Read Writ (2017) 30:121–141
DOI 10.1007/s11145-016-9666-4

The contribution of executive functions to naming digits, objects, and words

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Published online: 13 June 2016

Abstract Although it is established that reading fluency is more strongly related to serial naming of symbols than to naming of isolated items (*serial superiority effect*), the reason for the difference remains unclear. The purpose of this study was to examine the role of executive functions in explaining the serial superiority effect. One hundred seven Grade 6 Greek children were assessed on serial and discrete naming (digits, objects, and words), executive (inhibition, shifting, and updating) and non-executive tasks (simple choice reaction), and on a serial Rapid Alternating Stimuli task. Reading fluency correlated more strongly with serial naming than with discrete naming, consistent with the serial superiority effect. In hierarchical regression analyses, executive measures failed to account for variance shared between serial naming and reading fluency. In confirmatory factor analyses, including a discrete and a serial factor for the naming tasks, variance in the executive tasks not shared with simple choice reaction was not associated with the serial factor. Thus, the executive tasks failed to account for the serial superiority effect. The high correlation between the simple choice factor and the discrete naming factor suggests that method variance partially underlies the observed relationship between executive function tasks and word reading. We argue that the distinction between serial and discrete dimensions indicates that internally regulated cognitive control is crucial for the serial superiority in naming symbols and words.

Keywords Executive functions · Rapid automatized naming · Fluency · Reading · Serial superiority effect

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Introduction

It is well established that rapid automatized naming (RAN), defined as the ability to name as fast as possible familiar sets of visual stimuli, such as letters, digits, objects and colors, is a strong concurrent and longitudinal predictor of reading (e.g., Kirby, Georgiou, Martinussen, & Parrila, 2010). Several studies have shown that serial versions of RAN, where the items are presented simultaneously in grid formats, correlate more strongly with word reading than discrete formats, where the items are presented individually (e.g., de Jong, 2011; Logan, Schatschneider, & Wagner, 2011). This robust finding, termed *serial superiority effect*, implies that serial naming recruits additional cognitive processes, not shared with discrete naming, that boost the serial RAN-reading relationship. In this study, we aimed to examine the role of executive functions (EF) as a candidate explanation for the stronger relationship between serial RAN and word reading.

The serial superiority effect

The unique contribution of serial RAN to word reading has drawn the attention of researchers who argued that multiple stimulus presentation is a crucial element of the relationship between the two processes in typical readers (e.g., Georgiou, Parrila, Cui, & Papadopoulos, 2013) and a bottleneck in individuals with dyslexia (e.g., Jones, Branigan, & Kelly, 2009; Zoccolotti et al., 2013). For example, de Jong (2011) examined the relationship between serial and discrete versions of RAN and reading and reported that serial RAN was more strongly correlated with reading among novice readers; in contrast, the relationship between the tasks was format dependent among advanced readers. Overall, the pattern of correlations for fluent readers revealed a dissociation between serial and isolated item processing, while for both advanced and beginning readers, serial RAN was a unique predictor of reading fluency. Protopapas, Altani, and Georgiou (2013a) also indicated that serial item processing accounted for unique variance in reading fluency over and above the effects of isolated word recognition and discrete symbol naming.

An explanation for the serial superiority effect could be sought in the similar format of the tasks because visual scanning from left to right is required in both tasks. However, a serial backward naming task, with a scanning direction opposite to the direction of reading, has been found to correlate equally well (or even better) with reading fluency as the standard forward serial version of the task (Protopapas, Altani, & Georgiou, 2013b). This finding suggests that visual scanning directionality in itself cannot explain serial superiority. An alternative explanation could be sought in the role of EF in naming symbols and words. EF (or executive control) is an umbrella term that encapsulates a set of routines responsible for cognitive control during complex cognitive tasks (see Diamond, 2013, for a review), and has been linked to both RAN and reading (Klein, 2002). Although the term EF refers to a host of cognitive processes, Miyake et al. (2000) suggested that EF consists of three well-defined components: shifting of attention (henceforth termed *Shifting*), information updating and monitoring (*Updating*), and inhibition of prepotent responses (*Inhibition*).

During naming and reading, the eyes must move sequentially across the items, as the stimulus in fixation is encoded and its mental representation is accessed (Jones, Branigan, Hatzidaki, & Obregón, 2010; Morgan & Meyer, 2005). Several cognitive elements are required to orchestrate this process, including sequential disengagement of the previous and rapid engagement of the next stimulus (Shifting), suppression of the previously activated item, to be replaced by activation of the next one (Inhibition), and monitoring and updating of the phonological representations of the incoming stimuli in working memory (Updating). This suggests that naming of words and symbols may tap abilities of cognitive executive control involved in serial processing.

Executive functions and reading

Several studies have shown that performance on EF tasks is linked to both typical (e.g., Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014; Sesma, Mahone, Levine, Eason, & Cutting, 2009) and atypical (e.g., Booth, Boyle, & Kelly, 2014; Gathercole, Alloway, Willis, & Adams, 2006) reading. In general, children and adolescents who exhibit good performance in word reading tend to demonstrate better inhibition and shifting control (e.g., Arrington et al., 2014; Protopapas, Archonti, & Skaloumbakas, 2007).

However, some studies have found that reading is significantly related to updating and shifting ability, but not inhibition (e.g., Latzman, Elkovitch, Young, & Clark, 2010; van der Sluis, de Jong, & van der Leij, 2007). Christopher et al. (2012) analyzed reading, naming, and EF constructs into their shared and separable variance and found that only working memory—but neither inhibition nor naming of non-alphanumeric stimuli—was a unique predictor of word reading. Similarly, van der Sluis et al. (2007) used latent variables in a sample of 9- to 12-year-old children to examine whether EF components are distinguishable when non-executive variance (i.e., the common method between EF and control tasks reflecting non-executive demands) was controlled. Their results indicated distinct shifting and updating factors that were both related to reading; in contrast, an inhibition factor was not identified.[1]

Finally, individuals with dyslexia have been found to experience difficulties in EF tasks, particularly in inhibition and shifting (see Brosnan et al., 2002; Helland & Asbjørnsen, 2000; Protopapas, 2007). In general, it has been found that children with dyslexia show greater inhibitory difficulties (e.g., Everatt, Warner, Miles, & Thomson, 1997; Faccioli, Peru, Rubini, & Tassinari, 2008) and shorter working

[1] Both the distinction among EF sub-components in children and the timing of their emergence have been controversial. Although a multidimensional structure of EF components is apparent in adulthood (Miyake et al., 2000), a more unified construct has been identified earlier in development, with preschool EF attributed to a single global factor of executive control (Fuhs & Day, 2011; Wiebe et al., 2008). Recent studies suggest that EF is a global ability that gradually becomes differentiated from middle childhood through adulthood (De Luca et al., 2003; van der Ven, Kroesbergen, Boom, & Leseman, 2013).

memory span (e.g., Everatt, Weeks, & Brooks, 2008; Willcutt et al., 2005) than their age-matched controls with typical reading development.

Executive functions and RAN

Information regarding the relationship of EF with RAN comes from four different sources. First, studies have found that updating and inhibition are related to RAN, particularly object and color naming (Bexkens, Wildenberg, & Tijms, 2015; Shao, Meyer, & Roelofs, 2013; Shao, Roelofs, & Meyer, 2012). Second, well-known naming tasks that require the rapid naming of stimuli, such as color naming in the Stroop test (Stroop, 1935), have been used as measures of both inhibition and shifting in previous studies (e.g., van der Sluis, de Jong, & van der Leij, 2004; van der Sluis et al., 2007). Most of these naming tasks can be seen as variations of Stroop and show several patterns of association similar to that observed between RAN and reading (see McLeod, 1991, for a review). Third, some researchers have used one of the naming speed tasks, Rapid Alternating Stimuli (RAS; Wolf, 1986), as a measure of executive control in their studies (e.g., Altemeier, Abbott, & Berninger, 2008; Amtmann et al., 2007). RAS is structured similarly to RAN in a serial format, with two or three types of items (e.g., letters, digits, and colors) repeated alternately throughout the grid. This task is supposed to capture the additional demands of shifting and disengaging of attention in naming tasks, while processing sets of different stimuli (Wolf, 1986). Finally, studies examining the cognitive profile of children with ADHD (inattentive type) have shown that as a group they perform worse than controls on different RAN tasks (e.g., Bental & Tirosh, 2007; Semrud-Clikeman, Guy, Griffin, & Hynd, 2000; Shanahan et al., 2006). For example, Semrud-Clikeman et al. (2000) showed that children with ADHD performed significantly slower than a control group on color and object naming.

Evidence from studies that reported correlations between RAN and different EF components is mixed (e.g., Lervåg, Bråten, & Hulme, 2009; Närhi et al., 2005; Navarro et al., 2011; Pham, Fine, & Semrud-Clikeman, 2011; Stringer, Toplak, & Stanovich, 2004). For example, Stringer et al. (2004) found that inhibition, but not shifting or working memory, was significantly related to RAN letters and digits. In contrast, Lervåg et al. (2009) found that RAN letters and digits correlated significantly with working memory, and van der Sluis et al. (2007) reported significant correlations between RAN and shifting.

In sum, discrepancies among findings, as well as differences concerning task content and format, age range, and sample origin (clinical versus typical), hinder conclusions about the link between specific components of EF and word reading or symbol naming ability. EF appears to be important for reading and implicated in speeded naming of visual stimuli, such as objects or colors. However, whether word reading and rapid naming tasks reflect similar executive demands, responsible for their strong relationship, is yet to be explored.

The present study

The purpose of our study was to examine whether EF can account for the serial superiority effect in the RAN-reading relationship. To do this, we administered both serial and discrete word and symbol naming tasks, as well as EF tasks. We also administered control measures to distinguish the executive from the non-executive demands of the EF tasks. We hypothesized that executive control (i.e., monitoring of serial processing of individual items that minimizes interference) will be associated with both serial naming and reading performance and will underlie their interrelationship. Therefore, we expected that (a) EF would correlate more strongly with serial naming of words and symbols than with discrete naming and reading, and (b) controlling for the effects of discrete naming and EF would eliminate the effects of serial naming on reading fluency.

Method

Participants

The study population consisted of 107 Grade 6 children (58 girls; mean age = 141.7 months; SD = 3.8 months) previously described in Protopapas et al. (2013a). Briefly, children were recruited from the general student population in a middle-class Athens province, were native speakers of Greek and had no diagnosis of any intellectual, sensory, or behavioral difficulties. Parental consent and research permission from the Greek Ministry of Education was obtained prior to testing.

Materials

Rapid naming

Five naming tests were administered: serial and discrete digit naming (RAN-Digits), serial and discrete object naming (RAN-Objects), and serial RAS (objects and digits). The digits were 2, 3, 5, 7, and 9, pronounced /ˈðio/, /ˈtria/, /ˈpɛndɛ/, /ɛˈfta/, /ɛˈɲa/, respectively. Each test included 50 items in total. They were presented in black 28-point Arial font on a white background. The objects were color drawings of an apple, a chicken, a vase, a gift, and a ball, pronounced /ˈmilo/, /ˈkota/, /ˈvazo/, /ˈðoro/, /ˈbala/, respectively; All digit and object words were bisyllabic.

Reading

Two measures of word reading were administered: serial and discrete word reading. Each task included 50 items (31 two-syllable and 19 three-syllable words) selected from a reading fluency list used in previous research (Protopapas, Sideridis, Mouzaki, & Simos, 2007). All items in both tests were among the 1000 most frequent words in the Hellenic National Corpus (Hatzigeorgiu et al., 2000; hnc.ilsp.

gr) and more than half of the words appeared in the basic vocabulary of the second grade reading textbook.

Executive functions

Following Miyake et al.'s (2000) conceptualization of EF, we administered an inhibition task, a shifting task, and an updating task. All executive tasks were based on well-known measures and were adapted, where necessary, to be suitable for children. Each task, except for Updating, included two conditions: a baseline (control) condition, and a manipulated condition recruiting the target executive functions. The variance in the executive-loaded tasks that could not be explained by the control tasks was attributed to the additional executive requirements and was considered indicative of the executive function ability. An example of the tasks used is illustrated in Fig. 1.

Inhibition

The inhibition task was adopted from van der Sluis et al. (2004). The control task consisted of two geometrical figures, a circle and a square, drawn in a heavy black line. In this condition, children were asked to rapidly respond to the figures by pressing a button ("right button" for the circle, and "left button" for the square; stickers depicting the figures were placed on the buttons to help children associate the figures with the corresponding keys). In the manipulated condition, the same figures were presented, but an additional smaller gray figure (a circle or a square) was placed in varying positions within the larger figure. In the manipulated condition children were instructed to respond to the smaller, less noticeable object and ignore the larger prepotent figure by pressing the button associated with the target figure. A total of 24 figures were shown, 12 circles and 12 squares in each task. Each figure was presented isolated on the screen, black on white background, for a limited time period (3 s) or until a response was detected. The child's score was the mean response time.

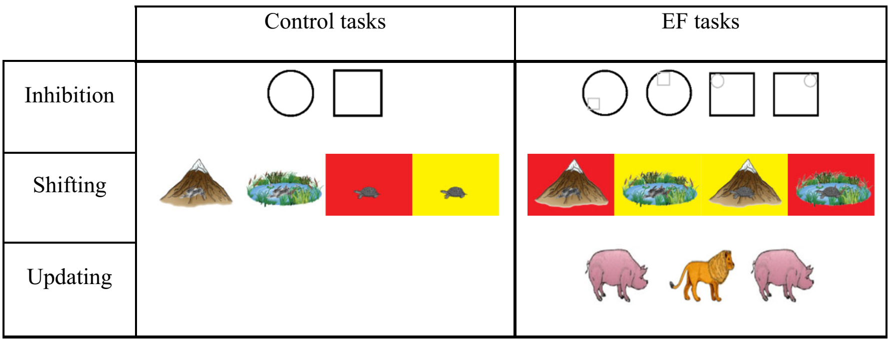

Fig. 1 Sample items of the three EF tasks and the two control counterparts of Inhibition and Shifting

Shifting

The shifting task was inspired by Zelazo, Müller, Frye, and Marcovitch (2003). The task was presented as a game in which “a rabbit *likes* lakes and *dislikes* mountains” and “a turtle *likes* red and *dislikes* yellow”. In a first block a rabbit was presented either in front of a lake or a mountain. According to task instructions, when the rabbit was shown in front of a lake the child had to respond by pressing the “yes” button and when the rabbit was shown in front of a mountain the child had to respond by pressing the “no” button. In a second block of the control condition, the rabbit was replaced by a turtle and the child was asked to sort the items according to the color of the background in which the turtle was presented by pressing the “yes” button for red and “no” for yellow. Two blocks were administered with 12 trials each. The manipulated condition (Shifting task) was a mixed block where 24 images in total were presented, consisting of 12 images depicting a rabbit and 12 images depicting a turtle upon every possible combination of background (e.g., rabbit-lake-yellow; turtle-mountain-red). In this condition, the child had to sort the items by pressing “yes” or “no” depending on whether the rabbit or the turtle was displayed, alternating between *lake-mountain* and *yellow–red* rules. A child’s score was the mean response time.

Updating

The updating task was based on the N-Back task developed by Smith and Jonides (1997). Sequences of pictures depicting five animals (frog, snail, pig, lion, and peacock) were presented on the screen. Children were instructed to respond to an image that was identical to that presented two trials back in the sequence (2-Back) by pressing a response button (“yes”) whenever a target event was detected. For example, in the sequence lion-frog-lion, the second picture of the lion corresponded to a target event, whereas in the sequence frog-lion-lion, there was no target event. The task included a block of 50 trials, with target frequency of 33.3 %. All images were taken from a standardized set of pictures for Modern Greek (Dimitropoulou, Duñabeitia, Blitsas, & Carreiras, 2009) from the color version of the Snodgrass and Vanderwart (1980) picture set. A child’s score was the d' measure of discrimination, calculated from the number of accurate and inaccurate responses (hits, false alarms).

Procedure

In the serial RAN tasks, items were presented in semi-random order in five rows of 10 (Denckla & Rudel, 1976). In the RAS task, five digits and five objects were presented alternately in each row in semi-random order on a single-screen array of five rows of 10. In the serial reading task, words were presented in a single-screen array of five columns of 10. For each test, the corresponding naming set was presented on the computer screen and the child was asked to name (or read) aloud the items one by one as quickly as possible without making mistakes. Digit and object RAN tasks were preceded by practice items to verify the production of the intended words. Each task was recorded on the computer via a headset and was subsequently measured on the waveform using praat (Boersma & Weeninck, 2012). The score was the total time to complete the naming of the 50 items, from the onset of the first item to the offset of the last one.

In the discrete tasks, the items were presented one by one in the middle of the screen, in black letters on a white background. Words were displayed in 25-point Arial Narrow; digits were displayed in 45-point Arial. Each item was presented for a limited time period or until a vocal response was detected using the microphone trigger. The intertrial interval was 750 ms. Maximum presentation time was 2000 ms for all RAN tasks and 3000 ms for word reading. Item presentation and response recording was controlled by the DMDX experimental display software (Forster & Forster, 2003). Individual responses were recorded to audio files, on which accuracy and onset time was subsequently marked using CheckVocal (Protopapas, 2007). The score was the mean naming time (speech onset latency) over 50 items.

For the executive function tasks, presentation and response recording was controlled by DMDX. Each item was presented isolated on the screen and a keypress response was required in all tasks. For inhibition and shifting, maximum presentation time was 3000 ms and the intertrial interval was 750 ms. A training block of 8 trials without feedback preceded each task to familiarize the child with the task instructions. Response latency for correct responses was measured from the appearance of an item on the screen until the onset of the motor response. For 2-Back maximum presentation time was 500 ms and intertrial interval was 1500 ms. In 2-Back, 9 trials (including 3 targets) with feedback were administered prior to the task.

Administration alternated between word, RAN, and executive tasks, in the same fixed order for all participants. Testing lasted approximately 40 min and was conducted in a quiet room at school during school hours by the first author.

Results

Data preprocessing

Serial naming and reading times were inverted and multiplied by the number of items to produce measures of items per second. Errors, including self-corrections, omissions, false starts and repetitions were rare (i.e., <1 % uncorrected errors, including omissions and false starts; <2 % self-corrections) and were not taken into account in the analyses. For the discrete and executive measures, mean response times per participant were computed based on correct responses only. Discrete total naming times were inverted and multiplied by 1000 to produce comparable scales with serial naming and to bring the data closer to the normal distribution. Response times for inhibition, shifting, and their control tasks were inverted and multiplied by 100 to produce comparable scales with the serial and discrete naming tasks. For the Updating task (2–Back), d′ was calculated.

A few outliers were noted, including one data point (>900 ms) in discrete word naming and one data point (>2000 ms) in the Shifting task. Table 1 presents the

Table 1 Descriptive statistics and tests of normality

Task	Descriptives						Shapiro–Wilk	
	M	SD	*min*	*max*	Skew	Kurt.	*W*	*p*
Discrete								
Objects	1.72	.19	1.24	2.06	−.27	−.42	.98	.12
Digits	2.03	.24	1.42	2.60	−.01	−.44	.99	.92
Words	1.84	.24	1.34	2.38	.12	−.51	.99	.38
Serial								
Objects	1.36	.22	.77	1.90	.11	−.32	.99	.89
Digits	2.13	.47	1.08	3.38	.09	−.10	.99	.74
RAS	1.59	.26	.98	2.28	.23	−.14	.99	.72
Words	1.60	.33	.92	2.40	.06	−.43	.99	.42
EF control								
Inhibition	4.98	.73	3.61	6.80	−.08	−.70	.98	.10
Shifting	4.10	.70	2.55	6.01	.12	−.08	.99	.74
EF manipulated								
Inhibition	3.62	.49	2.64	4.73	.35	−.66	.97	.02
Shifting	1.83	.29	1.16	2.61	.15	−.02	.99	.96
Updating (d')	2.69	.75	.29	4.23	−.68	.48	.96	<.01

Discrete and serial tasks in items (symbols and words) per second; EF control and manipulated tasks in inverse seconds times 100, except for Updating

descriptive statistics for each measure excluding these outliers. Higher scores represent faster performance (i.e., more items named or responded to per second). Exclusion criteria left 106 complete datasets. Examination of Q–Q plots and Shapiro–Wilk tests of normality indicated no significant deviations from normality, except for a small deviation of the Inhibition task. All analyses were conducted using R (R Core Team, 2014).[2]

Comparisons between EF and control tasks

Before examining the correlations between EF and naming/reading tasks, we compared the EF tasks with their control counterparts to quantify the magnitude of executive demands in the manipulated tasks. A sizeable and significant difference in the response times (RTs) of the manipulated versus control EF tasks was a prerequisite to considering the inhibition and shifting manipulations to be effective.

A *t* test was performed for each pair of EF manipulated task and its control counterpart to examine whether there was an executive load on the EF tasks over

[2] The serial and discrete naming data were derived from tasks previously reported in Protopapas et al. (2013a). Previous analyses were conducted with discrete naming response times including articulation (i.e., offset latency, from the onset of item presentation to the offset of the spoken response). In contrast, analyses reported here used onset latencies for the discrete tasks, which is the measure more frequently reported in the literature.

and above the non-executive demands measured with the control tasks. The results showed that the RTs of the EF tasks were significantly longer than their controls (Inhibition: t (106) = 26.13, p < .0005, Cohen's d = 2.19; Shifting: t (105) = 37.46, p < .0005, d = 4.24). These results suggest that the extra executive load of the manipulation affected response times, consistent with the assumption that manipulated EF tasks required additional executive resources beyond the non-executive demands of the tasks.

Correlations among EF, naming, and reading tasks

Correlational analysis among all tasks was performed to examine (a) the serial superiority effect, as reflected in the relation of serial and discrete naming to reading and (b) the relation of EF to serial and discrete naming and reading. Table 2 shows the correlations among all tasks. Reading (serial words) correlated more strongly with serial naming than with discrete naming. Specifically, comparing correlations with the Fisher r-to-z transformation, serial words correlated more strongly with serial digits than with discrete digits ($z = 3.50$, $p = .0005$) and with serial objects than with discrete objects ($z = 2.67$, $p = .008$). Moreover, higher correlations were observed among tasks of similar format for both discrete and serial naming and reading than among tasks of different formats.

Both manipulated and control EF tasks correlated more strongly with discrete naming tasks (both words and symbols) than with serial naming tasks. More specifically, inhibition and shifting correlated significantly with discrete naming of digits, objects, and words. In contrast, the same EF components were correlated only with serial naming of objects and alternating stimulus (RAS), and shifting and updating were also correlated with serial words. Conservative correction for 66 comparisons performed via Bonferroni adjustment to a = .0008 resulted in the following pattern of findings: (a) correlations among naming tasks of similar format were significant; (b) all EF and control tasks were interrelated except for updating; (c) discrete naming tasks (digits and objects) correlated with inhibition. The correlation of inhibition with discrete words and serial object naming barely missed the correction.

Hierarchical regression analyses

To examine the contribution of EF measures to the relationship between serial naming and serial word reading, we performed hierarchical regression analyses (see Table 3). Reading fluency, measured by serial word reading, was the dependent variable. In the top part of the table, each block of serial RAN, discrete RAN, and EF tasks was entered in the regression at Step 1 to examine the contribution of each set of tasks to reading fluency separately. In the bottom part of the table, serial RAN was entered at Step 3, after discrete RAN and EF had been entered at Step 1 and Step 2, respectively. If EF is responsible for the stronger correlations observed between serial naming and reading than between discrete naming and reading, then controlling for the effects of discrete naming and EF in regression analyses should eliminate the contribution of serial naming to reading.

Table 2 Correlations (Pearson's r) among tasks

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1.	d-Words											
2.	d-Digits	.59										
3.	d-Objects	.61	.71									
4.	s-Words	.36	.22	.23								
5.	s-Digits	.17	.18	.12	.61							
6.	s-Objects	.31	.30	.44	.54	.37						
7.	s-RAS	.38	.28	.32	.68	.51	.77					
8.	Inhibition	.31	.48	.36	.16	.09	.28	.22				
9.	Shifting	.26	.23	.23	.23	.17	.19	.20	.39			
10.	Updating	.16	.24	.15	.21	.10	.10	.12	.13	.15		
11.	C-Inh	.35	.50	.39	.16	.18	.16	.15	.68	.37	.18	
12.	C-Shift	.45	.49	.38	.22	.07	.14	.20	.52	.47	.24	.57

Correlations lower than .19 are not significant; correlations between .19 and .27 are significant at the .05 level; correlations higher than .27 are significant at the .01 level; and correlations higher than .31 are significant at the (Bonferroni-adjusted) .0008 level

d discrete, *s* serial, *RAS* Rapid Alternating Stimulus, *C-Inh* Control Inhibition, *C-Shift* Control Shifting

The results indicate that when entered at Step 1 serial RAN alone accounted for 45.5 % of the variance in serial word reading, while the corresponding percentages of discrete RAN and EFs (manipulated tasks) when entered at Step 1 were 4.5 and 7.9 %, respectively. However, when entered into the regression equation at Step 3, serial naming continued to account for 37.9 % of the variance in reading fluency, even after controlling for discrete RAN (Step 1) and EF (Step 2). In fact, the contribution of EF tasks was not statistically significant. Table 3 also lists the individual regression coefficients for each predictor variable in the final model.

Latent variable analyses

The previous analysis failed to reveal any significant effects of EF on reading fluency. However, it remains possible that the executive component of at least some of the EF manipulated tasks may be related to serial processing, after controlling for the non-executive demands of the tasks, in a way that may be interpreted as reflecting executive demands of serial processing. To examine this possibility we turned to the latent structure of naming and EF tasks, aiming to separate serial and executive factors from discrete naming and control task demands (choice reaction time). To approach this problem, given the modest size of our sample, we first fitted separate measurement models for the two domains (naming and EF). Thus, confirmatory factor analysis (CFA) was conducted separately for the EF and naming tasks, using R package sem (Fox, Nie, & Byrhnes, 2014).

To evaluate the model fit, Chi square values and a set of fit indexes were used: (a) the Tucker-Lewis Non-normed Fit Index (NNFI); (b) the Bentler Comparative

Table 3 Hierarchical regressions predicting reading fluency from serial and discrete naming tasks and EF

Step	Variables	β	ΔR^2	*p*
1.	Serial RAN		.455	$<.0005$
	Digits	.312		$<.0005$
	Objects	.547		$<.0005$
1.	Discrete RAN		.045	.111
	Digits	.101		.597
	Objects	.271		.275
1.	EF		.079	.051
	Inhibition	.028		.696
	Shifting	.232		.065
	Updating	.058		.176
1.	Discrete RAN		.045	.111
2.	Serial RAN		.409	$<.0005$
	Discrete digits	−.007		.962
	Discrete objects	.019		.927
	Serial digits	.313		$<.0005$
	Serial objects	.542		$<.0005$
1.	Discrete RAN		.045	.111
2.	EF		.050	.170
3.	Serial RAN		.379	$<.0005$
	Serial digits	.303		$<.0005$
	Serial objects	.536		$<.0005$
	Discrete digits	−.040		.801
	Discrete objects	.002		.990
	Inhibition	−.016		.796
	Shifting	.096		.332
	Updating	.050		.139

Measures are entered simultaneously as a block in the corresponding step

Serial RAN serial Object and Digit RAN, *Discrete RAN* discrete Object and Digit RAN, *EF* Inhibition, Shifting and Updating Tasks

Fit Index (CFI); (c) the Standardized Root Mean Square Residual (SRMR); and (d) the Root Mean Square Error of Approximation (RMSEA). A non-significant Chi square with NNFI and CFI above .95 suggest model acceptance (Hu & Bentler, 1999). In addition, SRMR and RMSEA values not exceeding .05 indicate a close fit, but values as high as .07 are regarded as acceptable (Browne & Cudeck, 1993).

Structure of the EF tasks

First, we examined whether EF can be decomposed into executive and non-executive task demands. By analyzing the control tasks and the executive tasks simultaneously, the unique contribution of EF tasks can be estimated in the presence of the control tasks. First, we introduced a 1-factor model, where all EF control and manipulated measures were modeled as indicators of a general method factor (Choice RT; Fig. 2, top right). The fit indices of this model (Model 1) were excellent

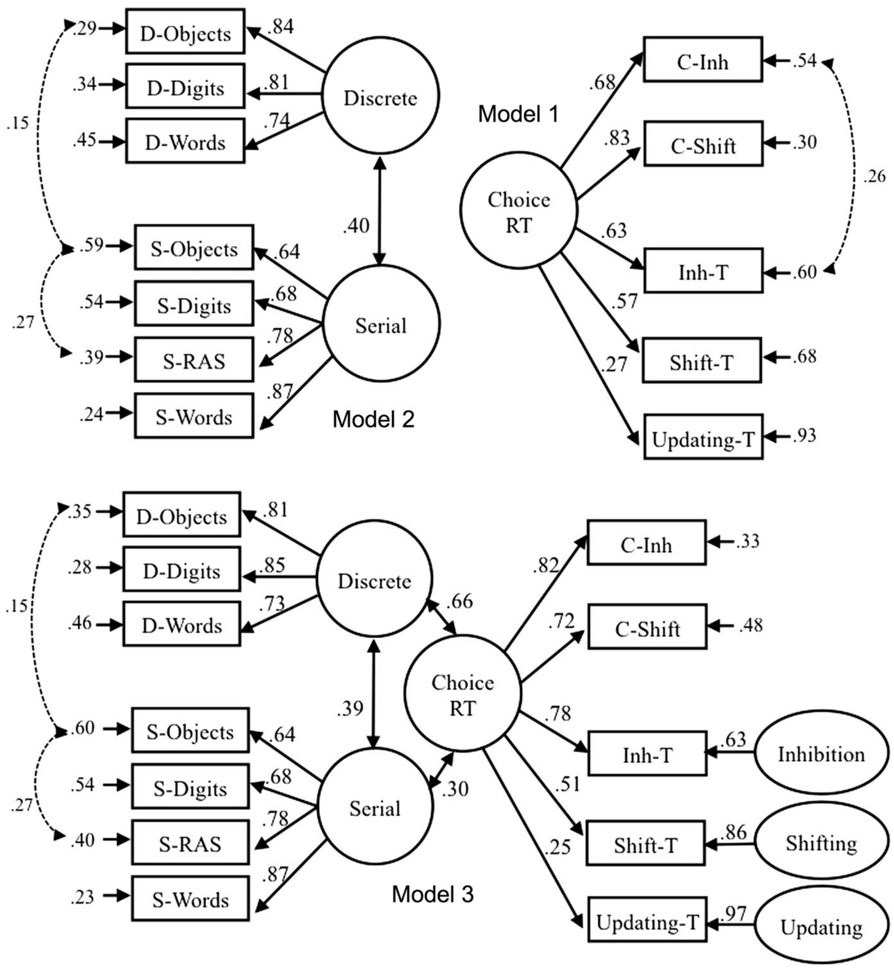

Fig. 2 Best fitting models resulting from confirmatory factor analysis. *Model 1* factor structure only for EF tasks; *Model 2* factor structure only for naming and reading tasks; *Model 3* factor structure including all measures. Standardized coefficients are shown (latent disturbance were set to 1.0). All indicated loadings are statistically significant ($p < .05$). *C-Inh* Control Inhibition, *C-Shift* Control Shifting, *Inh-T* Inhibition Task, *Updating-T* Updating Task, *Shift-T* Shifting Task, *Choice RT* Choice Reaction Time, *S* serial, *D* discrete

(χ^2 (4) = 1.28, p = .865, NNFI = 1.00, CFI = 1.00, SRMR = .02, RMSEA < .005).

The finding that all EF control and manipulated tasks (except updating) had significant loadings on the general factor likely reflects shared method variance. The small loading and high residual error of Updating, which is measured with d' rather than response time, corroborates this interpretation. After controlling for the non-executive requirements, a second model was introduced to examine whether an additional EF factor could be included in the model. However, as expected by the excellent fit of the 1-factor model, the 2-factor model could not be estimated. This does not mean that there were no executive demands in the manipulated EF tasks but, rather, that the executive demands of these tasks were distinct from one another. Therefore, there is no residual shared variance in the measures and no additional gain in model fit can be achieved by introducing further factors. In other words, variance associated with the executive demands of the manipulated EF tasks in this model is found in the corresponding residuals, which are sizeable and not significantly intercorrelated.

Structure of the naming tasks

In a similar fashion, we tested the fit of two models to examine the factor structure underlying the naming tasks. In the first model, all seven naming tasks were modeled as indicators of one general naming factor reflecting the common method. The fit of the 1-factor model was far from satisfactory (χ^2 (14) = 142.83, $p < .005$; NNFI = .47; CFI = .65; SRMR = .16; RMSEA = .29). In the second model, naming tasks were modeled by two factors. Consistent with previous studies in late elementary grades (de Jong, 2011; Protopapas et al., 2013a), all serial tasks were modeled as indicators of a serial factor and all discrete tasks were modeled as indicators of a discrete factor. The fit of the 2-factor model (Model 2; Fig. 2, top left) was acceptable (χ^2 (11) = 15.39, p = .165; NNFI = .98; CFI = .99; SRMR = .06; RMSEA = .06) and lends itself to further investigation of EF variance specifically related to the serial component.

Executive, non-executive, and naming constructs

To examine the relationship between EF and naming, the two well-fitting models from the previous analyses (Model 1 and Model 2) were combined, resulting in a full model. Our objective was to examine whether executive demands might be specifically related to serial processing in naming and reading. Because the executive demands in Model 1 were expressed in residual rather than latent variable variances, 'phantom factors'[3] were introduced for each EF component to capture this variance from the manipulated EF tasks. Each phantom factor is linked to a single manipulated EF task with a loading fixed to 1.0 and a task residual variance fixed to zero, so that any variance not associated with the Choice RT latent variable can be modeled as arising from the phantom factor. In this way, even though there are no multiple indicators for each EF component, we can examine at the latent level whether variance shared between serial naming tasks is also shared with the executive demands of one or more EF tasks.

The full model (Model 3; Fig. 2, bottom) included all 12 tasks and consisted of one general Choice RT factor, three EF phantom latent variables, a serial naming factor, and a discrete naming factor. The fit of the resulting full model was

[3] Phantom factors are "latent variables with no observed indicators" (Rindskopf, 1984, p. 38). These latent variables allow estimation of model parameters in alternative forms or metrics. In the present analysis, phantom factors were used to convert the residual variances of the observed variables (inhibition, shifting, and updating) to latent variables.

satisfactory (χ^2 (49) = 57.69, p = .185, NNFI = .98, CFI = .98, SRMR = .05, RMSEA = .04). Latent factors were allowed to correlate in the Full Model. The Choice RT factor correlated more highly with the discrete (.66) than with the serial naming factor (.30). To ensure that EF phantom factors were not significantly correlated with the serial naming factor, we tested three additional models, each including a covariance link between the serial naming factor and a phantom latent. None of these links were significant ($p > .15$) and there was no significant improvement in the model fit (by $1 - df\,\chi^2$ tests, $p > .15$), indicating that there was no unexplained relationship between the EF latent factors and the naming tasks. In other words, there was no specific association between serial naming and executive demands of the manipulated EF tasks. A small, but significant, improvement to the model could be achieved by allowing cross-loadings of either discrete digit naming or serial object naming onto the inhibition phantom factor, further corroborating that executive demands (expressed in the phantom latent variables) are not specifically associated with serial processing.

Discussion

In order to gain a better understanding of the factors contributing to the serial superiority effect in digit, object, and word naming, we examined the contribution of EF measures of inhibition, shifting, and updating to the RAN-reading relationship. We scrutinized the role of EF tasks hypothesizing that the serial superiority effect reflects executive demands. We first hypothesized that naming both words and symbols would correlate with EF. Our results indicated that inhibition correlated with discrete naming, consistent with previous studies relating inhibition to (non-alphanumeric) naming (e.g., Bexkens et al., 2015; Shao et al., 2012; Stringer et al., 2004). Shifting and updating did not correlate significantly with either serial or discrete naming, or reading.

We further hypothesized that EF would correlate more strongly with serial RAN and RAS than with discrete RAN tasks. Instead, the opposite pattern was found, as executive tasks correlated more strongly with the discrete than with the serial naming factors. The format of the tasks and the shared requirements based on the common measuring method appeared to shape the relationships among these tasks.

Finally, we hypothesized that if executive demands account for the serial superiority effect, then controlling for both discrete naming and EF should have left no variability in reading fluency to be explained by serial naming. The regression models, however, did not confirm our hypothesis, as serial naming was found to account for a substantial proportion of unique variance in serial reading. EF failed to pick up any of the residual variance after controlling for discrete naming. Therefore, executive control, as measured by the current EF tasks, does not seem to account for the serial superiority effect of naming in predicting reading fluency.

Executive control, naming, and reading: format versus content

The results indicated that a single-factor structure accounted well for individual differences in both manipulated and control EF tasks. The single-factor structure may appear compatible with a unified structure of EF in early development (see Wiebe et al., 2011). However, in the case of a common underlying structure of the EF tasks, a two-factor model should have emerged, including one common method factor and one global EF factor. The absence of the latter factor indicates that our manipulated EF tasks drew on distinct, rather than common, EF resources. Thus, the more likely reason for the one-factor structure is that different EF tasks assessed different cognitive EF components, consistent with the sizeable residuals of most manipulated EF tasks, not aligning with the common method factor. Therefore, to examine the relationship of executive demands with naming tasks we introduced a phantom factor for each EF component.

Combining the two best fitting models of EF and naming tasks we found that the Choice RT factor correlated more strongly with the discrete naming factor than with the serial naming factor. This can be attributed to the common format of the EF and discrete naming tasks, namely the requirement to process and respond rapidly and accurately to a single stimulus at a time as it is abruptly presented on the screen, controlled by an external process (in this case, by the software). In contrast, the phantom factors, presumably corresponding to the specific executive requirements of the manipulated tasks, did not correlate with the naming factors (either serial or discrete). The implications of this finding are far reaching, extending well beyond the conclusion that EF, as defined according to the structure proposed by Miyake et al. (2000), cannot account for the serial superiority effect. Specifically, if this finding proves to be robust in follow-up investigations, it may suggest that previous reports of interrelations between EF and reading or naming may have resulted, not from specific EF involvement in reading or naming, but due to method variance.

Strikingly, the majority of studies examining the relationship between EF and reading/naming have used the same format for EF and naming/reading tasks (either serial or discrete; Christopher et al., 2012; Rose, Feldman, & Jankowski, 2011; Shao et al., 2012, 2013; Stringer et al., 2004, van der Sluis et al., 2007). Furthermore, studies that have included EF tasks and control counterparts have reported that the relation between the manipulated inhibition task and serial naming did not hold once the corresponding control task (i.e., choice reaction time) was controlled for (e.g., Bexkens et al., 2015; Savage, Pillay, & Melidona, 2007). Van der Sluis et al. (2004) also found that the slower naming performance in an inhibition task reflected children's poorer performance on the control task (i.e., naming task) rather than a problem with inhibition ability. Therefore, it remains unclear whether it is the similar requirements (non-executive demands) of the tasks or the executive function demands that were responsible for the association between EF performance and reading or naming (see van der Ven et al., 2013, for a similar argument).

Arguably, the observed relationship between the Choice RT and Discrete naming factors reflects the ability to respond to externally driven stimuli. In stark contrast to this type of ability, serial processing in naming and reading requires endogenous (governed by the reader) rather than exogenous control (governed by environmental stimuli), because engagement with and disengagement from successive stimuli is cognitively initiated, presumably on the basis of the ongoing progress in processing previous items. Consistent with this idea, recent studies of eye movements have demonstrated a tight control of the gaze during reading (Laubrock & Kliegl, 2015) and naming (Gordon & Hoedemaker, 2015), in that participants regulate look-ahead to maintain a fixed distance between the currently viewed and the currently named item. Therefore, we propose that the critical element in the strong relationship between serial naming and reading fluency, resulting in the serial superiority effect, is due to *internally regulated* cognitive control (cf. Zoccolotti, De Luca, & Spinelli, 2015, on the importance of "self-pacing" in multiple word displays). Although this could be perceived as a kind of executive function or skill, it is not among the skills assessed with the usual EF measures and it is not included in current EF formulations, such as the three-factor structure proposed by Miyake et al. (2000). Future investigation of cognitive control might turn to the study of endogenously controlled processes and their EF requirements.

Some limitations of the present study are worth mentioning. First, we assessed only Grade 6 children and we do not know if our findings generalize to other ages. Wiebe et al. (2011), for example, have shown that in young children measures of EF load on one factor instead of the three factors proposed by Miyake et al. (2000). Second, we assessed only word reading skills. Some researchers have shown that EF skills are particularly predictive of reading comprehension (e.g., Kendeou, van den Broek, Helder, & Karlsson, 2014). Given that serial RAN is also related to reading comprehension (e.g., Johnston & Kirby, 2006), EF skills may be involved in the RAN-comprehension relationship than in the RAN-fluency relationship. Third, we administered only one EF task for each EF component. Although undesirable, this choice was dictated by the limited time available for testing each child. Future studies should replicate these findings using more tests for each EF component to allow the reliable estimation of distinct, multi-indexed latent variables associated with each EF dimension. Finally, definite conclusions on the effects of task format in the EF-reading/naming relationship can only be drawn when serial EF tasks are also administered, in future studies.

Conclusions

EF failed to explain the serial superiority effect. The common method factor (Choice RT) of control and manipulated EF tasks correlated more strongly with the discrete than with the serial factor, indicating a format-specific relationship. Specifically, the administered EF tasks assess latencies of externally driven responses to individually presented items. Naming isolated words or symbols, presented one-by-one on a screen, is determined by the display program and not by the reader. In contrast, naming lists of words or strings of symbols requires that the readers determine, plan, and monitor the visual processing duration for each symbol, control the rate of processing each word so that articulation does not interfere with the processing and retrieval of subsequent stimuli, estimate the appropriate points to pause, and overall implement efficient sequential processing. In agreement with

Zoccolotti et al. (2015), we suggest that a new perspective is necessary to address serial endogenous executive control and shed light on the serial superiority effect in naming and reading.

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