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de Jong, P.F.; van den Boer, M.

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The relation of visual attention span with serial and discrete rapid automatized naming and reading

Peter F. de Jong *, Madelon van den Boer

Research Institute of Child Development and Education, University of Amsterdam, 1001 NG Amsterdam, the Netherlands

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A B S T R A C T

Visual attention span (VAS) has been shown to make a unique contribution to reading skills over and above phonological awareness and rapid automatized naming (RAN). In the current study, we examined the nature of this unique relationship. In particular, we tested whether VAS reflects the retrieval of a verbal code, serial processing, or parallel multi-element processing. To this end, we presented 180 third graders with tasks for VAS, discrete RAN, and serial RAN as well as serial and discrete reading of short words, pseudowords, and long words. VAS was found to correlate with serial RAN but not with discrete RAN. More important, similar relations were found for VAS with serial and discrete reading, which clearly differed from the format-specific relations between RAN and reading. Together, these findings suggest that VAS and serial RAN are related but are associated with reading for different reasons. Serial RAN appears to reflect serial interword reading processes, whereas the unique contribution of VAS mainly involves the parallel processing of orthographic units within words.

* Corresponding author.
E-mail address: p.f.dejong@uva.nl (P.F. de Jong).

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Introduction

Reading development is often conceived as a gradual increase in word-specific orthographic knowledge enabling accurate and fluent reading through reading words by sight, that is, the retrieval of a word's spoken form from memory on the sight of its written form (Ehri, 2014; Share, 2008). Several abilities have been shown to fuel reading development, most importantly phonological awareness, the ability to detect and manipulate sounds in spoken words, and rapid automatized naming (RAN), the ability to name as quickly as possible a set of highly familiar stimuli such as digits or colors (e.g., Kirby, Georgiou, Martinussen, & Parrila, 2010; Wolf & Bowers, 1999). Another ability that seems to affect reading development is visual attention span (VAS), conceived as the number of orthographic units (e.g., letters, letter clusters, syllables) that can be processed in one glance (Valdois, Bosse, & Tainturier, 2004). VAS has been shown to relate to word reading skills across ages, languages, and ability levels (e.g., Bosse & Valdois, 2009; Germano, Reilhac, Capellini, & Valdois, 2014; van den Boer & de Jong, 2018; van den Boer, van Bergen, & de Jong, 2015), and its contribution to individual differences in reading is independent from the effects of phonological awareness and RAN (e.g., Antzaka et al., 2018; van Bergen, Bishop, van Zuijen, & de Jong, 2015; van den Boer, de Jong, & Haentjens-van Meeteren, 2013). In the current study, we examined why VAS uniquely contributes to reading development. Insight into the VAS–reading relationship will further enhance our understanding of the mechanisms that underlie reading development.

VAS is rooted in computational models of word recognition that provide a clear description of how VAS is related to the ability to process a word (Ans, Carbonnel, & Valdois, 1998; Ginestet, Phénix, Diard, & Valdois, 2019). A large VAS allows processing many letters in parallel and thereby enables reading three- to six-letter words by sight and reading longer words in larger units such as syllables. A small VAS requires visual attention to be focused sequentially on smaller sublexical units, such as letters and letter clusters, resulting in the slow and effortful process of serial decoding to decipher a written word. Thus, theoretically, the most prominent feature of VAS seems to be individual differences in processing multiple orthographic elements in parallel. This feature could be responsible for its unique relation with reading given that it is not involved in phonological awareness and is not the prime characteristic of RAN.

A common way to measure VAS is the whole report task (e.g., Bosse, Tainturier, & Valdois, 2007; Lobier, Zoubrinetzky, & Valdois, 2012; van den Boer et al., 2013, 2015). In this task, strings of five letters (e.g., R H S D M) are briefly presented (200 ms) and need to be orally reported. The average duration of a single fixation of children up to fifth grade tends to be larger than 200 ms (e.g., Vorstius, Radach, & Lonigan, 2014), supporting the assumption that in the whole report task the letter string needs to be processed in a single fixation and thus is processed in parallel.

But the extent to which VAS indeed reflects the visual and parallel processing of multiple elements is not entirely clear. First, the whole report task involves alphanumeric stimuli and requires oral report. The inclusion of letters in combination with oral report opens up the possibility that individual differences in VAS reflect the ability to rapidly retrieve phonological codes from memory instead of, or in addition to, visual attention (Collis, Kohnen, & Kinoshita, 2013; Hawelka & Wimmer, 2008; van den Boer et al., 2015; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). In addition, the extent to which the task reflects parallel processing is largely unknown. A common finding is that the probability to correctly report a letter depends on its position in the letter string. The probability correct decreases as letters are farther to the right (e.g., Valdois et al., 2003; van den Boer et al., 2015). Such a pattern, and especially the observation that the two letters farthest to the left are reported back nearly 100% correct, is commensurate with the serial processing of the letter string from left to right. If the letters in the string are processed in parallel, in many cases this would, due to visual crowding, result in a W-shaped pattern in which the second and fourth letters from the left are reproduced more poorly than the first, third, and fifth letters (e.g., Hawelka, Huber, & Wimmer, 2006; Ziegler et al., 2010). Although the string of letters in the whole report task is presented only briefly, processing of the string might continue after the string has disappeared from view because a mask is usually not presented. In all, it is unclear whether VAS, as measured by the whole report task, reflects the activation of phonological codes, and (more pertinent to the current study) it cannot be ruled out that VAS at least partly reflects serial processing.

To further shed light on the serial or parallel nature of VAS, we examined its relation with the discrete and serial formats of RAN and word reading. In the discrete format of RAN and word reading, stimuli (symbols and words, respectively) are presented one by one, that is, in isolation. The serial and more common format involves the simultaneous presentation of multiple stimuli, typically in rows, which remain visible until the last stimulus has been named. With respect to RAN, discrete RAN is regarded as a pure measure of the lexical retrieval speed of phonological codes (e.g., de Jong, 2011; Logan & Schatschneider, 2014). Current evidence on the nature of serial RAN suggests that it reflects both individual differences in lexical retrieval and the ability to process stimuli sequentially (Altani, Protopapas, & Georgiou, 2018; de Jong, 2011; Protopapas, Altani, & Georgiou, 2013). Therefore, correcting serial RAN for discrete RAN leads to a pure measure of serial processing abilities. It follows that if VAS (partly) reflects the serial retrieval of phonological codes, its correlation with serial RAN would be higher than that with discrete RAN.

However, there is an alternative interpretation of a stronger relation of VAS with serial RAN than with discrete RAN. VAS and serial RAN potentially have another feature in common, the processing of multiple elements, which might be done in parallel in VAS but also partly in parallel in serial RAN. Protopapas and colleagues have suggested that multiple successive stimuli in a serial RAN task enable cascaded processing (Altani, Protopapas, Katopodi, & Georgiou, 2019; Protopapas et al., 2013). A number of successive stimuli are processed in parallel but differ in the amount of processing that is yet accomplished. For example, one stimulus is articulated while a next stimulus is viewed and already some aspects of a stimulus down the line are previewed. Thus, establishing a relation between VAS and serial RAN does not offer clear evidence as to whether VAS mostly reflects serial or parallel processing. Therefore, we turn to the relation of VAS with both formats of reading. Both discrete and serial word reading, in contrast to discrete and serial RAN, clearly involve multi-element processing given that each word consists of multiple letters. If the unique feature of VAS is parallel multi-element processing, unlike discrete and serial RAN, it should be similarly related to discrete and serial word reading. Furthermore, if the relation between VAS and both formats of reading remains when controlling for serial RAN, this should provide further evidence that VAS primarily taps parallel processing.

In sum, we examined the relations of VAS, as measured by the whole report task, with discrete and serial RAN and word reading to delineate the unique contribution of VAS to word reading ability. We examined reading of short and long words, as well as pseudowords, in children in Grade 3. Because third-grade children are at an intermediate stage of reading development, we expected that short words might be read by sight, whereas pseudowords and long words might still require serial decoding. We hypothesized that the parallel processing of multiple elements is the unique feature of VAS. Accordingly, we expected that VAS is more strongly related to serial RAN than to discrete RAN and that the relation with discrete and serial word reading remains after discrete and serial RAN are taken into account.

Method

Participants

Participants were 180 children (50.6% girls) with a mean age of 8 years 11 months (*SD* = 5.40 months), all attending third grade of mainstream primary education. All children spoke Dutch as their dominant language, although 30 children (16.7%) also spoke at least one other language at home. Scores on a standardized test for word reading fluency (One Minute Test; Brus & Voeten, 1995) indicated that the sample included children with a representative range of reading abilities, with standardized scores (*M* = 10, *SD* = 3) ranging from 4 to 19 with a mean of 10.77 (*SD* = 2.88).

Materials

Visual attention span

VAS was assessed with a whole report task (Valdois et al., 2003). Children were presented with five-letter strings (e.g., R H S D M) composed of 10 consonants (B, D, F, H, L, M, P, R, S, and T). A total of 20 strings were presented, with each letter appearing twice in each letter position. The strings were presented in 24-point Arial font with two spaces between the letters. Children saw a plus sign (1000 ms) to focus attention, followed by a letter string (200 ms). The letter string was not followed by a mask, in line with most previous studies (e.g., Valdois et al., 2003; van den Boer et al., 2015). Children were asked to name as many letters as possible from each string in the correct order. There was no time limit for the response. The experimenter manually started the next trial when children had responded. The score consisted of the number of letters repeated correctly in the correct position, calculated separately for the uneven items (VAS 1, maximum score of 50) and even items (VAS 2, maximum score of 50). Split-half reliability for the current sample was .91.

Discrete RAN

Discrete RAN (RAN D) was assessed with digits (2, 4, 5, 7, and 9) and letters (a, d, o, p, and s) presented one at a time. Each item was presented eight times (total of 40 items). Children were asked to name each symbol as quickly and accurately as possible. The symbol remained on the screen until a voice key registered a response. The response time was recorded from stimulus onset until the onset of the response. The experimenter indicated whether the response was correct, incorrect, or invalid, thereby triggering the next stimulus. Each stimulus was preceded by a plus sign. Invalid response latencies, latencies of less than 200 ms or more than 8000 ms, and latencies more than 3 standard deviations from a participant's mean were excluded from the analyses. A fluency score was calculated by transforming the mean onset latency (for both correct and incorrect items without articulation time) to the number of items named per second and multiplying that score by the proportion of items correct separately for letters (RAN DL) and digits (RAN DD).

Serial RAN

Serial RAN (RAN S) was assessed with the same digits (2, 4, 5, 7, and 9) and letters (a, d, o, p, and s) as discrete RAN. The items were presented in five rows of eight. Participants were asked to name the 40 items as quickly and accurately as possible. A fluency score was calculated by transforming the total naming time (including articulation time) to the number of items named per second and multiplying that score by the proportion of items correct separately for letters (RAN SL) and digits (RAN SD).

Discrete word reading

Following the procedure of discrete RAN, children were presented with 40 short words of four letters each, 40 pseudowords of four letters each, and 40 long words of eight letters each. The four-letter and eight-letter words all were high-frequency words. The pseudowords were constructed by exchanging the onsets and rhymes of the four-letter words, thereby matching the words and pseudowords on consonant–vowel (CV) structure. Fluency scores were calculated in the same way as for discrete RAN and separately for two sets of 20 short words (SW D1 and SW D2), two sets of 20 pseudowords (PW D1 and PW D2), and two sets of 20 long words (LW D1 and LW D2). For each task, the two sets of words were matched on frequency and word onset.

Serial word reading

Serial word reading was assessed with sets of 40 short words, 40 pseudowords, and 40 long words. These sets were matched in onset, CV structure, and frequency to the words in the discrete word reading tasks. For each task, the 40 items were presented in two sets of 20 items presented in four rows of five. Fluency scores were calculated in the same way as for serial RAN and separately for both sets of 20 short words (SW S1 and SW S2), both sets of 20 pseudowords (PW S1 and PW S2), and both sets of 20 long words (LW S1 and LW S2). For each task, the two sets of words were matched on frequency and word onset.

Procedure

The data presented in the current study were part of a longitudinal project focused on reading development from Grade 2 to Grade 4 (see also van den Boer & de Jong, 2018). The tasks were administered individually (~30 min) in a fixed order: RAN digits, RAN letters, reading of short words, reading of pseudowords, and reading of long words. For RAN children started with serial naming, followed by discrete naming, whereas for the reading tasks the order was reversed. Next, children were presented with the VAS task, followed by two standardized reading tasks and tasks for phonological awareness and nonword repetition, but those were not taken into account for the current study. Also not considered were reading and spelling tests that were administered in an additional classroom session (~40 min). The study was conducted in accordance with the guidelines of the institution's ethics committee.

Analyses

To examine the relation of VAS with discrete and serial RAN, we used structural equation modeling (SEM) to fit a model to the data with three correlated latent variables based on two indicators each. Next, we added latent variables for the reading of short words, pseudowords, and long words (again with two indicators each) and examined the correlations of both VAS and RAN with discrete and serial reading. Finally, we conducted a fixed-order regression analysis within SEM to examine the unique contributions of VAS, serial RAN, and discrete RAN to reading. Fixed-order regression analysis within SEM is less vulnerable to Type I errors because latent factors do not contain error variance, whereas the (un)reliability of observed variables used in regular multiple regression leads to an increase in Type I error rates (Westfall & Yarkoni, 2016). Our prime interest was what the more complex measures of serial RAN and VAS would contribute to reading after controlling for pure lexical retrieval. Therefore, discrete RAN was always entered in the first step.

Fixed-order regression analysis in SEM requires an alternative specification of the correlations among the latent variables that serve as predictors in the regression model. The specification involves uncorrelated phantom factors, one for each predictor, with variances restricted to one (de Jong, 1999; Macho & Ledermann, 2011; van den Boer, van Bergen, & de Jong, 2014). All predictors load on the first phantom factor, the second and third predictors load on the second phantom factor, and the third predictor is the only one that loads on the third phantom factor. The square of the correlation of the first phantom factor with the dependent variable, a particular latent reading variable, represents the proportion of variance described by the first predictor (de Jong, 1999). The correlation of the second phantom factor with the dependent variable is the partial correlation after controlling for the first predictor. The proportion of variance explained by the second predictor is the square of this correlation. Finally, the square of the partial correlation between the dependent variable and the third phantom factor is the additional variance described by the third predictor after controlling for the first two predictors. The alternative specification does not alter model fit.

Two models were fitted using Mplus Version 7.11 (Muthén & Muthén, 1998–2013) with full information maximum likelihood estimation. Model fit was evaluated using the chi-square statistic of overall goodness of fit, the comparative fit index (CFI), and the root mean square error of approximation (RMSEA). A chi-square p value larger than .05 indicates exact fit (Hayduk, 1996). A CFI larger than .95 indicates good fit (Hu & Bentler, 1999). Values of the RMSEA below .05 indicate close fit, values below .08 indicate satisfactory fit, and values over .10 indicate poor fit (Browne & Cudeck, 1993).

Results

Descriptive statistics

Before running analyses, the data were checked for missing values and outliers (i.e., scores more than 3 standard deviations from the group mean). A total of 11 scores (0.34% of the data) were missing due to problems in task administration. An additional 16 scores (0.49% of the data) were identified as outliers (3 extremely low scores and 13 extremely high scores) and were coded as missing. Outliers were mainly due to 2 participants. Because for both participants less than one third of the scores were excluded, the other scores were still included in the analyses. Scores on all tasks were normally distributed. The exact N for each of the tasks is presented in Table 1 with the descriptive statistics.

The correlations for all measures are presented in Table 2. As expected, the highest correlations were generally found between tasks used to measure the same skill. The correlations between VAS and discrete RAN appeared to be low and mostly not significant. VAS did correlate significantly with the serial RAN tasks, slightly stronger with letters than with digits. In general, discrete word reading correlated most strongly with discrete RAN. Correlations between discrete word reading and serial RAN were also significant but were lower than those between discrete word reading and discrete RAN. Correlations of VAS with reading were weak to moderate. VAS correlated somewhat more strongly with discrete reading of pseudowords and longer words than with short words. Correlations of VAS with serial word reading were generally slightly stronger than those with discrete word reading. The correlations were rather similar in magnitude to those of discrete RAN with serial word reading. Serial RAN correlated most strongly with serial word reading.

Relations of VAS with discrete and serial RAN

The model and standardized parameter estimates of the relations between VAS and RAN are presented in Fig. 1. As a start, we assumed equal factor loadings for the two indicators of a skill. This model provided a poor fit to the data, $\chi^2(9) = 27.309$, $p < .001$, RMSEA = .106 (confidence interval (CI) [.062–.153]), CFI = .964, standardized root mean square residual (SRMR) = .08. We made two adaptations. First, the factor loadings of the indicators of the serial RAN factor were allowed to differ. Second, we added a correlation between the residuals of serial and discrete digit naming because the relation between these measures was not accounted for sufficiently. With these adaptations, the model provided a good fit to the data, $\chi^2(7) = 9.55$, $p = .191$, RMSEA = .048 (CI [.000–.111]), CFI = .994, SRMR = .03. VAS was found to correlate moderately with serial RAN. The relation of VAS with discrete RAN was not significant. When both correlations were set to be equal, model fit deteriorated significantly, $\Delta\chi^2(1) = 8.48$, $p < .01$.

Relations of VAS with discrete and serial reading

Next, we added latent variables for the reading of short words, pseudowords, and long words to the model. This model provided a satisfactory fit to the data, $\chi^2(100) = 157.131$, $p < .001$, RMSEA = .056 (CI [.039–.073]), CFI = .982, SRMR = .03. The correlations of the latent variables for VAS, discrete RAN, and

Table 1
Descriptive statistics.

	N	*M* (*SD*)	Range
VAS 1	179	35.00 (7.55)	18–50
VAS 2	179	31.97 (7.14)	17–49
RAN DL	178	1.88 (0.27)	1.01–2.58
RAN DD	176	2.03 (0.31)	1.01–2.81
RAN SL	177	1.79 (0.35)	0.91–2.69
RAN SD	178	1.82 (0.33)	0.85–2.71
SW D1	178	1.93 (0.33)	1.07–2.92
SW D2	178	1.91 (0.33)	1.02–2.73
PW D1	179	1.52 (0.43)	0.55–2.65
PW D2	179	1.55 (0.42)	0.46–2.67
LW D1	180	1.59 (0.47)	0.36–2.85
LW D2	179	1.56 (0.42)	0.45–2.75
SW S1	179	1.79 (0.39)	0.87–2.65
SW S2	180	1.78 (0.41)	0.88–2.89
PW S1	179	1.07 (0.34)	0.39–2.07
PW S2	177	0.93 (0.31)	0.23–1.78
LW S1	179	0.93 (0.35)	0.23–1.89
LW S2	179	1.00 (0.36)	0.24–1.99

Note. VAS, visual attention span; RAN, rapid automatized naming; SW D, short word reading discrete; PW D, pseudoword reading discrete; LW D, long word reading discrete; SW S, short word reading serial; PW S, pseudoword reading serial; LW S, long word reading serial.

Table 2
Correlations.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. VAS 1	–																	
2. VAS 2	.847*	–																
3. RAN DL	.086	.161*	–															
4. RAN DD	.105	.130	.726*	–														
5. RAN SL	.368*	.334*	.416*	.403*	–													
6. RAN SD	.222*	.176*	.298*	.432*	.618*	–												
7. SW D1	.188*	.177*	.635*	.652*	.370*	.354*	–											
8. SW D2	.160*	.153*	.684*	.691*	.379*	.368*	.876*	–										
9. PW D1	.264*	.243*	.578*	.534*	.471*	.331*	.718*	.744*	–									
10. PW D2	.249*	.226*	.600*	.547*	.473*	.332*	.696*	.740*	.891*	–								
11. LW D1	.286*	.259*	.513*	.523*	.415*	.345*	.731*	.752*	.731*	.757*	–							
12. LW D2	.281*	.247*	.552*	.569*	.383*	.339*	.723*	.792*	.703*	.745*	.891*	–						
13. SW S1	.266*	.232*	.328*	.376*	.568*	.534*	.564*	.506*	.542*	.575*	.570*	.523*	–					
14. SW S2	.285*	.263*	.377*	.399*	.528*	.554*	.618*	.590*	.602*	.653*	.671*	.616*	.761*	–				
15. PW S1	.313*	.209*	.244*	.318*	.515*	.522*	.524*	.499*	.615*	.647*	.600*	.585*	.705*	.730*	–			
16. PW S2	.367*	.245*	.204*	.342*	.558*	.483*	.527*	.465*	.582*	.598*	.578*	.559*	.657*	.693*	.855*	–		
17. LW S1	.340*	.272*	.250*	.263*	.478*	.395*	.510*	.481*	.572*	.595*	.697*	.651*	.627*	.697*	.777*	.762*	–	
18. LW S2	.335*	.278*	.269*	.258*	.515*	.437*	.536*	.526*	.575*	.590*	.686*	.631*	.652*	.750*	.762*	.726*	.864*	–

Note. VAS, visual attention span; RAN, rapid automatized naming; SW D, short word reading discrete; PW D, pseudoword reading discrete; LW D, long word reading discrete; SW S, short word reading serial; PW S, pseudoword reading serial; LW S, long word reading serial.

* $p < .05$.

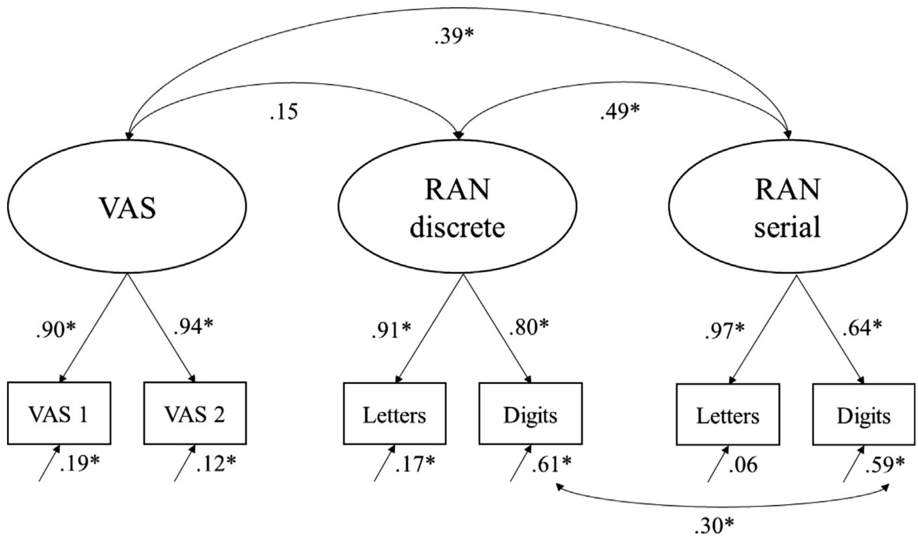

Fig. 1. Three-factor model of visual attention span (VAS), discrete rapid automatized naming (RAN), and serial RAN. **p* < .05.

serial RAN with the discrete and serial format of reading for the three word types are presented in Table 3. We also specified separate models for each type of word (short words, long words, and pseudowords), but this yielded highly similar results. Overall, the relations of VAS with the serial reading format seemed to be somewhat higher than those with the discrete format, especially for short words. As a multivariate test, we constrained for each word type the correlation of VAS with the serial format to be equal to the discrete format. The fit of this model did not differ significantly from the unconstrained model, $\Delta\chi^2(3) = 4.131$, $p = .248$, suggesting that overall VAS was similarly related to both formats of reading. In contrast, imposing similarity constraints for discrete and serial RAN showed severe decreases in model fit, $\Delta\chi^2(3) = 77.267$, $p < .001$, and $\Delta\chi^2(3) = 20.371$, $p < .001$, respectively. Unlike VAS, RAN–reading relationships were clearly format specific.

Unique relations of VAS and RAN with discrete and serial reading

Next, we applied fixed-order regression analyses within SEM (de Jong, 1999; see also "Analyses" section in Method above) where all latent reading factors in the model were regressed on the latent factors of discrete RAN, serial RAN and VAS. The order in which the RAN and VAS factors were entered

Table 3
Correlations of VAS, discrete RAN, and serial RAN with discrete and serial word reading.

Word type/format	VAS	RAN discrete	RAN serial
Short words			
Discrete	.190*	.829**	.492**
Serial	.330**	.464**	.773**
Short pseudowords			
Discrete	.276**	.724**	.553**
Serial	.340**	.324**	.698**
Long words			
Discrete	.305**	.665**	.499**
Serial	.365**	.331**	.620**

Note. VAS, visual attention span; RAN, rapid automatized naming.
* $p < .05$.
** $p < .01$.

in these analyses was varied to examine the additional amount of variance in reading that was accounted for by serial RAN and VAS after controlling for discrete RAN.

Part of the model is presented in Fig. 2. For ease of presentation, only two of the six reading variables are depicted, but in the full model all reading factors were included. In this particular example, the phantom factor PH-RAN discrete is identical to the first-order factor RAN discrete. PH-RAN serial is the factor that remains after accounting for the variance that serial RAN has in common with discrete RAN. Finally, PH-VAS is the factor that captures individual differences in the first-order VAS factor after controlling for discrete and serial RAN. As a result of this specification, discrete RAN is entered in the first step, serial RAN is entered in the second step, and VAS is included last in the model. The square of the correlations between the phantom factors and the reading factors denotes the variance accounted for by discrete RAN, the additional variance explained by serial RAN after controlling for discrete RAN and the additional variance described by VAS after accounting for discrete and serial RAN. The order of inclusion of the predictors was altered by changing the factor loadings of the predictors on the phantom factors.

The results of the fixed-order regression analyses are reported in Table 4. Clearly, both serial RAN and VAS added more variance in the second step to serial reading than to discrete reading for all types of words. However, the difference in additional variance between the serial and discrete formats was much larger for serial RAN than for VAS. This was further confirmed in the third step, showing the unique contributions of serial RAN and VAS. The unique variance accounted for by serial RAN in serial reading was much larger than that in discrete reading. Interestingly, its relation with discrete word reading observed in the second step largely disappeared when VAS was taken into account. The unique contribution of VAS was restricted to the longer words—both discrete and serial. A model in which all partial correlations of VAS with the reading factors were restricted to be equal significantly decreased the fit of the model, $\Delta\chi^2(1) = 5.325$, $p = .021$. However, a model in which the partial correlations of VAS with serial and discrete reading of long words were equated fitted equally well, $\Delta\chi^2(1) < 1$. In this model, VAS added a small but significant additional amount of variance of 2% after controlling for discrete and serial RAN.

Discussion

VAS has been shown to relate to word reading skills across ages, languages, and ability levels independent of phonological awareness and RAN (e.g., Antzaka et al., 2018; Bosse & Valdois, 2009; Germano et al., 2014; van den Boer et al., 2013, 2015). In the current study, we examined why VAS uniquely contributes to reading. We used discrete and serial formats of RAN and reading to gain

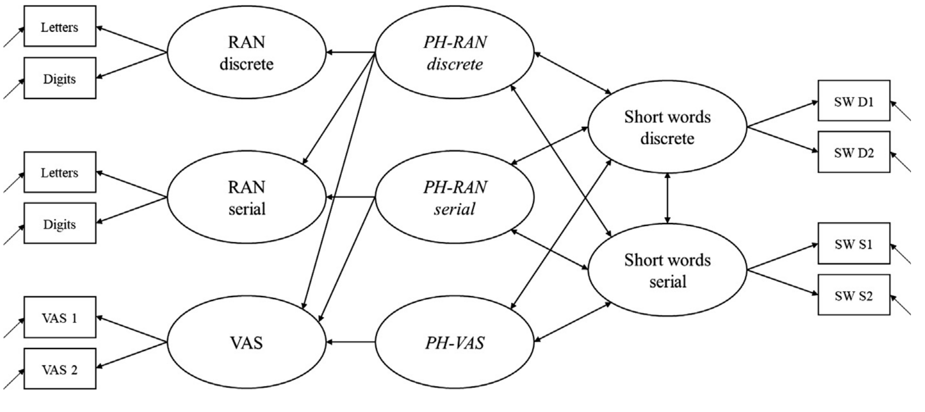

Fig. 2. Fixed-order regression model predicting short word reading (discrete and serial) from discrete rapid automatized naming (RAN), serial RAN, and visual attention span (VAS). PH, phantom factor; SW D, short word reading discrete; SW S, short word reading serial.

Table 4
Percentages of added variance in the fixed-order regression of different types of items on discrete RAN, serial RAN, and VAS.

	Short words		Pseudowords		Long words	
Predictor	Discrete	Serial	Discrete	Serial	Discrete	Serial
Step 1						
RAN discrete	68.7**	21.5**	52.4**	10.5**	45.6**	11.0**
Step 2						
RAN serial	0.3	38.7**	3.8**	38.6**	2.6*	27.6**
VAS	0.3	6.7**	2.6**	8.5**	4.0**	10.0**
Step 3						
RAN serial	0.1	32.0**	2.1*	30.5**	0.9	19.2**
VAS	0.2	0.1	0.9	0.4	2.2*	1.6+
Total	68.9	60.3	57.1	49.5	50.4	40.2

Note. RAN, rapid automatized naming; VAS, visual attention span.
* $p < .05$.
** $p < .01$.

insight into the VAS–reading relationship. We aimed to reveal the unique contribution of VAS to reading by eliminating the effects of discrete and serial RAN, that is, the retrieval of phonological codes and serial processing (Georgiou & Parrila, 2020). VAS, similar to both discrete and serial RAN, typically includes alphanumeric stimuli and requires the retrieval of the names of these stimuli for naming aloud. Theoretically, however, the most prominent feature of VAS is individual differences in processing multiple orthographic elements in parallel (Ans et al., 1998; Valdois et al., 2004). As such, a relation was expected with serial RAN, which also involves the processing of multiple stimuli, but not with discrete RAN. However, whereas elements in serial RAN are generally assumed to be processed serially, a VAS task typically presents stimuli only shortly, enforcing parallel processing. As a result, serial RAN and VAS might be related yet reflect different aspects of the word reading process. This was examined through the relations of VAS and RAN with serial and discrete reading. We hypothesized that VAS was related similarly to both formats of reading, which independent of format requires parallel processing, whereas serial RAN is more strongly related to the serial format of reading, which by definition requires serial processing.

For a better understanding of the unique relation between VAS and reading, we first consider the relations between the discrete and serial formats of RAN and reading. As in earlier studies (Altani et al., 2019; de Jong, 2011; Protopapas et al., 2013; van den Boer, Georgiou, & de Jong, 2016), we found clear format-specific relationships. For all types of words, the relationships between similar formats of RAN and reading (serial–serial or discrete–discrete) were stronger than those between dissimilar formats. Especially for short words, correlations between similar formats were very high (discrete–discrete $r = .83$, serial–serial $r = .77$) (see Table 3), suggesting that the reading of short high-frequency words is essentially a RAN task. These findings are in line with previous suggestions that high format-specific RAN–reading relationships are to be expected if words are read by sight, that is, when the pronunciation of a word is immediately retrieved from memory when encountering its written form (de Jong, 2011; van den Boer & de Jong, 2015; van den Boer et al., 2016). Then, both RAN and reading involve the retrieval of the names of stimuli from memory.

More important, the current study showed that the relation between serial RAN and discrete reading of pseudowords and long words nearly disappeared after controlling for discrete RAN, whereas the relation of serial RAN with serial reading was hardly affected. This strongly suggests that serial RAN mainly reflects the processing of series or lists of words and is primarily related to interword processes. Moreover, these results reveal that intraword and interword processes can be very different and should be considered separately. This conclusion is supported by the fact that the correlation between serial and discrete reading of short words was only .68, clearly lower than the format-specific RAN–reading relations (see also Altani et al., 2019; van den Boer et al., 2016). In contrast, for pseudowords and longer words, a small unique relation with serial RAN remained after controlling for discrete RAN (see also van den Boer et al., 2016). One interpretation is that pseudowords and longer words might require some decoding and that this is also a serial process (de Jong, 2011). In other words, the relation between serial RAN and discrete word reading is due to intraword serial processing, that is, the serial processing of sublexical units within (pseudo)words.

Our contention that serial RAN is mainly related to interword processes seems at odds with the finding that the relation of serial RAN with the serial reading of short pseudowords and long words is lower than that with the serial reading of short words (see Table 3) and also with the lower amount of variance accounted for by serial RAN after controlling for discrete RAN (Table 4). Note, however, that individual differences in serial reading are dependent on both intraword and interword reading processes. If the intraword process involves mainly retrieval, as in the serial reading of short words, the variation in reading speed seems to be almost entirely determined by interword processes that are similar to the processes in serial RAN. Instead, the intraword process in the reading of pseudowords and long words seems to be less based on retrieval than that in word reading. Indeed, the correlations with discrete RAN are lower. To some extent, the intraword process is serial, and this would increase the relation with serial RAN. However, there are also other processes that are required to read these pseudowords and long words. In pseudoword reading, this could be the extra step of the conversion of the sounds in the letter string into a novel pronunciation. Variation in this process might also affect individual differences in reading speed and thereby decrease the relation with serial RAN. The reading of long words—in this study two- and three-syllable words—might require the blending of syllables and stress assignment. In all, the relation of serial RAN with the reading of pseudowords and longer words might be relatively weak because of individual differences in nonserial intraword processes that, unlike in the reading of short words, also account for variance in the reading of these types of (pseudo)words.

We now turn to our results on the relations of VAS with RAN and reading in serial and discrete formats. In line with previous studies, VAS was moderately related to serial RAN (van den Boer et al., 2013, 2014). To our knowledge, the current study is the first to show that VAS is not related to discrete RAN. These results clarify that it is not the pure retrieval of verbal codes that RAN and VAS have in common (e.g., Collis et al., 2013; Hawelka & Wimmer, 2008; Ziegler et al., 2010). However, these results do not illuminate whether the moderate relation of VAS and serial RAN is due to the serial or multi-element processing feature or both.

The relations of VAS with both serial and discrete reading can shed light on this issue. We found similar relations of VAS with serial and discrete reading. In addition, the unique contributions of VAS to serial and discrete reading after controlling for discrete and serial RAN appeared to be similar, although these contributions were small. However, these results clearly differ from the format-specific relations between RAN and reading, and as such they support the interpretation that the contribution of VAS to reading is mainly due to parallel multi-element processing (Ans et al., 1998; Ginestet et al., 2019). Recent views on serial RAN suggest that it partially reflects parallel processing as well, denoted as cascaded processing by Protopapas et al. (2013). If this is correct, it follows that the relation between serial RAN and VAS might be due to serial RAN partially reflecting parallel processing rather than VAS partially reflecting serial processing.

Similar contributions of VAS to serial and discrete reading also suggest that VAS is mainly related to intraword reading processes. This is in line with computational models that implemented a visual span (e.g., Ans et al., 1998; Perry, Ziegler, & Zorzi, 2007). Because these models were designed to simulate the reading of single words, it is implicitly assumed that VAS concerns intraword processes. However, in principle, VAS might extend across a word boundary when reading multiple words because VAS has been shown to be related to wordlist reading (e.g., Bosse & Valdois, 2009; Valdois et al., 2003; van den Boer et al., 2015) and text reading (Germano et al., 2014; Lobier, Dubois, & Valdois, 2013; van den Boer et al., 2014) in addition to reading of single words. If VAS is relevant to both intraword and interword processes, we would expect VAS to be more strongly related to serial reading than to discrete reading, which was not the case. The current findings, therefore, seem to suggest that the relation of VAS with serial reading is mainly due to individual differences in processing single words efficiently.

This interpretation of our results also fits with the somewhat surprising finding that the unique relation of VAS with serial and discrete reading was restricted to long words. VAS did not contribute to the reading of short words and pseudowords after accounting for serial and discrete RAN. Based on the relation between discrete RAN and discrete reading of short words, we have argued that these short words are likely mostly read by sight. This would mean that the VAS of most participants was sufficiently large to allow for the parallel processing of short words and that remaining individual differences in the ability to process orthographic units in parallel were no longer relevant (Ans et al., 1998). Note here that if VAS was also related to interword processes, a larger span would remain relevant in the serial reading of short words and individual differences in VAS would be expected to be more strongly related to serial reading. Similar to the short words, the pseudowords were only four letters long. Of course, pseudowords cannot be read by sight because, by definition, the spoken form of a pseudoword cannot be retrieved from memory. However, it has previously been shown that the letters in short pseudowords, as in sight words, can be processed in parallel (van den Boer & de Jong, 2015). Therefore, similar to the short words, the VAS of most of the participants might have been large enough to allow parallel processing of these pseudowords as well. In contrast, the long (eight-letter) words were probably not read by sight. It seems unlikely that VAS, measured by the short presentation of five letters, was sufficient to read an eight-letter word. So, for the long words, it is understandable that individual differences in VAS made a unique contribution to the reading of these words. Indeed, in most earlier studies, VAS has been shown to be related to reading measures, word lists, and text that involved words that varied extensively in the number of letters (often ranging from one to four syllables; e.g., van den Boer et al., 2013, 2014, 2015). Most important, the relation of VAS with reading could not be accounted for by serial RAN. Taking the latter as an index of serial processing, this supports the notion that the unique contribution of VAS to reading concerns the parallel processing of multiple elements within words. Whether this is the parallel processing of visual units (Valdois, Lassus-Sangosse, & Lobier, 2012; Valdois, Roulin, & Bosse, 2019) or concerns the number of sounds that can be activated in parallel from a string of letters (van den Boer et al., 2015) cannot be determined based on the current study.

We need to acknowledge that in the current study the unique contribution of VAS to reading was rather small and restricted. Evidently, our explanation as to why the unique effects of VAS were restricted to the reading of longer words awaits further scrutiny. The explanation can easily be tested because it implies that in younger readers, having a smaller visual span, VAS would contribute to the reading of both short and long words. However, we should also mention the possibility that the unique contribution of VAS to the reading of long words—that is, after controlling for serial RAN—might underestimate the importance of VAS for these words. VAS and serial RAN were moderately related, and (as argued in the Introduction) both involve multiple stimulus processing and therefore serial RAN also might require some parallel processing. Thus, accounting for serial RAN in the prediction of the reading of long words might control not only for serial processing but also for the parallel processing that serial RAN and VAS have in common. The extent to which this is the case is not yet clear because the nature of the parallel processing involved in serial RAN and VAS seems to differ. In serial RAN, as well as in serial reading, parallel processing is cascaded, enabled by the sequential nature of the task (e.g., Protopapas et al., 2013). At each point in time, the amount of processing of each stimulus varies, and what is done in parallel is determined by the reader. It is a top-down process denoted by Altani et al. (2019) as endogenously controlled. The amount of processing of each stimulus in an array of stimuli is under the control of the reader. In contrast, presentation of the letter string in the whole report task, used to measure VAS, seems too short for a deliberate control of the processing strategy. It merely reflects a bottom-up process and can be considered as a pure measure of the number of stimuli that have been fully processed in parallel in a very short amount of time. Stimuli that have not been completely processed cannot be reported back. Importantly, the relation between individual differences in the ability to process the letters in a string in parallel and the ability of cascaded processing is unknown. In fact, it could even be argued that cascaded processing is a characteristic of the serial nature of serial RAN (and serial reading). As a result, it is currently not possible to determine the amount of common variance of serial RAN and VAS that is due to the shared parallel processing of multiple stimuli.

In this study, we focused specifically on VAS and RAN and did not include a measure of phonological awareness. Luckily, there is already a large body of evidence showing that VAS makes an independent contribution to reading over and above phonological awareness (Antzaka et al., 2018; Bosse & Valdois, 2009; Germano et al., 2014; van den Boer et al., 2015). Our aim in this study was to disentangle which feature of VAS is responsible for its unique relation with reading—retrieval of a verbal code, serial processing, or parallel multi-element processing. We suggest that the current study makes two important contributions to our understanding of the relation between VAS and reading. First, VAS was not related to discrete RAN, suggesting that VAS does not merely tap the retrieval of verbal codes. Second, and most interesting, VAS and serial RAN were found to be related to reading for different reasons. The relation of serial RAN with serial word reading was far stronger than that with discrete word reading, suggesting that serial RAN mainly reflects interword processes. In contrast, VAS was related similarly to both formats of reading, suggesting that it mainly reflects intraword processes, specifically parallel multi-element processing.

CRediT authorship contribution statement

Peter F. de Jong: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Madelon van den Boer: . :** Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Project administration.

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Author contributions

Peter de Jong was responsible for conceptualization, methodology, formal analysis, writing–original draft, and writing–review and editing. Madelon van den Boer was responsible for methodology, formal analysis, investigation, writing–original draft, writing–review and editing, and project administration.

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