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How executive functions contribute to reading comprehension

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Background. Executive functions have been proposed to account for individual variation in reading comprehension beyond the contributions of decoding skills and language skills. However, insight into the direct and indirect effects of multiple executive functions on fifth-grade reading comprehension, while accounting for decoding and language skills, is limited.

Aim. The present study investigated the direct and indirect effects of fourth-grade executive functions (i.e., working memory, inhibition, and planning) on fifth-grade reading comprehension, after accounting for decoding and language skills.

Sample. The sample included 113 fourth-grade children (including 65 boys and 48 girls; Age *M* = 9.89; *SD* = .44 years).

Methods. The participants were tested on their executive functions (working memory, inhibition and planning), and their decoding skills, language skills (vocabulary and syntax knowledge) and reading comprehension, one year later.

Results. Using structural equation modelling, the results indicated direct effects of working memory and planning on reading comprehension, as well as indirect effects of working memory and inhibition via decoding (χ^2 = 2.46).

Conclusions. The results of the present study highlight the importance of executive functions for reading comprehension after taking variance in decoding and language skills into account: Both working memory and planning uniquely contributed to reading comprehension. In addition, working memory and inhibition also supported decoding. As a practical implication, educational professionals should not only consider the decoding and language skills children bring into the classroom, but their executive functions as well.

Becoming proficient in reading comprehension is an important goal of primary education. Reading comprehension, however, is a complex process, which requires several higher cognitive skills. As proposed by the 'Simple View of Reading' (Hoover & Gough, 1990) and consistently supported by other studies, reading comprehension is largely predicted by decoding and listening comprehension (i.e., the linguistic processes involved in the comprehension of oral language, which is commonly assessed with language skills such as

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vocabulary and syntax knowledge). In addition, it has been found that executive functions significantly account for individual variation in reading comprehension beyond the contributions of decoding skills and language skills (e.g., Cutting, Materek, Colé, Levine, & Mahone, 2009; Kieffer, Vukovic, & Berry, 2013; Sesma, Mahone, Levine, Eason, & Cutting, 2009). Executive functions can be seen as a multi-componential construct including, among others, working memory, inhibition, cognitive flexibility (also referred to as shifting or switching), and planning (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000). The significant relation between executive functions and reading comprehension has been demonstrated repeatedly (for a review, see Butterfuss & Kendeou, 2018; Follmer, 2018; Jacob & Parkinson, 2015). However, indirect effects of executive functions on reading comprehension via decoding and language skills have hardly been examined (Follmer & Sperling, 2019; Georgiou & Das, 2018; Ober, Brooks, Plass, & Homer, 2019), and studies including children in the upper primary grades (grades 4–6; children between the ages of 10–12 years) are even scarcer (Kieffer *et al.*, 2013). Moreover, although several longitudinal studies regarding the relations between executive functions and early literacy have been conducted (e.g., Blair & Razza, 2007; De Franchis, Usai, Viterbori, & Traverso, 2017; Monette, Bigras, & Guay, 2011; Röthlisberger, Neuenschwander, Cimeli, & Roebers, 2013), studies applying a longitudinal approach in the upper primary grades are limited. In the present study, it was therefore investigated to what extent multiple executive functions in Grade 4 predicted reading comprehension in Grade 5. Specifically, we will be regarded both direct effects of executive functions on reading comprehension and indirect effects via decoding and language skills.

The role of decoding and language skills in reading comprehension

It is generally accepted that text comprehension depends on the ability to decode words (Lyon, 1995; Torgesen, 2000), as it allows the reader to draw word representations from the text (Perfetti, 1992; Stanovich, 2000). Another major component in establishing reading comprehension is the ability to construct semantic relations among successive words, phrases, and sentences to form a coherent and meaningful representation of the discourse (Kintsch, 1998). These components are captured in the Simple View of Reading (Hoover & Gough, 1990), which suggests that reading comprehension is the product of decoding and listening comprehension (Hoover & Gough, 1990). Listening comprehension comprises the processes involved in the comprehension of oral language, which include language skills such as vocabulary and grammar knowledge, and higher-level comprehension skills such as the ability to draw inferences within and between sentences and to integrate information across sentences and ideas in a text (Perfetti, Landi, & Oakhill, 2005; Verhoeven & Perfetti, 2008). Studies have demonstrated that decoding and language skills predict individual variation in children's reading comprehension both in the lower grades (Muter, Hulme, Snowling, & Stevenson, 2004) and in the upper grades of primary school (Goff, Pratt, & Ong, 2005; de Jong & van der Leij, 2002; Nation & Snowling, 2004; Oakhill, Cain, & Bryant, 2003; Verhoeven & van Leeuwe, 2008). The relative contribution of decoding and language skills to reading comprehension changes, however, with grade level (Gough & Tunmer, 1986; Hoover & Gough, 1990). Decoding is found to be particularly important for reading comprehension in beginning readers, (Bast & Reitsma, 1998; Catts, Hogan, & Adlof, 2005; Verhoeven & van Leeuwe, 2008), whereas when decoding becomes automatic (typically around Grade 4), more resources become available to process the meaning of a text (Perfetti, 1998; Samuels & Flor, 1997; Tunmer & Hoover, 1992), and the contribution of language skills to reading comprehension increases (Bast & Reitsma, 1998; Catts *et al.*, 2005; Verhoeven & van Leeuwe, 2008).

The role of executive functions in reading comprehension

Evidence for the role of executive functions in reading comprehension can be derived from the Reading Systems Framework (Perfetti & Stafura, 2014), in which decoding and language comprehension take place within a cognitive system that affects reading comprehension. To be more specific, given that the cognitive system has a limited processing capacity, the processes involved in reading comprehension need to compete for the resources available in the cognitive system (see also Just & Carpenter, 1992; Kintsch, 1998). Effortful reading comprehension processes require more resources than automatic reading comprehension processes – that is, processes that occur without the need for attention (Bargh & Uleman, 1989). Automaticity of decoding would, therefore, allow for an increase of resources for other cognitive demands involved in reading comprehension (e.g., Cunningham, Stanovich, & Wilson, 1990; Perfetti, 1985). Given this, executive functioning takes a more prominent role in the upper primary grades, when the focus of primary education shifts from learning to read to reading to learn (Chall, 1983). Children are presented with larger passages and more complex sentences, which increases the demand on both language skills (Bast & Reitsma, 1998; Catts *et al.*, 2005; Verhoeven & van Leeuwe, 2008) and executive functioning (e.g., Cunningham *et al.*, 1990; Perfetti, 1985). Indeed, it has been demonstrated that, in addition to decoding and language skills, executive functions explain significant variance in reading comprehension in the upper grades of primary school (e.g., Cain, Bryant, & Oakhill, 2004; Christopher *et al.*, 2012; Cutting *et al.*, 2009; Kieffer *et al.*, 2013; Locascio, Mahone, Eason, & Cutting, 2010; Sesma *et al.*, 2009). Moreover, several longitudinal studies evidenced that the contribution of executive functions to reading comprehension increases in the upper primary grades when decoding skills are more developed (Nouwens, Groen, Kleemans, & Verhoeven, 2018; Seigneuric & Ehrlich, 2005).

Direct contributions of executive functions to reading comprehension

Executive functions reflect a family of top-down mental processes that control and coordinate lower-level cognitive abilities to reach goals as efficiently as possible. Hence, executive functions are proposed to facilitate reading comprehension by coordinating and controlling specific reading processes, such as integrating information, retrieving information from the mental lexicon, using strategies and simultaneously engaging in these multiple reading processes. Previous research has identified three core executive functions in adults (Miyake *et al.*, 2000) and children (Lehto *et al.*, 2003) including updating and monitoring of working memory processes (which is closely linked to the notion of working memory as reflected by Baddeley's model; Jonides & Smith, 1997; Lehto, 1996), inhibition, and cognitive flexibility (also referred to as switching and/or shifting). From these core executive functions, higher-order executive functions are built such as reasoning, problem solving, and planning (Collins & Koechlin, 2012; Lunt et al., 2012). Three executive functions that have been reported to significantly contribute to reading comprehension are as follows: working memory (e.g., Carretti, Borella, Cornoldi, & De Beni, 2009; Daneman & Merikle, 1996; Seigneuric & Ehrlich, 2005), inhibition (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014; Kieffer *et al.*, 2013), and planning (Cutting *et al.*, 2009; Sesma *et al.*, 2009).

Working memory

One of the most dominant theoretical accounts in the literature concerning executive functions and reading comprehension is the working memory model of Baddeley and

Hitch (1974; see also Baddeley, 2000). It proposes that working memory is a mechanism that facilitates the ability to store information while simultaneously carrying out processing operations (Daneman & Carpenter, 1980). The relationship between working memory and reading comprehension is well established (for reviews, see Butterfuss & Kendeou, 2018; Carretti *et al.*, 2009; Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Follmer, 2018). Working memory is considered to be drawn upon when integrating stored representations with incoming information (Baddeley & Hitch, 1974; Daneman & Carpenter, 1980; Masson & Miller, 1983). More specifically, when children are reading, they have to integrate the situation described by the text with information that has been read previously, and/or with prior knowledge. Previous research has consistently indicated significant direct contributions of working memory to reading comprehension in adults and children in both cross-sectional (for meta-analyses, see Carretti *et al.*, 2009; Daneman & Merikle, 1996; Follmer, 2018) and longitudinal designs (Seigneuric & Ehrlich, 2005), after controlling for decoding and language skills (e.g., Cain *et al.*, 2004; Kieffer *et al.*, 2013; Oakhill *et al.*, 2003; Sesma *et al.*, 2009).

Inhibition

Inhibition is assumed to be needed for reading comprehension to form coherent text representations. During reading, a child may come across text passages that contain various sources of irrelevant information or ambiguity in the overall context that needs to be inhibited to form an accurate representation of the text (Cain, 2006; Carretti *et al.*, 2009; De Beni & Palladino, 2000). Friedman and Miyake (2004) have distinguished three inhibitory-related functions: (1) prepotent response inhibition, which reflects the inhibition of dominant and automatic responses activated by the presented stimulus; (2) response to distracter inhibition, which reflects the ability to be focus on relevant items by ignoring simultaneously presented irrelevant items; and (3) resistance to proactive interference, which reflects the ability to decrease the activation of no longer relevant items, and thus to resist memory intrusions (intrusion errors). Borella and de Ribaupierre (2014) investigated the role of these three types on inhibition in reading comprehension in 10- to 12-year-old children. They found that only resistance to distractor interference contributed significantly to individual differences in reading comprehension. De Beni and Palladino (2000), however, revealed that resistance to proactive interference in 8-year-olds, measured by intrusion errors, predicted their reading comprehension skills one year later. Both response to distracter inhibition and resistance to proactive interference have been found to be entwined with working memory (Friedman & Miyake, 2004). Therefore, the current study focused on prepotent response inhibition only, as the aim was to investigate the unique contribution of inhibition to reading comprehension, separate from working memory. Although some studies found prepotent response inhibition, and not working memory, to contribute significantly to reading comprehension while accounting for word reading and language comprehension (Kieffer *et al.*, 2013), other studies found the opposite effect while accounting for word reading (e.g., Christopher et al., 2012). In a recent meta-analysis, it was shown that the relation between prepotent response inhibition and reading comprehension was significant, but weak (Follmer, 2018).

Planning

Finally, planning can be seen as the ability to decide which actions are necessary to efficiently reach and complete a goal (Cartwright, 2009), and has been shown to significantly account for variation in reading comprehension, after controlling for decoding, language skills, and working memory in 9- to 15-year-olds (Cutting *et al.*, 2009; Sesma *et al.*, 2009). Similarly, Georgiou and Das (2018) demonstrated a contribution of planning to reading comprehension in young adults (M = 21.82 year). It has been proposed that good planners regularly monitor whether their text representations are correct and if not, may even change strategies, to achieve a correct understanding of the text (Cartwright, 2015).

Direct contributions of executive functions to decoding and language skills

In parallel to their relevance to reading comprehension, executive functions may also be needed for decoding and language skills. Concerning decoding, working memory is proposed to facilitate the mapping of graphemes to corresponding phonemes, while retaining the retrieved phonemes and syllables in storage so that words can be recognized (Just & Carpenter, 1992). The results concerning the relation between working memory and decoding are somewhat inconsistent. This might be because working memory can be measured by various tasks that tap into different underlying domains. When a more verbal-oriented working memory measure was used, significant relations between working memory and decoding have been consistently reported (Arrington *et al.*, 2014; Christopher *et al.*, 2012; Gottardo, Stanovich, & Siegel, 1996; Miyake, Keenan, Pennington, & DeFries, 2012), but this was not the case for working memory measures that tapped into the visual spatial domain (Kieffer *et al.*, 2013).

During the process of decoding, incorrect representations need to be suppressed, which is controlled by inhibition mechanisms (Altemeier, Abbott, & Berninger, 2008; Arrington *et al.*, 2014). There is some evidence that prepotent response inhibition contributes significantly to decoding skills (Altemeier *et al.*, 2008; Arrington *et al.*, 2014; Kibby, Lee, & Dyer, 2014). However, others have reported the contribution of prepotent response inhibition to decoding not to be significant (Kieffer *et al.*, 2013). This contradicting finding may be caused by differences in the assessment of decoding. Planning does not appear to contribute to individual differences in decoding. It has been hypothesized that higher-order executive functions (such as planning) are only involved in complex tasks and not in simple tasks such decoding (Sesma *et al.*, 2009).

Concerning language skills, it is generally assumed that working memory is needed to integrate information across individual word meanings (vocabulary knowledge) and word functions (syntax knowledge) in sentences while holding those representations in memory (Daneman & Carpenter, 1980; Masson & Miller, 1983). Previous research has demonstrated that individual differences in language skills can be explained by both verbal working memory (Adams & Gathercole, 1995) and non-verbal working memory (Kaushanskaya, Park, Gangopadhyay, Davidson, & Weismer, 2017). Moreover, verbal working memory has been shown to account for listening comprehension (Florit, Roch, Altoè, & Levorato, 2009; Florit, Roch, & Levorato, 2011). However, listening comprehension taps cognitive factors in addition to language skills, complicating the interpretation.

Though positive significant relations between working memory and language skills have been reported (Adams & Gathercole, 1995; Florit *et al.*, 2011; Kaushanskaya *et al.*, 2017), relationships between other executive functions and language skills in typically developing children in the upper primary grades have rarely been investigated (Kaushanskaya *et al.*, 2017). Kaushanskaya et al. (2017) investigated the contributions of inhibition, updating, and task shifting – all assessed with non-verbal measures – to lexical–semantic and syntactic abilities in children between the ages of 8–11 years. Non-verbal inhibition (but not shifting or updating) was found to predict children's syntactic abilities. It has been proposed that inhibition may facilitate the suppression of ambiguous word representations and in turn aid in forming accurate integrations to establish a coherent representation of the text (Cain, 2006; Carretti *et al.*, 2009; De Beni & Palladino, 2000).

Indirect and direct contribution of executive functions to reading comprehension

To our knowledge, only a few studies have examined both direct and indirect effects of executive functions on reading comprehension via decoding or language skills. These include studies with adults (Follmer & Sperling, 2019; Georgiou & Das, 2018), young adolescents (Ober *et al.*, 2019), and children (Kieffer *et al.*, 2013). However, the results across these studies vary, which may be explained by several factors.

When regarding working memory, studies showed either no effect on decoding, language skills, or reading comprehension (Georgiou & Das, 2018; Kieffer *et al.*, 2013) or, in the study by Ober et al. (2019), no effects on decoding, but a significant contribution to reading comprehension. These varying findings may be explained by the way these studies assessed different constructs. For example, Georgiou and Das (2018) allowed participants to go back and forth between the text and questions, which may have affected working memory load. Moreover, differences in the extent to which working memory tasks (i.e., digit span and listening span, Georgiou & Das, 2018; visual matrix subtest, Kieffer *et al.*, 2013; operation span, Ober *et al.*, 2019) tapped into verbal processing may have influenced the relation between working memory on the one hand, and decoding, language skills, and reading comprehension on the other hand. Additionally, inhibition was found to explain variance solely in word fluency (Georgiou & Das, 2018), solely in reading comprehension (and no indirect associations of inhibition via word reading or language skills; Kieffer *et al.*, 2013) or in both decoding and reading comprehension (Ober *et al.*, 2019). Ober et al. (2019) proposed that the relation between executive functions, decoding, language skills, and reading comprehension may differ between adults and children (Georgiou & Das, 2018), as executive functions have been shown to develop well into adulthood (De Luca & Leventer, 2008), which may explain diverging results. Moreover, varying results were found for the indirect relations between executive functions, vocabulary, and reading comprehension (Follmer & Sperling, 2019; Georgiou & Das, 2018). However, these studies are hard to compare, as Follmer and Sperling (2019) used a latent variable to reflect executive functions (including inhibition, shifting, and updating) and Georgiou and Das (2018) regarded the unique contribution of separate executive functions to reading comprehension.

Together, these variations in research design make comparisons across studies difficult. Inherently, more research is needed to obtain more insight into the relations between executive functions and reading comprehension. Besides, although these studies provide insight into the direct and indirect contributions of executive functions to reading comprehension, only a few of these studies included variables representing both decoding and language skills, as mediating variables (Georgiou & Das, 2018; Kieffer *et al.*, 2013). Moreover, to our knowledge, only Kieffer et al. (2013) have investigated these relations in children.

The present study

From the research conducted so far, it is clear that decoding skills, language skills, and executive functions directly contribute to reading comprehension. Additionally, there is some evidence that executive functions affect decoding and language skills. However, the possible indirect effects of executive functions via decoding and language skills on reading comprehension skills are less well known. Furthermore, only a few attempts have been made to study the role of executive functions on reading comprehension throughout the upper primary grades using a longitudinal approach (Nouwens *et al.*, 2018; Seigneuric & Ehrlich, 2005), which makes it difficult to draw conclusions regarding the predictive role of executive functions in reading comprehension. The research question of the present study was, thus, to what extent fourth-grade executive functions (i.e., working memory, inhibition, and planning) directly and indirectly (through decoding and language skills) predict fifth-grade reading comprehension. We expected that both decoding skills and language skills would contribute to variation in reading comprehension (hypothesis 1). Furthermore, we hypothesized that executive functions would contribute directly to reading comprehension (hypothesis 2), and, finally, we expected that executive functions contributed indirectly to reading comprehension through decoding skills and language skills (hypothesis 3; an overview of included relations is depicted in Figure 1).

Method

Participants

A total of 122 Dutch fourth-grade children were recruited from four primary schools in the Netherlands. We decided to include fourth graders as in this grade children's decoding becomes automated, and as a consequence, more cognitive resources become available

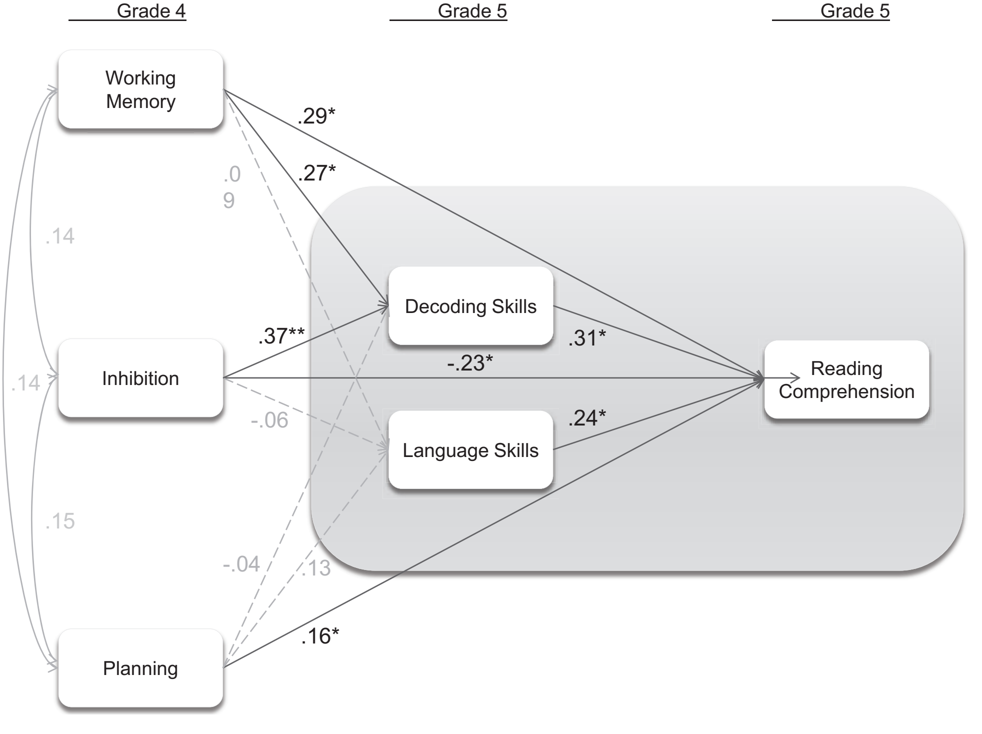

Figure 1. Proposed research questions represented in a structural equation model.

for higher-level comprehension processes (e.g., Cunningham *et al.*, 1990; Perfetti, 1985). These four schools had a total of six fourth-grade classes.

In Grade 4, we assessed children's non-verbal cognitive ability by using the Raven's Coloured Progressive Matrices (Raven, Raven, & Court, 2003). Five children scored below the 25% percentile on this standardized measure and were therefore excluded from the present study. After Grade 4, two children dropped out of the study due to having moved ($n = 1$) or repeating Grade 4 ($n = 1$). Furthermore, in Grade 5, another two children were excluded because they failed to answer over 10% of the questions on the reading comprehension test. Therefore, in the present study, the final sample consisted of 113 children, including 65 boys and 48 girls (Time 1, Grade 4: Age $M = 9.89$; $SD = .44$ years; Time 2, Grade 5: Age $M = 10.07$; $SD = .42$ years). Decoding criteria for inclusion were not applied. Scores on a variety of tasks were not obtained for seven additional children, due to illness or technical malfunctions. Therefore, these children were not included in further analyses, leading to a total of 106 children. The percentage of non-native speakers of Dutch included in the analyses was less than 3%, which falls below the average minority representation (15%) in Dutch primary schools (Tesser, Merens, & Van Praag, 1999).

Thirty-six schools situated in the Netherlands were informed over the research by personalized letters and subsequently contacted by telephone. Of the 30 schools that were reached, four schools (i.e., 13%) – all in regions with an average to slightly higher than average social–economic status (Sociaal Cultureel Planbureau, 2017) – showed interest in participating. Recruitment of participants included informing children and their parents or guardians about the research and obtaining passive consent from parents or caregivers. For each school, children were informed about the research in class, and an announcement was placed in the school newsletter. Subsequently, parents and caregivers were given a brochure with information concerning the research (e.g., 'what will be investigated and why', 'what will happen to the results', 'what does participation entail', 'consent' etcetera). For questions, parents and caregivers were directed to the school principal. Informed parental consent was obtained for all children. Within these four schools (including six classes), 100% of approached participants agreed to be in the study.

Materials

Executive functions measured at Time 1 (Grade 4)

Working memory. Working memory was assessed by means of the backward digit span (Wechsler Intelligence Scale for Children-III-NL, 2004) and a Dutch translation of Gaulin and Campbell's (1994) Competing Language Processing Task.

The backward digit span required participants to store orally presented digits and to reproduce these in reverse order. The backward digit span contained seven blocks, including two sequences per block. The number of digits in a sequence increased over blocks, starting with two and ending with eight digits. When participants were able to successfully recall at least one sequence per block, they moved up to the next block, with a longer sequence of digits. The test ended when the participant incorrectly recalled both trials within a block. The number of correctly recalled trials reflected working memory. The maximum possible score was 14. The internal consistency reliability for this test is reported to be .78 (Wechsler Intelligence Scale for Children-III-NL, 2004).

Gaulin and Campbell's (1994) Competing Language Processing Task requires participants to recall sentence-final words after judging if the orally presented sentences are semantically correct or incorrect. It is therefore very similar to Daneman and

Carpenter (1980)'s listening span task, but contains shorter and simpler sentences and is, therefore, more suitable for use with children. The task contained five blocks of two sets. The number of sentences increased gradually for each pair of sets, starting with two sentences per set and increasing to six sentences per set. The percentage of correct judgements (whether sentences were semantically correct or incorrect) was over 90% for all participants. The total number of correctly recalled words was taken as an indication of working memory. The maximum possible score was 42. The split-half reliability of the task (calculated by dividing the equal-sized sets) was .68 after Spearman–Brown correction for test length.

Inhibition. Inhibition was assessed with the Colour–Word Interference Test (Delis, Kaplan, & Kramer, 2001). Participants were presented with the words 'red', 'green', and 'blue' and were asked to name the incongruent ink colour (red, green, or blue) of the printed words out loud, as quickly and accurately as possible. For example, the ink colour of the word 'red' was blue (correct answer: blue). Naming the ink colour of the word requires suppression of the overlearned response (reading the word) to execute the less automatized response (naming the ink colour) and is an effortful process. Inhibition was reflected by the time (in s) needed to complete the task. In case the participant was not able to finish the task within 180 s, the task was ended. Hence, the maximum possible score was 180, where a higher score reflected a poorer performance. During the task, errors (naming the wrong colour) were also measured. As very few errors and very little variation in errors were observed, errors were not taken into account in the computation of the final score. The reliability of this task is reported to range between .70 and .79 (Delis *et al.*, 2001).

Planning. Planning was measured with the tower task (Delis *et al.*, 2001). Participants were required to build nine increasingly difficult towers from a prearranged initial state to a goal state (a tower) that was presented in a picture. Participants were limited by a time frame. Towers were built by moving a set of three to five discs varying in size across three pegs. The instructions were to use as few moves as possible while adhering to specific rules regarding the movement of the discs. The trials ended when participants completed the tower or were discontinued after the time limit had been reached. The total number of moves used to reach the goal states of all towers was used to reflect planning skills. A higher score, therefore, reflected a poor performance. The minimum possible score to complete all towers was 85. Internal consistency reliability for this task is reported as .84 (Delis *et al.*, 2001).

Reading measures at Time 2 (Grade 5)

Reading comprehension. Reading comprehension was assessed with a standardized Dutch task, Diatekst (H. I. Hacquebord, personal communication, school year 2011–2012). The task consisted of six textbook texts with an average difficulty level suitable for Grade 5. For each text, participants were instructed to read the text before answering the 10–12 accompanying multiple-choice questions. Questions covered micro-, meso-, and macrostructures of the text. Questions on micro-level covered word knowledge and syntactical constructions. Meso-level questions reflected relations between sentences of the text. Macro-level questions reflected global text comprehension. The texts remained available for reading during the entire test. The total score reflected the total number of correct answers, with a maximum of 67. The reliability analyses showed Cronbach's alpha of .89.

Decoding. Decoding was assessed by means of the Klepel (Brus & Voeten, 1999), a standardized Dutch test where participants were asked to read a list of pseudowords as quickly and accurately as possible. The list contained 116 items, increasing in length and difficulty. The total number of pseudowords read correctly within two minutes of reflected decoding. The parallel-forms correlation for Grade 5 is reported to be .92.

Language skills. Language skills assessed were receptive vocabulary and productive syntactic complexity.

Vocabulary was measured using the Peabody Picture Vocabulary Test-III-NL (PPVT-III-NL; Dunn & Dunn, 2005). Participants were presented with four pictures on a computer screen, while they heard a word. Children were requested to indicate which picture best reflected the presented word. Words were presented in blocks of 12 items. The task was discontinued when participants made nine mistakes or more within one block. The maximum possible score was 204. The test–retest reliability is reported to range between .89 and .97 (Dunn & Dunn, 2005).

Syntactic complexity was measured using the Beach Story of the Expression, Reception, and Recall of Narrative Instrument (ERRNI; Bishop, 2004). The participants were presented with 15 pictures that were linked together sequentially to form a story. After careful examination of all the pictures, participants were asked to tell the story that the pictures displayed. We transcribed the recorded audio files and subsequently calculated the mean length of T-Units in words (minimal terminable syntactic units; for guidelines see Hunt, 1966), as an indicator of the child's syntactic complexity, using Child Language Analysis – a programme for analysing transcripts (MacWhinney, 2000).

Procedure

This study includes the data of a comprehensive longitudinal study into the role of executive functions in children's reading comprehension development in the upper primary grades (i.e., grades 4-6). Other aspects of the study are reported in Nouwens *et al.* (2018); Nouwens, Groen, and Verhoeven (2016a); Nouwens, Groen, and Verhoeven (2016b) and therefore include the same sample of children as the current study. While these studies also regarded the relation between executive functions and reading comprehension – while taking decoding and vocabulary into account – these studies differ from the current study on several points. Specifically, although it was demonstrated that working memory and cognitive flexibility (and not inhibition and planning) significantly explained variance in reading comprehension, indirect effects were not assessed and findings were based on cross-sectional data (data from Grade 5; Nouwens *et al.*, 2018; Nouwens *et al.*, 2016a). On the contrary, a third study did apply a longitudinal approach (data from grades 4, 5, and 6), but this focused on the relation between memory retrieval processes and reading comprehension. It therefore did not include standardized measures of working memory, inhibition, cognitive flexibility, and planning.

Reading comprehension and non-verbal cognitive ability were administered in class by one researcher. The remaining tasks were administered individually and were divided over two sessions in a fixed order (session 1: vocabulary knowledge, decoding, inhibition; session 2: working memory, planning, and syntax knowledge) to prevent cognitive overload.

The assessments were administered by that same researcher and two assistants who each underwent a training programme consisting of (1) observing two assessment sessions carried out by the researcher, (2) performing two 'mock' assessment sessions carried out by the assistant, which included a comparison of scores (between the researcher and assistant) and feedback, and (3) two assessments carried out independently by the assistant and observed by the researcher, including intervention and feedback when necessary. Reliability checks were not conducted, as there appeared to be little to no variation in the scores obtained when testing was carried out by the researcher or the assistants.

Data-analyses

Before performing the correlation and structural equation model analyses, we conducted several steps to transform the data. First of all, as a higher score on inhibition and planning reflected a poorer performance, these scores were transposed such that a higher score reflected a better performance. Next, all raw scores were converted into z-scores ($M = 0$; $SD = 1$). We then computed composite scores for language skills (PPVT-III-NL and ERRNI) and working memory (backward digit span and Competing Language Processing Task), by calculating the average z-scores.

Structural equation modelling, using LISREL software (Jöreskog & Sörbom, 2003), was undertaken to test the contribution of (1) decoding and language skills to reading comprehension (Model 1); (2) the contribution of executive functions (i.e., working memory, inhibition, and planning) to individual differences in reading comprehension (Model 2); and (3) the contribution of executive functioning to individual differences in decoding, language skills, and reading comprehension (Model 3). To evaluate data fit, the p-value associated with the chi-square distribution should exceed .05 (Barrett, 2007). Furthermore, the root mean square error of approximation (RMSEA) should not exceed .06, and the value of the standardized root mean square residual (SRMR) should be smaller than .08. Finally, both the comparative fit index (CFI) and the non-normed fit index (NNFI) should exceed .95 (Hu & Bentler, 1999).

The direct effects were calculated by the analyses in LISREL. The indirect effects of X predicting Z via Y were calculated by multiplying the direct effects. For example, the indirect effect of working memory on reading comprehension was calculated by multiplying the path between working memory and decoding and the path between decoding and reading comprehension. The total effects were calculated by adding the indirect effects to the direct effects.

Results

Descriptive statistics are in raw scores and displayed in Table 1. All variables met the criteria for normal distribution as skewness and kurtosis were <1.5 and > -1.5 (cf. Voeten & Van den Bercken, 2003).

The Pearson correlations are displayed in Table 2. The results showed that both decoding and language skills correlated significantly with reading comprehension. Furthermore, reading comprehension was significantly correlated with the executive functions working memory and planning, but the correlation with inhibition was not significant. Finally, decoding was positively correlated with inhibition and working memory. We found no correlations between working memory, inhibition, and planning. Although this appears somewhat remarkable at first sight, weak-to-moderate correlations among executive tasks have been observed by others as well (Kieffer *et al.*, 2013; Miyake *et al.*, 2000). These findings appear to reflect the proposed independence of underlying executive functions (Miyake & Shah, 1999).

The results of the structural equation modelling analysis are displayed in Figure 2. The values represent standardized coefficients. Model 1 regarded the relative contribution of decoding and language skills in Grade 4 to reading comprehension in Grade 5. The analyses yielded a saturated model indicating that both decoding and language skills contributed significantly to reading comprehension. Furthermore, Model 2 regarded the relative contributions of working memory, inhibition, and planning to reading comprehension. The analyses yielded a saturated model indicating that both working memory and planning, but not inhibition, predicted reading comprehension one year later. Finally, Model 3 again showed an excellent model fit ($\chi^2 = 2.46$, $df = 7$, $p = 0.930$, RMSEA < 0.001, SRMR = 0.031, CFI = 0.992, NNFI = 1.140). Both working memory and planning had a direct, significant effect on reading comprehension. In Model 3, the direct relation between inhibition and reading comprehension was also significant (i.e., in contrast to the findings in Model 2). Furthermore, working memory and inhibition also had indirect, significant contributions to reading comprehension via decoding skills. None of the executive functions contributed to language skills.

Table 1. Descriptive statistics (*N* = 106) of executive functions (at Time 1), and decoding skills, language skills, and reading comprehension (at Time 2). Table 1 includes mean scores and standard deviations (*SD*), minimum (Min.) and maximum (Max.) scores, and kurtosis and skewness values

	M	*SD*	Min.	Max.	Skewness	Kurtosis
Time 1						
Working memory						
Backward digit span	4.491	1.587	0	8	−0.004	−0.301
Competing Language Processing Task	25.085	3.765	18	36	0.577	−0.033
Inhibition	86.698	20.295	51	153	0.988	1.367
Planning	170.793	37.527	98	307	0.543	0.592
Time 2						
Decoding skills	62.613	18.142	22	102	0.088	−0.363
Language skills						
PPVT-III-NL	124.594	13.617	96	155	−0.427	−0.186
ERRNI	7.926	0.951	4.67	10.63	−0.367	1.449
Reading comprehension	50.81	9.915	25	66	−0.881	0.083

Notes. All scores reflect raw scores. The score for working memory, decoding, vocabulary (PPVT-III-NL), and reading comprehension reflects the number of correct answers. The score for planning reflects the number of moves made to complete the task; the score for inhibition reflects the time needed (in s) to complete the task. The score for syntactic complexity reflects the mean length of T-Units in words.

Table 2. Correlations ($N = 106$) among executive functions (at Time 1), and decoding, language skills, and reading comprehension (at Time 2)

	1	2	3	4	5	6
Time 1						
1 Working memory	–					
2. Inhibition	.141	–				
3. Planning	.144	.147				
Time 2						
4. Decoding skills	.320**	.402**	.049	–		
5. Language skills	.096	–.033	.130	.139	–	
6. Reading comprehension	.396**	–.055	.214*	.344**	.336**	–

Note: $*p < .05$; $**p < .01$; $***p < .001$.

Discussion

The present study investigated how executive functions (i.e., working memory, inhibition, and planning) contributed to decoding skills, language skills, and reading comprehension. Consistent with the previous literature (Goff *et al.*, 2005; de Jong & van der Leij, 2002; Nation & Snowling, 2004; Oakhill *et al.*, 2003; Verhoeven & van Leeuwe, 2008) and confirming our first hypothesis (Model 1), the current study demonstrated the importance of decoding and language skills in reading comprehension, supporting the Simple View of Reading (Hoover & Gough, 1990). With respect to the second hypothesis (Model 2), the contribution of executive functions to reading comprehension, the results indicated that both working memory and planning as measured in Grade 4, accounted for variance in reading comprehension one year later. This is in line with previous research that showed both working memory (Daneman & Merikle, 1996; Seigneuric & Ehrlich, 2005) and planning (Cutting *et al.*, 2009; Sesma *et al.*, 2009) to have direct, significant relations with reading comprehension. Moreover, the current study demonstrated that a domain-general, higher-order executive function (i.e., planning) contributes to reading comprehension, after controlling for working memory. Inhibition, on the contrary, did not directly predict reading comprehension skills in Model 2, but did have a significant effect in Model 3. With respect to the third hypothesis and the final model (Model 3, see Figure 2 and Table 3), the results showed that, in addition to direct effects of executive functions on reading comprehension, executive functions had significant indirect effects on reading comprehension, via decoding skills but not via language skills.

Direct and indirect contributions of working memory to reading comprehension

The current study demonstrated significant contributions of working memory to decoding skills in addition to its contribution to reading comprehension. Significant effects for working memory on decoding skills have been reported in other studies as well (Arrington *et al.*, 2014; Christopher *et al.*, 2012; Gottardo *et al.*, 1996; Miyake *et al.*, 2012). Working memory is proposed to be needed for decoding to efficiently integrate graphemes with corresponding phonemes (Just & Carpenter, 1992). When comparing our findings to those of previous studies that have regarded both direct and indirect effects of executive functions to reading comprehension via decoding and language skills (Georgiou & Das, 2018; Kieffer *et al.*, 2013), there are several differences that need to be

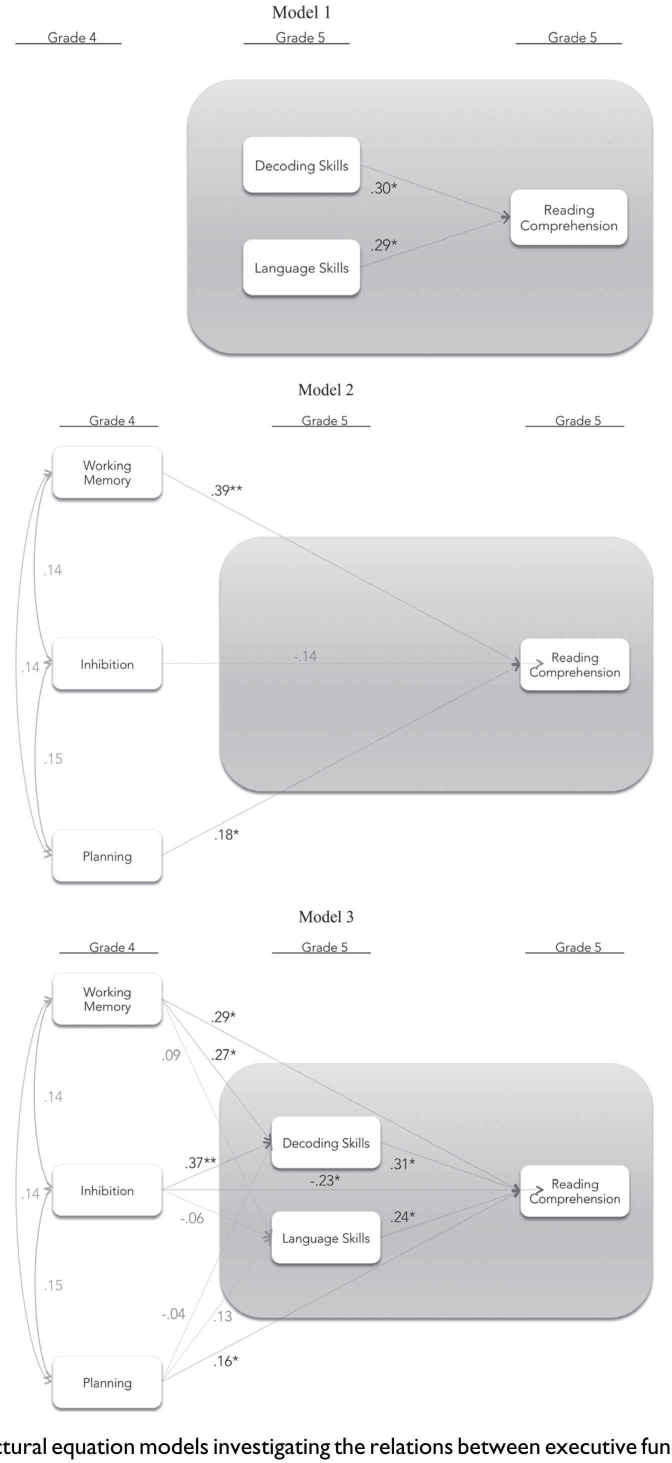

Figure 2. Structural equation models investigating the relations between executive functions, decoding, language skills, and reading comprehension, in line with our research questions. *Note.* The values in figure 2 represent standardized coefficients.

Table 3. Direct and indirect effect of the structural equation models, which reflects the relations between executive functions, decoding, language skills, and reading comprehension, in line with our research questions

Relationships	Direct	Indirect	Total
Working memory → decoding skills	.27	–	.27
Inhibition → decoding skills	.37	–	.37
Planning → decoding skills	–.04	–	–.04
Working memory → language skills	–.09	–	–.09
Inhibition → language skills	–.06	–	–.06
Planning → language skills	.13	–	–.13
Decoding skills → reading comprehension	.31	–	.31
Language skills → reading comprehension	.24	–	
Working memory → reading comprehension	.29	.10	.39
Inhibition → reading comprehension	–.23	.10	–.13
Planning → reading comprehension	.16	.02	.18

discussed. First of all, unlike these other studies, we found a significant direct relation between working memory and reading comprehension, and an indirect relation via decoding. The absence of significant relations in other studies is remarkable given the extensive evidence of the relationship between working memory and reading comprehension (Butterfuss & Kendeou, 2018; Carretti *et al.*, 2009; Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Follmer, 2018). Georgiou and Das (2018) propose that this may be explained by the nature of their comprehension task. Kieffer et al. (2013) pointed out that they used a visual working memory task and not a verbal working memory task. It has been reported repeatedly that tasks measuring working memory in the language domain (i.e., domain-specific tasks) are better predictors of children's reading comprehension than tasks measuring working memory in a domain other than language (Shah & Miyake, 1996). In short, these studies show inconsistent results; however, the studies regarding the direct and indirect effects of working memory to reading comprehension in the upper primary grades, via decoding and language skills, are limited. Future work should address this issue, using working memory tasks that vary in the language processes that are involved.

Direct and indirect contributions of inhibition to reading comprehension

With respect to inhibition, the results showed that the direct relation between inhibition and reading comprehension was significant in Model 3. In contrast, the direct relation between inhibition and reading comprehension was not significant in Model 2. These latter findings support the results of Christopher et al. (2012), who also found no contribution of prepotent response inhibition to reading comprehension in children aged 8–16 years old. Similar results have been reported in adolescents (Arrington *et al.*, 2014).

Based on the correlation analysis and Model 2, it appears that the results of Model 3 are due to a statistical artefact (possibly caused by the strong relationship between inhibition and decoding skills). Moreover, all other results in Model 3 are in line with the correlation analysis, and models 1 and 2, suggesting that the statistical artefact is limited to the relation between inhibition and reading comprehension. Another explanation for these results might be the lack of correlations between the executive functions measures. Although this finding is not uncommon in itself (Kieffer et al., 2013; Miyake *et al.*, 2000), it may have influenced the structural equation model analyses.

Our findings concerning prepotent response inhibition and decoding skills are concurrent with other studies (Altemeier *et al.*, 2008; Arrington *et al.*, 2014). It has been suggested that inhibition mechanisms facilitate decoding skills as it facilitates suppressing incorrect mental representations, evoked by the words in the text, such as homophones and homonyms (Altemeier *et al.*, 2008; Arrington *et al.*, 2014). It would be interesting to further explore the relationship between inhibition and decoding by including both word and non-word reading tasks. According to the dual-route hypothesis, these tasks vary in the extent in which different types of mental representations (phonological, orthographic, syntactic, and semantic representations) are required for processing (e.g., Coltheart, 2000). Inhibition may play a different role in these processes. Similarly, it would be interesting to investigate whether the relation between inhibition and decoding is influenced by factors such as word frequency and text difficulty. Moreover, if inhibition skills depend on a child's quality of phonological, orthographic, syntactic, and semantic representations, this may also affect the relation between inhibition and decoding.

No significant results were found regarding the contributions of executive functions to language skills. This is in contrast to what has been reported in pre-schoolers (Florit et al., 2009, 2011) and in 4- to 5-year-old children (cf. Adams & Gathercole, 1995). One explanation is that retrieval and integration of linguistic information may be more effortful for younger children than for older children. Another explanation may be the way language skills are assessed. While in the current study language skills were assessed with receptive vocabulary and productive syntactic complexity, Florit et al. (2009), Florit et al. (2011) used a listening comprehension task, which taps into cognitive factors in addition to language skills, which may explain why they found a contribution of executive functions.

Again, regarding studies that included direct and indirect effects of executive functions to reading comprehension, we see that our results are in line with Georgiou and Das (2018), but in contrast to Kieffer et al. (2013). Kieffer et al. (2013) found that prepotent response inhibition accounted for individual differences in reading comprehension in 9- to 10-year-old children, but not in word reading. The diverging findings of Kieffer et al. (2013) may again be caused by the type of task: The current study used a colour–word interference task – that requires participants to suppress language processing – to reflect inhibition. Kieffer et al. (2013) used an inhibition task where participants had to suppress number processing. The differences in the way that these inhibitions tap into language processing may have affected their relations with (pseudo)word reading. Moreover, as mentioned previously, the presence of a significant relation between prepotent response inhibition may be caused by their sample's below-average performance on reading comprehension. Lastly, others have suggested that, rather than prepotent response inhibition, resistance to proactive interference (the ability to suppress or remove outdated information to help maintain relevant stimuli in working memory; Friedman & Miyake, 2004) is relevant for reading comprehension (Arrington *et al.*, 2014). Future work should clarify the specific nature of the contribution of inhibition to reading comprehension, as different types of inhibition appear to contribute to different aspects of reading comprehension.

Direct and indirect contributions of planning to reading comprehension

Finally, the results of the present study indicate that planning only contributed directly (and not the indirectly) to reading comprehension. These results seem to fit with previous cross-sectional studies (Cutting *et al.*, 2009; Sesma *et al.*, 2009), but our results are the first to provide a longitudinal indication for the role of planning in reading comprehension skills. Planning can be seen as a higher-level executive function, which is involved in metacognitive processes such as monitoring of one's own understanding and reasoning (Diamond, 2013; Vellutino, Scanlon, & Lyon, 2000). This may explain why planning is important for reading for comprehension, but not for decoding and language skills. However, the role of planning in reading comprehension development is still somewhat inconclusive, and this relation should be clarified in future studies by using different types of planning tasks and regarding multiple components of reading (e.g., decoding, word reading) and reading comprehension (e.g., sentence comprehension, micro- and macro-level reading comprehension, inference making).

Limitations and suggestions for future research

Some limitations should be acknowledged at this point. To begin with, it should be noted that there is no clear consensus about how executive functioning and working memory are being conceptualized. While some authors have proposed working memory to be a distinct and separate executive function (Lehto *et al.*, 2003; Miyake *et al.*, 2000), others have proposed that multiple executive functions are involved in working memory (Baddeley, 1996; Baddeley, Della Sala, Roberts, Robbins, & Weiskrantz, 1996). Moreover, it is generally agreed that there are three core executive functions including updating and monitoring of working memory processes, inhibition, and cognitive flexibility. In the current study, we did not address the contribution of cognitive flexibility – the ability to shift between multiple operations and mental states (Anderson, 2002; Diamond, 2013) – to reading comprehension. Cognitive flexibility is needed for reading comprehension to adapt existing text representations to new text representations (Diamond, 2013) or to adjust reading strategies based on the reading goal and task difficulty (Ramsel & Grabe, 1983). Indeed, recent studies have shown that cognitive flexibility significantly explained variance in reading comprehension, even after accounting for working memory and/or inhibition in children (Kieffer *et al.*, 2013; Nouwens *et al.*, 2016a), young adolescents (Latzman, Elkovitch, Young, & Clark, 2010), and adults (Georgiou & Das, 2018). Moreover, it is thought to aid in simultaneous processing of phonological and semantic information for reading comprehension or to retrieve multiple mental representations from the mental lexicon or long-term memory (Cartwright, 2009), which indicates that cognitive flexibility may be involved in decoding and language skills. Indeed, there is some evidence that cognitive flexibility contributes significantly to decoding skills in children (e.g., Cartwright, 2012) and adolescents (Ober *et al.*, 2019), and to language skills in children (Kieffer *et al.*, 2013). However, there is also some evidence that contradicts a relation between cognitive flexibility and language skills (Georgiou & Dass, 2018). Future work should investigate the unique contribution of cognitive flexibility – alongside other executive functions – to decoding, language skills, and reading comprehension in children.

Similarly, other cognitive processes that are related to executive functioning, such as attention (Diamond, 2013), have been positively related to reading comprehension (e.g., Arrington *et al.*, 2014). Therefore, it would be interesting to include these processes in future research. Moreover, previous studies have demonstrated indications for a reciprocal relationship between executive functions and reading comprehension (for a review, see Follmer, 2018). It would be interesting to examine these bidirectional associations between executive functions and reading comprehension, as this may be greatly beneficial for fundamental insights and practical implications.

Lastly, studies applying a longitudinal approach could provide more insight into the developmental trajectory of these relations. Although the current study included data from time-points one year apart, an autoregressive effect for reading comprehension was not included. Hence, our findings are only partly longitudinal. Additionally, the results await replication in follow-up studies following a longitudinal design with larger samples of children, as this may strengthen future results.

Conclusion and practical implications

To conclude, the present study on reading comprehension highlighted the importance of executive functions in addition to decoding and language skills, in the upper grades of primary school. These findings are in line with other research showing that the automaticity of decoding allows for an increase of resources for other cognitive demands involved in reading comprehension (e.g., Cunningham *et al.*, 1990; Perfetti, 1985), and fit well with the proposal of a limited cognitive system, as suggested by the Reading Systems Framework (Perfetti & Stafura, 2014). As a practical implication, when it comes to assessment and intervention of reading comprehension skills, educational professionals should not only consider decoding and language skills children bring into the classroom but their executive functions as well. More specifically, teachers should be aware that children first need to form a solid basis in decoding in order to free up cognitive resources needed for executive functioning (Perfetti, 1998; Samuels & Flor, 1997; Tunmer & Hoover, 1992). Furthermore, planning is a higher-order executive function that is built on the three executive functions working memory, inhibition, and cognitive flexibility (Lehto *et al.*, 2003; Miyake *et al.*, 2000). This entails that deficiencies in working memory may result in planning problems. This may be important to realize as great emphasis is placed on planning in the reading comprehension curriculum by teaching reading strategies, such as reading titles, monitoring comprehension, and summarizing.

Conflicts of interest

All authors declare no conflict of interest.

Author contributions

Suzan Nouwens (Conceptualization; Formal analysis; Methodology; Writing – original draft) Margriet A. Groen (Supervision; Writing – review & editing) Tijs Kleemans (Writing – review & editing) Ludo Verhoeven (Conceptualization; Supervision; Writing – review & editing).

Data availability statement

Data available on request from the authors.

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