require explicit and effortful processing, children need to recruit more of their executive control resources to process these reading abilities. This will be at the expense of executive resources to reading comprehension (e.g., Dally, 2006; Perfetti, 1992). In kindergarten and first-grade, children need attentional control to consciously process and decode phonological information by, exemplarily, suppressing attention to irrelevant phonological codes and flexibly shifting attention between different sounds and graphemes (Altemeier et al., 2008, Dally, 2006; Foy & Mann, 2013; Walcott, Scheemaker, & Bielski, 2010). And for external control of their actions as well, evidence has shown that it helps to benefit from (informal) reading instruction in kindergarten and first-grade (Diamond & Lee, 2011; Kegel, van der Kooy-Hofland, & Bus, 2009; McClelland, Cameron, Connor, et al., 2007; von Suchodoletz, Trommsdorff, Heikamp, Wieber, & Gollowitzer, 2009).

1.2 Indirect contributions of attentional and action control to early reading development

Executive control both on the attentional and action level thus seems necessary to accommodate the full developmental trajectory from kindergarten phonological awareness that is present before formal reading instruction, to first-grade and second-grade phonological awareness, decoding and reading comprehension. It can hence be assumed that early executive control might set a gradual basis for benefits to later reading via its influence on prerequisites phonological and decoding abilities. To date, however, such indirect long-term effects are just beginning to be understood. For attentional control, Dice and Schwanenflugel (2012) showed that phonological awareness fully mediates the relation between attention in preschool and decoding in kindergarten. And Dally (2006) showed mediation by decoding between kindergarten (subjective) inattention and reading comprehension two years later. For the control of action, mediation by phonological awareness was implicitly established by Lepola, Poskiparta, Laakkonen, and Niemi (2005), who showed mediation between second-grade task-focused behavior and word recognition by benefits to kindergarten and first-grade phonological awareness

and task-focused behavior. Examination of mediation effects from action control up to the stage of second-grade reading comprehension remains, to our knowledge, yet unknown.

Studies examining mediation for both types of executive control in one and the same design are even more scarce. In a recent study we examined mediation effects for both types to first-grade decoding, with prior phonological awareness being the mediator (Van de Sande et al., 2013). We tested separate models and only included decoding as an outcome to enable refined examination of exact mediation effects. We found a full mediation effect for attentional control, while for action control only an indirect effect (i.e., no initial effect) could be established. In another longitudinal study we found a similar mediation pattern of executive control to early reading development (Segers et al., 2016). These results suggest that both types of executive control provide children with different basics to pick up on reading abilities in early formal education. It remains to be explored, however, how the development of both types of executive control over the three years relate to early reading development. Such insights are important given that executive control undergoes a developmental spurt in the timeframe in question, and are also recruited differentially in the informal kindergarten setting compared to formal education in first- and second-grade (Ramscar & Gitcho, 2007). Also, it remains to be examined what are their contributions over time for the next complex stage of reading comprehension. Thus, to gain more fine-grained insights into the long-lasting role of executive control to early reading development, direct and indirect contributions of both types of executive control over time need to be examined for the full developmental trajectory of early reading skills.

1.3 The present study

The current longitudinal study examined the role of two components of executive control between kindergarten and second-grade to the development of multiple early reading skills that develop in this same age span (See Figure 1).

The research question addressed in the present study was:

To what extent do attentional and action control directly and indirectly predict subsequent reading development?

We expected initial (i.e., without control for the mediators) relations between attentional control with phonological awareness, decoding, and reading comprehension, as spoken and written information needs to be processed and the resulting mental models need to be updated. For action control, initial relations with phonological awareness and reading comprehension were expected, but not with decoding. With regard to mediation effects, we hypothesized that benefits of both

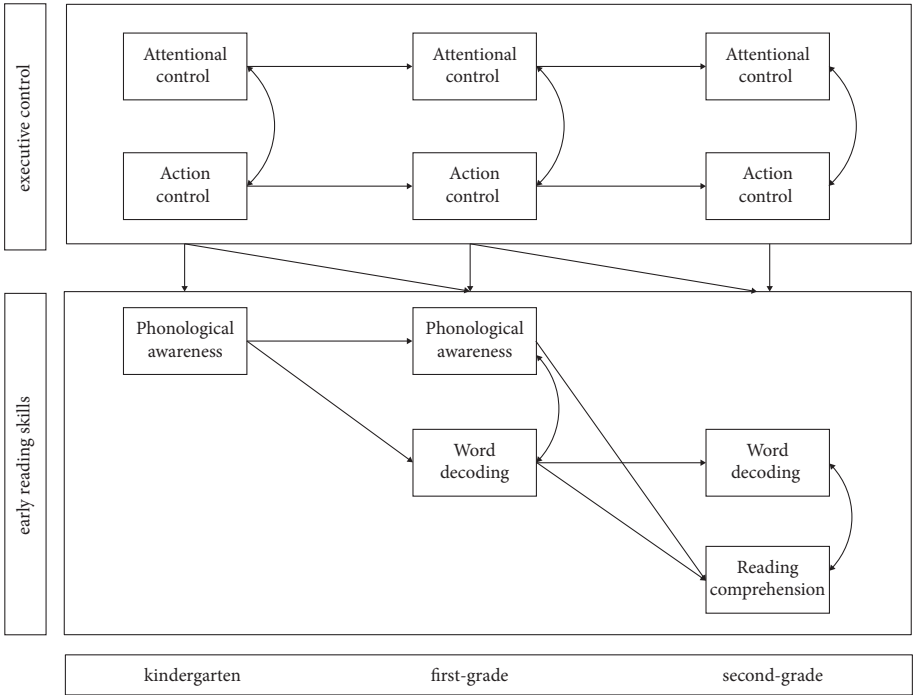


Figure 1. The components of executive control and reading development that are examined from kindergarten to second-grade

attentional and action control to concurrent phonological awareness would provide the children with a more proficient phonological basis and that this basis, in turn, would set the stage for subsequent reading abilities. For attentional control, we expected that a direct effect to reading comprehension would remain as well, due to its complex and continuous monitoring demands. Thus, partial mediation to early reading skills over time was expected for attentional control, and full mediation for action control. Moreover, in line with the current viewpoint that the major contributions of executive control take place before formal education begins (see for example Lepola et al., 2005 and von Suchodoletz et al., 2009), we expected that initial relations of first- and second-grade attentional and action control would disappear if we included their influence on reading development in kindergarten in the model.

2. Method

2.1 Participants

We approached twelve schools, of which eight agreed to participate. This study was a subset of a study for which a proportion of the children per class were selected. Selection was done randomly. All parents gave consent for their children's participation. An initial number of 109 children participated in the present study. These children were approximately six years of age at the start of the study and thus in kindergarten. The sample was collected from nine different schools that were located in middle-class neighborhoods. All children were native Dutch and came from middle to upper-middle class families. Two years later at measurement occasion three, fifteen children had dropped out due to attrition or retainment in kindergarten. No differences were found in initial measures between the children that dropped out and those that remained in the final sample (phonological awareness: $p = .44$; attentional control: $p = .09$; action control: $p = .07$). The final sample of 94 children contained 50 boys and 44 girls with a mean initial age of 6 years and 3 months ($SD = 0;04$, ranging from 5;04 years to 7;04 years).

2.2 Measures

2.2.1 *Executive control*

We assessed executive control of attention and action with two domain-general and direct (objective) tasks. Flanker Fish was used to assess attentional control, and Hearts & Flowers to assess the control of action (Diamond et al., 2007; Rueda, Posner, & Rothbart, 2005).

Both tasks had three blocks with different rules that reflect different experimental conditions: congruent, incongruent, and mixed. While correct performance on these tasks is mainly driven by inhibitory demands, the second and third block also put an increasing demand on working memory and cognitive flexibility (see Diamond et al., 2007: supplemental material). The tasks were administered via the computer. For every trial, a stimulus appeared on the right or left side of the screen and the children had to press one of two marked buttons on the keyboard according to the game rules. All of the items had a restricted stimulus presentation time (trial durations of 2000 ms. for Flanker Fish and 1500 ms. for Hearts & Flowers). Items that were responded to in less than 200 milliseconds following stimulus onset were deleted, as these items were too likely to be inhibitory failures (see Davidson, Amso, Anderson, & Diamond, 2006; Shing, Lindenberger, Diamond, Li, & Davidson, 2010). This resulted in an initial removal of 19.22% for the Flanker Fish task and 2.59% for the Hearts & Flowers task. All remaining

items that were correctly responded within the allocated time frame were assigned a score of one (Diamond, Barnett, Thomas, & Munro, 2007; Davidson et al., 2006). Given the age span of the children, we analyzed the number of correct answers.

2.2.1.1 *Attentional control.*

The Flanker Fish task assessed attentional control by having children pay special attention to some features of the stimuli while inhibiting others (Diamond et al., 2007; Rueda, Posner, & Rothbart, 2005). The children had to feed hungry fish by pressing the button corresponding to the direction in which the hungry fish were facing. These fish were generally accompanied by five other fish that together could appear in one of three possible combinations. The middle fish either swam in the opposite direction from the flanker fish; all fish swam in the same direction; or only the stimuli fish were shown. There were three blocks with different game rules. In the first block, the fish were blue and the children were told that the hungry fish was in the middle. Consequently, the children had to inhibit their tendency to pay attention to the flanker fish. Due to ceiling effects, block 1 was deleted from analyses from first-grade ($M = 15.02$, $SD = 1.88$). In the second block, the fish were pink and the hungry fish were in the flankers, and hence the middle fish should be ignored. Also, the children should now keep the new game rule in mind, putting more demands on working memory. In block three, blue and pink fish appeared by turns, and the children had to flexibly switch between the rules that applied for the colors in the first two blocks. There were sixteen items in the first and second block. In the third block, 44 items were included (Cronbach's $\alpha = .89$).

2.2.1.2 *Action control.*

The Hearts & Flowers task was assessed as an indication of children's control to acting out impulsively. Children were elicited an action (i.e., motor) response of pressing a button that they had to control, and replacing it by a less salient alternative opposite response (Davidson, Amso, Anderson, & Diamond, 2006; Diamond, 2013; Shing, Lindenberger, Diamond, Li, & Davidson, 2010). A heart or flower appeared either on the left or right side of the screen. Both objects were of the same color and size. Similar to the Flanker Fish task, there were three blocks with different game rules. In the first block, children saw hearts and had to press a marked button on the same side of the heart. This block showed ceiling effects ($M = 12.91$, $SD = 1.63$) and was therefore omitted. During the second block, only flowers were presented and children had to press the button opposite to the flower. In the third block, hearts and flowers trials were alternated and the children had to respond according to the rules in the previous blocks. There were fourteen items in the second block. In the third block, 32 items were included (Cronbach's $\alpha = .83$).

2.2.1.3 Aggregated executive control measures.

To ensure that the different tasks tapped the two distinct types of executive control as showed in the literature (e.g., Diamond, 2013; Rueda, Posner, & Rothbart, 2005; Van de Sande, Segers, & Verhoeven, 2015), we conducted a Principal Factor Analysis with Oblimin Rotation over the standardized sum-scores per block. Two distinct factors were revealed. Factor 1 (attentional control) showed high loadings (.70–.84) on the items from the Flankers Fish task and explained 44.13% of the variance. Factor 2 (action control) showed high loadings (.76–.84) on the items from the Hearts & Flowers task and explained 20.78% of the variance in the children's responding on this task. To keep the scoring level constant across time points, z-scores were calculated over the blocks and the sum of those z-scores was used for the analyses.

2.2.2 Phonological awareness

To measure the children's phonological awareness, we administered the *Screeningsinstrument Beginnende Geletterdheid* [Screening Instrument for Emerging Literacy] (Vloedgraven, Keuning, & Verhoeven, 2009). This task measures different aspects of children's early phonological awareness: rhyming, phoneme segmentation, phoneme blending and phoneme deletion (Vloedgraven, Keuning, & Verhoeven 2009; Vloedgraven & Verhoeven, 2007).

These tasks were administered via the computer. All items were provided both auditory and visually on the computer screen. The children were presented three or four pictures accompanied by the auditive name of these stimuli. The children had to select a picture from this set to answer an auditive provided question. Each task included fifteen high-frequency monosyllabic words as items. The items in the rhyming task all had a Consonant Vowel Consonant (CVC) structure. The other subtasks included items with three, four or five phonemes and a varying Consonant Vowel (CV) structure. In the rhyming task, the children heard a word and had to select the response alternative that rhymes. In the phoneme segmentation task, the target word was presented in its individual phonemes and the children were asked to indicate which of the three alternatives on the computer screen corresponded to it. In the phoneme blending task, the children were asked to select that response alternative which began with the same phoneme as the one in the target word. In the phoneme deletion task, the children are asked to indicate that alternative from which a phoneme was deleted in the target item, which resulted in another existing word (see Vloedgraven, Keuning, & Verhoeven, 2009). For all these subtasks, every correct item was assigned a score of one (Cronbach's $\alpha = .80$). The sum of z-scores per subtask were used for the analyses for the measures in kindergarten. In first-grade, only phoneme deletion was assessed as indication for phonological skills due to children's more advanced level of phonological awareness.

2.2.2.1 Aggregated phonological awareness measures.

Principal Factor analysis with Oblimin Rotation on the z-scores of the subtasks resulted in a single underlying factor that explained 43.94% of the variance, with component loadings ranging from .48 to .85.

2.2.3 Word-decoding

The Three-Minutes-Reading-Test was administered in first- and second-grade. This test consists of three cards with 150 high-content words (Verhoeven, 1995). For each card, children had to read as many words aloud as possible within one minute. Every card represented a different type of words with increasing difficulty. Card one consisted of monosyllabic CVC words, card two of monosyllabic words with consonant clusters, and card three of polysyllabic words. Only the first and second card were assessed in first-grade due to the difficulty level of the third card. In second-grade all three cards were assessed. For first-grade we used the sum of the z-scores per card and in second grade the standardized scores over the three cards (Cronbach's $\alpha = .96$; Krom, Jongen, Verhelst, Kamphuis, & Kleintjes, 2010).

2.2.4 Reading comprehension

To measure reading comprehension abilities, the *Begrijpend Lezen Groep 4* [Reading Comprehension Grade 2] was administered (Krom, Jongen, Verhelst, Kamphuis, & Kleintjes, 2006). This task consists of 50 multiple-choice questions regarding the main idea of the text, specific details, cloze items, and inferential questions. Questions concerned texts from five different text genres (e.g., expository, letter, narrative). Scores on the test were normalized to account for relative differences in complexity and weight of the questions (reliability $\tau(0) = .92$; Feenstra, Kamphuis, Kleintjes, & Krom, 2010).

2.3 Procedure

The children were tested on executive control and reading skills at three occasions, in kindergarten, in first-grade, and in second-grade. Time of testing was always in spring, and was kept similar for every occasion as much as possible. Second-grade decoding and reading comprehension were assessed groupwise per class. All other measures were assessed individually in a quiet room at the children's school with only the child and experimenter present.

In kindergarten, the children's attentional and action control together with their phonological awareness were assessed. Testing was divided in two sessions of approximately fifteen minutes each. In both sessions, the first minutes were devoted to instructions and practice items. To let the children feel comfortable about their participation, the first session contained the tasks that were easier and more

fun to do. During the first session, the children thus performed the Flanker Fish and the Hearts & Flowers tasks. The children's phonological awareness was assessed during the second kindergarten session.

In first-grade, the children's attentional and action control were assessed, as well as their phonological awareness and decoding abilities. The first session again contained the executive control measures, the second session their phonological awareness and decoding were assessed. Test sessions took approximately ten minutes.

In second-grade, again their attentional and action control were assessed, together with children's decoding and reading comprehension. Procedure was similar to kindergarten and first-grade, except for reading comprehension. This was assessed groupwise per class, divided over two sessions of approximately 45 minutes per class.

In-between the measurement occasions, the children continued their normal Dutch reading curriculum. In Kindergarten, there was thus a focus on storybook reading. Incidentally, there was also some informal practice in phonological awareness. In first and second-grade, the children received formal reading instruction which in the Netherlands is highly phonics-based (Vloedgraven & Verhoeven, 2009).

2.4 Data analyses

A series of Structural Equation Modeling with LISREL (Jöreskog & Sörbom, 2003) were conducted on the correlation matrices to analyse the longitudinal contributions of attentional and action control to the developmental trajectory of reading from kindergarten to second-grade. First, a simplex model was undertaken to test the assumption of reading development from phonological awareness in kindergarten to phonological awareness and decoding in first-grade, resulting in decoding and reading comprehension in second-grade. Then, attentional and action control at each of these three time points were added to the model, to test their unique contributions to the developmental trajectory of reading. To test for mediation effects, both direct and indirect contributions were formally tested using the Maximum Likelihood Estimation method. Non-significant paths to reading skills were stepwise removed to obtain the most parsimonious model. Next to the chi-square, other fit indices were evaluated to attain a robust estimation of the goodness of fit. Root Mean Square Error of Approximation (RMSEA) and Comparative Fit Index (CFI) were included because these are the more sensitive fit indices for testing with small sample sizes (Fan, Thompson, & Wang, 1999). The Goodness of Fit Index (GFI) was also included. The chi-square test should exceed .05, and a smaller χ^2 relative to the degrees of freedom indicates a stronger fit

(Ullman, 2001). An RMSEA < .08 indicates an acceptable fit and an RMSEA < .06 a strong fit (Browne & Cudeck, 1993; Jaccard & Wan, 1996). CFI and GFI should exceed .90 (Hu & Bentler, 1999; Jaccard & Wan, 1996; Tabachnik & Fidell, 2001).

Analyses of background variables were conducted to check relations with initial measures of the predictors (i.e., attentional and action control) and with initial reading scores (i.e., phonological awareness). In this respective order, no effects were found for school ($F(8, 91) = 1.31, p = .25$; $F(8, 92) = 0.96, p = .48$; $F(8, 93) = 0.87, p = .55$), age ($r = .03, p = .76$; $r = -.20, p = .051$; $r = -.02, p = .84$) and gender ($F(1, 91) = 3.53, p = .06$; $F(1, 92) = 2.40, p = .13$; $F(1, 93) = 0.13, p = .72$). These background variables were therefore excluded from further analyses.

3. Results

3.1 Descriptive statistics and intercorrelations

The descriptive statistics for the measures of attentional control, action control and phonological awareness, decoding and reading comprehension are shown in Table 1.

Table 1. Descriptives for the measures of executive control and early reading abilities

Variable	kindergarten			first-grade			second-grade		
	<i>M</i>	<i>SD</i>	min-max	<i>M</i>	<i>SD</i>	min-max	<i>M</i>	<i>SD</i>	min-max
Attentional control	51.38	11.36	24–68	48.46	5.01	34–59	47.79	5.93	31–58
Action control	35.81	5.74	15–44	38.40	3.56	28–44	36.61	3.74	25–44
Phonological awareness	41.45	6.69	23–57	9.28	3.38	3–15	–	–	–
Decoding	–	–	–	49.8	27.94	12–145	144.76	53.53	43–327
Reading comprehension	–	–	–	–	–	–	11.05	13.98	–16–51

Notes. Raw scores are reported for informative purposes, but factor and standardized scores are used in the analyses. Normed scores are reported for reading comprehension to account for the relative weight per question in this task.

Next, we correlated the sumscores for attentional and action control, phonological awareness, decoding, and normed scores for reading comprehension with each other (see Table 2).

Table 2. Correlations among the measures of executive control and reading

	1	2	3	4	5	6	7	8	9	10	11
1. attentional control _K	1										
2. action control _K	.34**	1									
3. phonological awareness _K	.35**	.33**	1								
4. attentional control _{G1}	.48**	.15	.33**	1							
5. action control _{G1}	.33**	.22*	.08	.29**	1						
6. phonological awareness _{G1}	.27**	.23*	.38**	.28**	.25*	1					
7. decoding _{G1}	.23*	.07	.58**	.23*	.03	.46**	1				
8. attentional control _{G2}	.52**	.37**	.38**	.53**	.35**	.41**	.28**	1			
9. action control _{G2}	.15	.19#	.19#	.31**	.35**	.34**	.23*	.41**	1		
10. decoding _{G2}	.08	.03	.35**	.18	-.01	.41**	.73**	.24*	.13	1	
11. reading comprehension _{G2}	.21*	.18	.38**	.19#	.14	.52**	.52**	.28**	.26*	.47**	1

Notes.

** $p < .01$

* $p < .05$

$p = .07$.

K = Kindergarten; G1 = Grade 1; G2 = Grade 2.

As can be seen from Table 2, all reading abilities correlated moderately to strongly with each other over the three school years. Attentional and action control correlated moderately with each other at each time point and did not all correlate over the years. These different relational patterns indicated that much variation is left and that the measures indeed tap different underlying aspects of executive control. With regard to the correlations of both types of executive control with reading abilities, attention and action control were related with kindergarten and first-grade phonological awareness. However, for later decoding skills we could establish a correlation with initial attentional control in first-grade, but not in second-grade. No correlations of action control with decoding could be established at all time points. For reading comprehension, a relation with attentional control at kindergarten and first-grade was found but for action control only a concurrent relation could be established.

3.2 Analyses of the direct and indirect effects of executive control to early reading development

To explore the unique contributions of attentional and action control to phonological awareness, decoding and reading comprehension, standardized path coefficients were calculated on correlation matrices in Lisrel 8.54 (Jöreskog & Sörbom, 2003).

First we tested the simplex model (see Figure 2). As can be seen from Figure 2, the fit of the simplex model was good: $\chi^2(4) = 4.97$, $p = .29$, RMSEA = .05, CFI = 0.99, and GFI = .98. The standardized beta coefficients show that phonological awareness was a strong predictor for decoding. Decoding, in turn, loaded high on subsequent reading comprehension. Moreover, phonological awareness was indirectly related to decoding and reading comprehension in second-grade via their prerequisites in first-grade (standardized indirect effect decoding: $\beta = 0.42$, $p < .001$; reading comprehension: $\beta = 0.34$, $p < .001$).

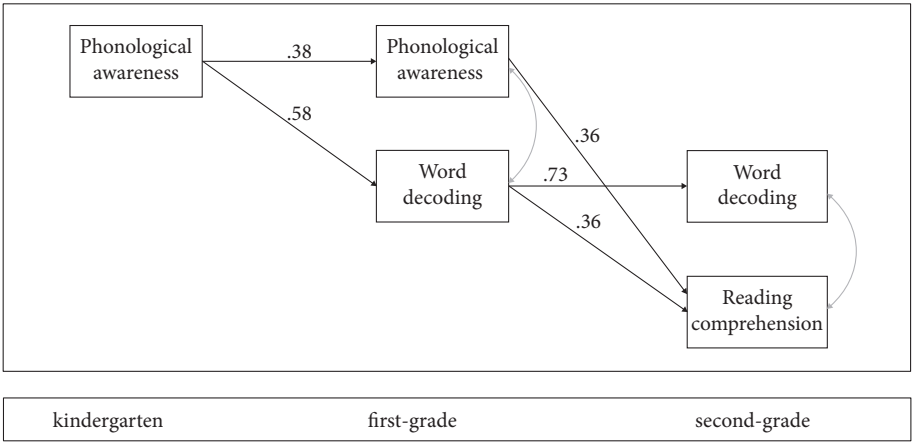


Figure 2. Standardized path coefficients for the developmental model of early reading
Note. All paths displayed in black are significant at $p < .05$.

In the next step, a set of analyses were conducted to test the contributions of attentional and action control to early reading development. To test the hypothesized mediation model, both types of executive control were simultaneously included as prerequisites to the model as well as in first grade and second grade. All paths that were above the p -level of $< .05$ were excluded, resulting in the final model as depicted in Figure 3. The fit of this final model shows that attentional and action control represented an additional component of the early development of reading: ($\chi^2(12) = 13.23$, $p = .35$, RMSEA = .03, CFI = 0.99, and GFI = .96).

Figure 3 also shows that full mediation effects were present: the initial significant correlations of attentional control to decoding and reading comprehension (see Table 2) vanished when the mediators were taken into account. Contrary to our expectations, no direct effect of attentional control to reading comprehension could be established when the influence of attentional control to prerequisite reading skills were considered. For action control, formal interference testing showed that the indirect contributions to all reading abilities were significant, and almost of similar strength as for attentional control (see Table 3).

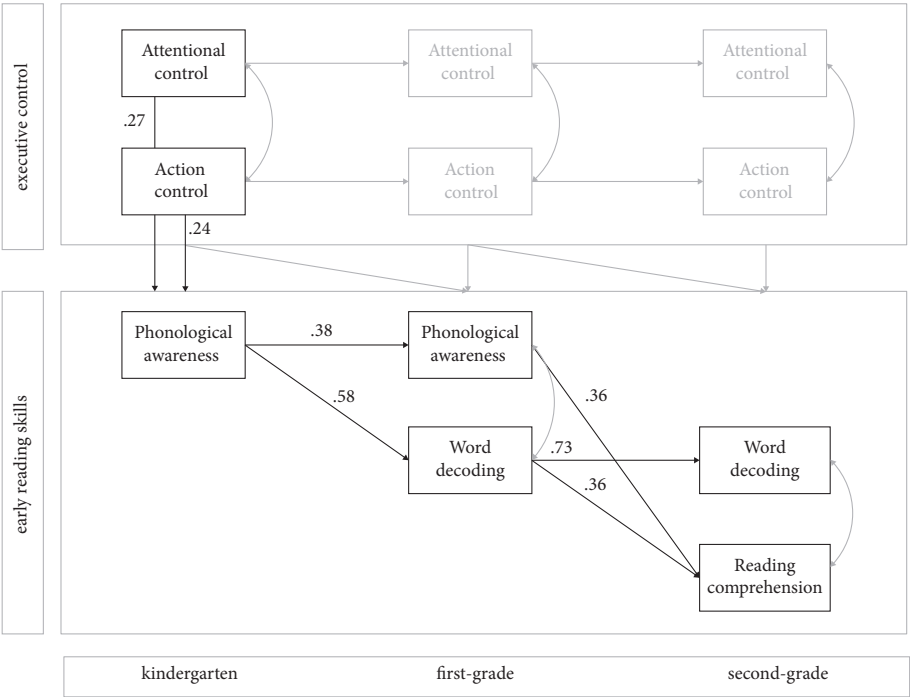


Figure 3. Final model for the role of attentional and action control to early reading development

Note. All paths displayed in black are significant at $p < .05$.

Furthermore, as expected, all influence of attentional and action control to three-year reading development lays in kindergarten, despite significant correlations in first-and second grade with reading skills.

Table 3. Standardized indirect coefficients of the control of attention and action to phonological awareness, decoding, and reading comprehension

	attentional control	action control
	β	β
phonological awareness _{G1}	.10*	.09#
decoding _{G1}	.16*	.14*
decoding _{G2}	.11*	.10*
reading comprehension _{G2}	.09*	.08*

Notes. G1 = Grade 1; G2 = Grade 2.

* $p < .05$

$p = .05$

4. Discussion

In this study, we longitudinally examined how children's attentional (cognitive) and action (behavioral) control facilitates reading development from kindergarten to second-grade. We expected that attentional and action control would provide children with a stronger basis for the development of reading skills in kindergarten and first-grade, and that this basis would mediate the benefits to reading skills in second-grade. For attentional control, both direct and indirect effects were expected to phonological awareness and reading comprehension, and an indirect effect to decoding. For action control, only indirect effects were expected to reading development over time.

4.1 Direct and indirect contributions of attentional and action control to early reading development

Our results show direct and mediation effects of attentional control to reading skills, while for action control only indirect effects were found. These results are in line with our expectations that there would be indirect effects from kindergarten executive control up to second-grade reading skills. Contrary to our expectation, full mediation was found for attentional control to reading comprehension. For action control, however, the model fits our hypotheses well: although the initial correlations between action control with later reading abilities were absent, substantial indirect effects were found. Moreover, all concurrent initial relations of attentional and action control with reading skills in the formal grades vanished in the model when the contributions of both types in kindergarten were included. Both components of the executive control system in kindergarten thus seemed to enable a prosperous advantage during early phonological development, which in turn functioned as a hallmark for benefits to the development of later decoding and reading comprehension.

These results shed further light on previous results showing effects of executive control to reading. First, the direct contributions of attentional and action control to reading skills were different, showing that multiple types of executive control should be considered simultaneously in studies that consider benefits to reading development, instead of isolated as in most studies (but see Blair & Razza, 2007; Segers et al., 2016). Second, we considered separate reading abilities in a longitudinal design, compared to the composite reading scores that are generally measured concurrently (e.g., Conners, 2009; McClelland, Cameron, Connor, et al., 2007; Spira, Bracken, & Fischel, 2005). The rationale behind this design was that prior phonological awareness and decoding are essential prerequisites to reading comprehension, which implies that the benefits of attentional and action control

to these reading abilities must be examined separately and chronologically. Our results strongly confirmed this assumption.

In a similar vein, Dally (2007; and see Dice & Schwanenflugel, 2012) also proposed that indirect effects of attentional control to early reading development should be considered. They found that attentional control in kindergarten indeed had a strong influence on second-grade reading comprehension via first-grade decoding. This result is in line with ours, but came from subjective measures of attentional control (i.e., teacher-ratings) and regression analyses, while we used objective measurements, formally tested the indirect effects and tested a model that included measures over time of reading skills as well as of executive control. For the control of action, indirect relations to longitudinal reading development are previously established as well, but not up to the stage of reading comprehension (only to decoding) and again generally with teacher-ratings (e.g., Lepola et al., 2005).

Although our results indicate that both types of executive control contribute to early reading development from kindergarten to second-grade, the correlation matrix in Table 2 shows that only kindergarten action control was initially related to decoding. Action control in first-grade did not correlate with concurrent and subsequent decoding. The absence of such correlations in formal education seems to be at odds with the findings by Lepola et al. (2007). They, however, included word-recognition and teacher-ratings of task-focused behavior instead of the underlying action control mechanisms of such behavior. A tentative explanation could therefore be found in the different nature of the learning environment in playful kindergarten and formal education, resulting in such different demands to action control that relations with a generally quick and automatized task such as decoding – in a transparent orthography – would not be strong enough to demand action control in a formal learning environment (see also Van de Sande et al., 2013).

The full mediation effect for attentional control to later reading comprehension was unexpected. Due to the continuously high attentional demands for the complex skill of comprehension monitoring, we hypothesized that there would be a direct attentional effect over the indirect effect though prior phonological and decoding abilities. Conners (2009) did establish unique variance of attentional control to reading comprehension in 8-year olds beyond decoding and linguistic comprehension. But their conclusions were based on concurrent findings and did not account for the contributions of prior reading skills and executive control. Especially phonological awareness, which was not included in their study, has a complex nature as it demands multiple processes to segment and connect sounds. Due to this complexity, it is possible that phonological awareness have put such high demands on concurrent attentional control that it left no room for direct

effects to exert on later reading comprehension. Moreover, our findings that the initial relations of attentional control with reading comprehension vanished when we included kindergarten attentional control fit with the viewpoint that early executive control can have increasing effects to academic achievements over time (Wass et al., 2012).

4.2 Limitations and future directions

Of course, there are some limitations to the present study. First, our main focus was on how attentional and action control would enable reading development via early precursors that emerge before formal education, so we included concurrent executive capacities and phonological awareness in kindergarten. However, given that mediation analyses are about causality, a more genuine mediation approach would be to assess the first measures of executive control at an earlier time point as well (MacKinnon, Fairchild, Fritz, 2007). In addition, our sample consisted of children from middle-class neighborhoods which limits the generalizability of the present findings. Furthermore, given the number of variables in the current models there were no possible confounder variables included to avoid false-positive report likelihood, but of course other constructs play a role as well (Simmons, Nelson, & Simonsohn, 2011). For example, although decoding and phonological awareness are the main prerequisite reading skills for reading comprehension in second-grade, other facilitative skills such as vocabulary and listening comprehension were not included in our model (Verhoeven, Van Leeuwe, & Vermeer, 2011; Perfetti, Landi, & Oakhill, 2005; Kendeou, Van den Broek, White, & Lynch, 2009).

Despite these limitations, the present study demonstrates that there is a crucial role to early reading development for both the attentional and action components of executive control. Future research should therefore be devoted to further unravel the role of both types of executive control to early reading development. Reciprocal effects of reading abilities with executive control might enrich the current insights (e.g., Metcalfe, Harvey, & Laws, 2013). For example, Hirvonen et al. (2010) studied the relation of task-focused behavior to reading from first-grade to fourth-grade, and found that reading failures in time reduced task-focused behavior. Furthermore, as this study was carried out in a highly transparent orthography, more research is needed to find out whether these results can be generalized to more opaque orthographies (see Georgiou, Parilla, & Papadopoulos, 2008; Hirvonen et al., 2010). Third, given the crucial role to reading of executive control in kindergarten, interventions can be developed that explicitly engage attentional and action control during phonological awareness interventions (Van de Sande, Segers, & Verhoeven, 2016, 2017).

4.3 Conclusions

In the present study, attentional and action control have both shown important types of executive control for reading development: attentional control to become aware of the structural features of a language and to control information monitoring while reading, and action control to empower task-focused behavior during early reading instruction in class. The mediation effects show that both attentional and action control in kindergarten influence phonological awareness in such a way that it functions as a hallmark to subsequent reading abilities. Theoretically, our results further identify the role of different types of executive control to early reading development by longitudinally examining indirect contributions via multiple prior and concurrent reading skills, and by incorporating different types of executive control, also at all time points. For educational practice, our results make it clear that – next to early reading abilities – special attention should be paid to the development and stimulation of kindergarten executive control, to create the necessary stepping stones for successful academic achievements at formal primary education.

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