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Differential relationships between RAN performance, behaviour ratings, and executive function measures: Searching for a double dissociation

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Abstract. In this study, we investigated the relationships between rapid naming of letters, digits and colours, and reading ability and executive function. We gave fifty-six grade three and four children rapid automatised naming tasks using letters and digits as stimuli, executive function measures including the Stroop task, a working memory task and the Trailmaking B task. The latter three tasks were used as measures of executive function. We also administered tests of verbal ability, reading and a behaviour checklist. The rapid naming of letters and digits was significantly correlated with reading, but not with executive function or behaviour ratings. The rapid naming of colours (from the Stroop task) was significantly correlated with the executive function tasks and the behaviour ratings but not with reading. We discuss the implications of this double dissociation for further studies of RAN.

Key words: Behaviour ratings, Executive function, Reading, Rapid automatised naming, Rapid colour naming

Abbreviations: RAN, rapid automatised naming; RANC, rapid automatised naming of colours; RAND, rapid automatised naming of digits; RANL, rapid automatised naming of letters; RANO, rapid automatised naming of objects.

Introduction

Connections between performance on naming tasks (particularly the naming of colours) and reading ability have been hypothesized for over 35 years (Geschwind, 1965; Geschwind & Fusillo, 1966). Denckla and others demonstrated in the early 1970s that the speed with which participants can name colours, objects, letters or digits is correlated with their reading performance (Denckla, 1972; Denckla & Rudel, 1974). This finding has since been replicated many times (see Denckla & Cutting, 1999; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000; for recent reviews). The initial observation of this correlation has been refined over the years by virtue of extensive research. The speed with which individuals name letters and digits is a robust predictor of reading ability, while the speed to name objects and colours is less predictive (Denckla & Cutting, 1999). Performance on these rapid automatized naming (or RAN) tasks adds unique variance to the prediction of reading skill even beyond that explained by the best individual predictor variable, phonological processing skill (Blachman, 1984; Chiappe, Stringer, Siegel, & Stanovich, 2002; Cutting, Carlisle, & Denckla, 1998).

One reason why RAN might predict reading skill is clear – RAN is an apparent analogue of the reading process. RAN and reading share many processes (Blachman, 1984; Foorman, Chen, Carlson, Moats, Francis, & Fletcher, 2003; Wolf & Bowers, 1999). It requires the identification of a visual stimulus (with all the cognitive processing that involves), the assembly of a verbal response and its articulation, then visual scanning to the next stimulus or line to repeat the process. However, the reasons why RAN actually predicts reading performance are not clear (Scarborough & Domgaard, 1998). As mentioned above, not all RAN tasks are equal when it comes to the prediction of reading (see Compton, 2003; Compton, Olson, DeFries, & Pennington, 2002).

RAN comes in four common and standard forms identified by the types of stimuli used: letters, digits, objects and colours (henceforth, RANL, RAND, RANO and RANC). In all of these variations, the standard format is to lay out fifty letters, digits, pictures or drawings of common objects or colour samples in five rows of ten stimuli each. The participant then simply names each stimulus in order, left to right, top to bottom, as quickly as he/she can. The elapsed time and number of errors are recorded, though the error rates are usually minimal and uninformative. A second, less-used format presents each letter individually on a computer screen and records the time necessary for the participant to name it. This "discrete trial RAN" is less consistently related to reading ability than the continuous format (Perfetti, Finger, & Hogaboam, 1978; Stanovich, 1981; Stanovich, Feeman, & Cunningham, 1983).

As mentioned above, the letter and digit forms of the RAN (particularly the letter form, see Neuhaus, Foorman, Francis & Carlson, 2001) are good and robust predictors of single word reading, though not always of reading comprehension (Meyer, Wood, Hart, & Felton, 1998; Scarborough & Domgaard, 1998). While the rapid naming of objects and colours do not consistently predict reading ability (Blachman, 1984; Denckla, & Rudel, 1974; Denckla & Rudel, 1976a; Manis & Doi, 1995; Wimmer, 1993; Wolf, Bally, & Morris, 1986), RAN tasks, particularly RANL and RAND, would seem to be specific predictors of reading problems.

The connection between RAN and reading is usually attributed to the phonological processing component of RAN. As we have stated above, the most powerful predictor of reading performance has repeatedly been shown to be phonological processing ability; that is, the ability to recognize and manipulate the phonological components of spoken language (Bruck, 1992; Bruck & Treiman, 1990; Fox & Routh, 1984; Liberman, Shankweiler, Fischer, & Carter, 1974; Pennington, Van Orden, Smith, Grenn, & Haith, 1990; Siegel & Ryan, 1988; Stanovich, 1988; Stanovich, Nathan, & Vala-Rossi, 1986). As RAN tasks clearly involve a search through phonological space for a phonological label for the current stimulus as well as the articulation of the stimulus, RAN has often been subsumed into the "family" of phonological processing tasks (Manis, Seidenberg, & Doi, 1999; Wagner & Torgesen, 1987). The unique variance in reading ability that RAN explains, beyond that explained by phonological processing, may simply reflect a different aspect of phonological ability, such as phonological retrieval (Chiappe, Stringer, Siegel & Stanovich, 2002). However, it seems to be the case that, in studies looking at reading acquisition in more transparent orthographies, phonological processing variables account for less variance in reading and RAN for more (see, for example, Wimmer, 1993; Wimmer & Hummer, 1990, Wimmer, Mayringer, & Landerl, 2000; Wolf, Pfeil, Lotz, & Biddle, 1994). This would imply that as variation in phonological processing becomes less of an impediment to reading acquisition, other processes, related to RAN, become the new bottleneck.

For this and other reasons, some have proposed a different explanation of RAN's usefulness as a predictor of reading. This alternative view, extensively documented in a series of papers by Wolf and Bowers (Bowers & Wolf, 1993; Wolf & Bowers, 1999; Wolf et al., 2000) sets RAN apart from other phonological tasks (though it does not deny that it does have a phonological component). Wolf and Bowers have argued that the association between RAN and reading might stem from a connection to orthographic sensitivity, or to the association between orthography and phonology via a hypothesized precise timing mechanism. Their model (Wolf & Bowers, 1999) indicates several areas where impediments to rapid serial processing might arise.

In an attempt to ascertain the cognitive locus of the RAN effect, Neuhaus, Foorman, Francis and Carlson (2001) recorded and digitized the verbal responses of 50 grade one and two participants as they performed RANL, RAND and RANO tasks. They used the articulation times of the responses and the pauses between responses as separate predictors of reading ability. They found that only the processing time (the pauses) and not the time taken to articulate the responses was predictive of reading ability. This is generally in keeping with work done previously by Anderson, Podwall and Jaffee (1984) and Obrégon (1994). In all of these investigations performance on RANL was consistently predictive of reading ability; performance on RAND was inconsistently predictive of reading and performance on RANO was not predictive of reading. Neuhaus et al. (2001) interpreted their results as indicating that the processing time for stimuli, particularly letters, was the predictive factor in the RAN tasks. It seems sensible, then, to attribute the predictive power of RAN to the fluency of serial processing of written language stimuli, at least for letters though to a lesser degree for digits. Why, then, do we have some evidence of correlations between reading and non-symbolic RAN tasks such as RANO and RANC? To answer this, we shift our attention from the continuous correlations of the RAN task across normal populations, to interesting findings that have arisen in clinical populations. Purvis and Tannock (2000) administered RAND and RANL to children with reading disability (RD), attention deficit/hyperactivity disorder (ADHD) and comorbid RD/ADHD. Children with RD and RD/ADHD performed more poorly on the RAN tasks than children with ADHD alone (no normal control group was included). This was taken to indicate that difficulties in the performance of RAND and RANL, at least, are specific to children with RD. However, in a recent study by Tannock, Martinussen, and Frijters (2000), a discriminant function analysis of task performance by controls and children with ADHD and combined RD/ADHD isolated two factors that discriminated between groups. One factor was composed of phonological processing, RANL and arithmetic scores while the second contained only RANC. Both ADHD groups were slower in performing RANC than the control group. The ADHD/RD group was slower than the ADHD-only group on RANL performance. The DFA correctly identified 82% of the ADHD group, 92% of the ADHD/RD group and 96% of the controls. Moreover, quite intriguingly, the administration of methylphenidate (Ritalin) in doses of 0 (placebo), 10, 15 and 20 mg to a subset of the ADHD and RD/ADHD children improved performance on RANC but not on RANL or RAND in a fashion linearly related to dose. Unfortunately, no RD only group was included in this study.

Investigations such as these, which demonstrate a link between RANC and ADHD, suggest an answer to the question raised above. The relationship between RANC and ADHD implies that RANC is tapping into some underlying cognitive process that is impaired in ADHD. The class of cognitive processes believed to be impaired in

ADHD is referred to as executive function, and in fact, performance on some executive function tasks have been positively associated with behaviour ratings of ADHD (Riccio, Hall, Morgan, Hynd, & Gonzalez, 1994). Pennington and Ozonoff (1996), in their review of executive function measures, identified several classes of executive function tasks, including those which reflect inhibitory processes, those which require the shifting of set, and those which involve working memory (which has, itself, been considered in similar, executive function terms; see Chiappe, Hasher, & Siegel, 2000). The performance of a serial task such as RAN will necessarily involve these classes of functions: attention must be directed to the correct spatial location of the first stimulus and its label activated in working memory, then attention must be shifted to the next stimulus, then the old response must be inhibited while the new response is activated. In the present investigation, we attempted to tap these three classes of executive functions in the context of a normal continuum of attention and activity. In the process we attempted to explicate the connections between reading ability, executive functions, behaviour, and non-symbolic RAN tasks. (Given the high population rates of ADHD and the high comorbidity rates for RD and ADHD, it would not be surprising if some of the inconsistent correlations of RANC and reading were due, in part, to contamination of RD samples with ADHD participants.)

Several investigators have argued that RAN and phonological processing are not coextensive. Denckla and Cutting (1999) divide the processing necessary for RAN performance into two components: phonological processing and "processing speed," explicitly equating processing speed with executive function. Wolf and Bowers (1999), in explaining their "double deficit" hypothesis, also assert that RAN and phonological processing are driven by different underlying cognitive processes. Their conceptual model indicates very clearly the need for some processing speed resource at nearly all levels of RAN performance. In the present study we explore the hypothesis that it is RANC, rather than RANL or RAND, that is related to executive function, in the classes discussed above. We attempted to link RANC to each of the underlying components of executive function discussed in Pennington and Ozonoff's (1996) taxonomy, within a normal population. It was important to ascertain whether the effects found by Tannock et al. (2000) could also be found in a normally varying population. While related work can be found in the clinical literature, it is very important to know how executive functions, reading performance, behaviour, and RAN are related for children at different levels of ability and difficulty (Welsh, Pennington, & Groisser, 1991).

In order to measure the inhibitory processes identified by Pennington and Ozonoff (1996), we focused our attention on the well-known Stroop task. The Stroop task is important because it spans the distinction between RAN and executive function tasks. The Stroop task has three parts. In each part, a set of stimuli is presented on a card to be processed quickly and in serial. In the first part, participants are asked to quickly read a set of colour names. In the second part, participants are asked to quickly name the colours of non-word symbol strings. Finally, participants are asked to name the colours in which colour naming words are printed, when these differ from the colours that they name (for example, the word "blue" is printed in green). We considered the first two Stroop cards to be rapid automatised naming tasks, in which the stimuli are words and colours. The third card, the interference component of the task, is a measure of executive function, particularly of the inhibitory component of executive function (Pennington & Ozonoff, 1996). Grodzinsky and Barkley (1999) found that performance on the Stroop interference component discriminated between children with ADHD and normal controls. Barkley, Grodzinsky and DuPaul (1992) reported that children with ADHD, particularly of the hyperactive type, showed greater interference on the Stroop task relative to children without ADHD and children with ADHD of the inattentive type. Barkley (1994) has suggested that this deficit may disappear with development. However, Barkley et al. (1992) also reported that children with ADHD showed deficits on the colour-naming component of the task as well as the interference portion. Shapiro and Herod (1994) found deficits for ADHD children on all three components of the Stroop task relative to their control children. Interestingly, half of their ADHD sample had been identified as learning disabled and, of the three aspects of the Stroop task, it was the Stroop words portion that best discriminated between ADHD and control children. On the basis of these findings, we asked whether performance on the colour naming component of the Stroop task would be related to executive function or to performance on RANL, RAND and reading.

In addition to the Stroop interference task, we also included tests of other components of executive function as identified by Pennington and Ozonoff (1996). We included Gottardo, Stanovich and Siegel's (1996) version of Daneman and Carpenter's (1980) sentence span test as a measure of working memory. We also included one of the most commonly used of the set-shifting tasks, the Trailmaking Task, Part B (Reitan, 1955, 1958). Finally, both symbolic (RANL and RAND) and non-symbolic (RANC) RAN tasks were used in this study. Reading measures were included and behaviour ratings were obtained from parents and teachers. Thus, representative measures of executive function, reading, RAN and behavioural ratings were included in order to compare performance on these important constructs in a normal developmental sample. We chose to use a normally varying population of participants rather than recruiting special populations for two reasons. First, since we were likely to find variation in a normal sample on all measured dimensions, we could use correlational methods to look for a double-dissociation. Secondly, we believed it was important to see whether relationships between RAN and executive function could be found along a normally varying continuum rather than simply at the extremes forced on researchers using identified populations. A broad set of tasks were included in order to allow us to explore the full multivariate relationship between these measures without committing us to an unnecessary reliance on a particular theoretical position.

In this study, we wished to explore which cognitive domains are tapped by rapid naming tasks. One of these domains is almost certainly phonological processing, and this would be evidenced by significant relationships between speed of naming letters and the phonological processing and reading measures. We wished to know whether or not the second domain of interest would be executive function. We explored whether the speed of naming letters, digits and colours is also predictive of performance on executive function measures. We also examined whether naming speed performance was related to attentional and behavioural difficulties reported by teachers and parents. It may be the case that one type of RAN task, that involving the rapid naming of symbolic, linguistic stimuli (letters and digits), may predict performance only on linguistic tasks. On the other hand, performance on another type of RAN task, a task involving the rapid naming of non-symbolic, non-linguistic stimuli (colours) may predict performance only on executive function tasks and/or behaviour ratings.

Participants and Method

Participants

The participants were 56 children (25 boys and 31 girls) recruited from four classrooms in two schools in a small town/rural area. Twenty-two students were enrolled in third grade and 34 students were in fourth grade. Testing took place in May and June of the school year. The children were native English speakers with no reported history of speech, language or hearing difficulties. The mean age of the children was 9 years, 7 months (SD = 7.4 months).

Outliers

There were some individuals who displayed extreme performance on individual tasks but were within a normal range on others. We included the data from these multivariate outliers in the statistical analyses. We used Tabachnick and Fidell's (1989) most conservative score changing option only for those tasks on which these participants deviated so extremely. Each deviant score was changed to equal the next highest score in the distribution, plus one unit. Thus the score remained as the most extreme in the distribution while at the same time the skew they created in the sample was minimized. This procedure was applied on the following measures: two participants' time score for rapid automatised naming of letters, one participant's time score for the Stroop interference condition, two participants' time scores for Trail-making B, four participants' total recall on the working memory task, five participants' total number of correct responses on the working memory task, and two participants' total hyperactivity score on the behaviour checklist.

Tasks

The tasks were administered individually to each child in a fixed order. The fixed order was necessitated by the interaction of the structure of the battery (several tasks could not be interrupted by breaks and therefore had to be scheduled for certain times during the day) and the structure of the school day (accommodating recess, gym, class changes, etc.).

Standardized measures The children completed standardized measures of reading and spelling. To assess word recognition ability, the children were given the reading subtest of the Wide Range Achievement Test – Third Edition (WRAT–3; Jastak & Wilkinson, 1993). The ability to spell individual words was assessed by the Spelling subtest of the WRAT-3 (Jastak & Wilkinson, 1993). The mean reading standard score of the grade three participants was 102.8 (SD = 11.01), for the grade four participants, 98.7 (SD = 11.37). The mean reading raw score for the grade three participants was 31.9 (SD = 3.82) and for the grade four participants was 32.6 (SD = 4.91). The mean spelling standard score for the grade three participants was 101.68 (SD = 13.28) and for the grade four participants was 101.88 (SD = 12.9). The mean spelling raw score of the grade three participants was 27.36 (SD = 3.9), for the grade four participants, 29.53 (SD = 4.32).

The children also completed a standardized measure of verbal and non-verbal cognitive ability. The children were all given an abbreviated version of the Wechsler Intelligence Scales for Children – Third Edition (WISC-III; Wechsler, 1991) in which an estimated IQ score is calculated from the Vocabulary and Block Design subtests (Sattler, 1992). This particular dyad of subtests is reported to (Sattler, 1992) have the highest internal consistency subtest reliabilities (Vocabulary subtest, $r = 0.86$; Block Design subtest, $r = 0.85$) compared to all of the other subtests in the WISC-III. In addition, the combined Vocabulary and Block Design subtests provide the most valid estimate of Full Scale IQ ($r = 0.906$) compared to all other dyad short forms of the WISC (Sattler, 1992). These two subtests were prorated to give an estimated Full-scale IQ score. The Full Scale IQ estimate score was 104.05 (SD = 16.51).

Rapid Automatized Naming Tasks (RAN) Two RAN tasks were used, one with digits as stimuli and the other with letters as stimuli. In the digit version of this task (RAND), based on the task used by Denckla and Rudel (1974, 1976b), participants named five monosyllabic digits (1, 2, 4, 6, and 8). Participants were given a chart of 50 numbers presented in a matrix of 10 columns and 5 rows. The order of the digits was randomized, with each digit presented 10 times. Participants named the 50 digits from left to right, starting with the top row and ending on the bottom row. The total naming time was recorded by the experimenter, using a stopwatch. The dependent variables of the continuous version of the RAND were the total number of errors and total naming time. The mean total naming time on this task was 24.32 s (SD = 4.49), and the mean number of errors was 0.07 (SD = 0.26).

In the letter version of this task, participants named five letters chosen randomly (T, K, S, L, and Q). The stimulus presentation and procedure were the same as for the RAND. Again, the dependent variables were accuracy and total naming time. The mean total naming time on this task was 29.63 s (SD = 4.74), and the mean number of errors was 0.21 (SD = 0.53).

Phonological Processing Task

The phonological processing task used was Rosner's Auditory Analysis Task (Rosner & Simon, 1971). This task requires participants to delete single phonemes from initial and final positions in words to form another word. They must also delete phonemes from blends, in the initial or final position, or internal to the blend. They are also asked to delete syllables from compound words as well as medial syllables, some of which did not form real words. The range of scores on this task was from 12 to 39. The mean score was 28.48 (SD = 7.01). The maximum possible score was 42.

Executive function tasks Three executive function tasks were employed in the present study, each reflecting one of the categories of executive function identified by Pennington and Ozonoff (Pennington & Ozonoff, 1996). The interference condition of the Stroop Test was used as an indicator of inhibitory processing, the Sentence Span Task was used as an indicator of working memory and the Trailmaking Task, Part B was used as a measure of set shifting ability.

The version of the Stroop Task used in this study (Cohen & Servan Schreiber 1992), included three different conditions: a word reading condition, a colour naming condition, and an interference condition. For each condition, participants named stimuli from a practice card prior to the experimental trial. In the word reading condition, participants were presented with a chart of 48 words comprised of four colour names (orange, red, green, blue) presented in a matrix of 6 columns and 8 rows. Participants were asked to read the words as quickly as possible without making any errors. In the colour naming condition, participants were presented with a chart of 48 patches of colour (orange, red, green, blue; each composed of three to six X's) presented in a matrix of 6 columns and 8 rows. Participants were asked to name the colours as quickly as possible without making any errors. In the interference condition, participants were presented with a chart of 48 words presented in a matrix of 6 columns and 8 rows. In this condition, the colour-naming words (orange, red, green, blue) appeared in a colour (orange, red, green, blue) different than the colour named. For example, the word "red" appeared printed in orange. Participants were asked to name the colour as quickly as possible without making any errors. The interference condition was the most difficult of the three conditions because participants needed to inhibit the competing response, that is, naming the words. The dependent variables in all of the Stroop task conditions were the total number of errors and total naming time. For the interference condition, the mean total performance time was 78.62 s (SD = 15.64), and the mean number of errors was 2.09 (SD = 3.90).

The Trailmaking Test (Reitan, 1955, 1958) consists of two parts, Part A and Part B. Participants completed practice items for both Part

A and Part B. Part A requires the participant to connect 25 numbered circles in numerical order with a pencil line. Part B consists of 13 numbered and 12 lettered circles, and the participant is instructed to alternate between numerical and alphabetical order, going from 1 to A to 2 to B to 3 to C, etc., until they have exhausted all of the circled numbers and letters. The dependent measure was total completion time on each part. Total time performance on Part B was the metric of interest in this study, as this part of the task required that participants ''shift set'' between numbers and letters. For the Part B version, the mean performance time was 109.38 s (SD = 42.47).

The sentence span task selected was taken from Gottardo, Stanovich, and Siegel (1996), which was a variation of a memory task developed by Daneman and Carpenter (1980). Children were required to listen to a series of two to five statements and to indicate whether each statement was ''true'' or ''false''. After responding to each of the sentences in a set, the child was required to recall the final word of each sentence in the set. The sentences used in the task contained information familiar to most primary school children, the sentences were quite short (mean length 5.5 words, range 4–9 words), and they were grammatically quite simple (e.g., ''cars have four wheels,'' ''fish swim in the sky''). The children received three 2-item sets, three 3-item sets, and three 4-item stimulus sets and, depending on performance, up to three 5-item sets. Across the twelve sets of items, the children responded to 42 true/false sentences and attempted to recall 42 words. The mean recall score was 16.11 items (SD = 4.41) out of a maximum possible total of 42, and the mean number of correct responses to the true/false questions was 25.27 (SD = 1.61).

Behaviour checklist

The Child Symptom Inventory-4 (CSI-4; Gadow & Sprafkin, 1994) is a behavior rating scale intended to screen for emotional and behavioural disorders in children between 5 and 12 years old. The CSI-4: Teacher Checklist contains 77 items and the corresponding Parent Checklist contains 97 items. Only the first 18 items, which are identical on the two checklists, were used in this study. The first nine items screen for inattentive behaviours (e.g., ''Fails to give close attention to details or makes careless mistakes''), while the second 9-items screen for hyperactive behaviours (e.g., ''Fidgets with hands or feet or squirms in seat''). The respondent answers on a four-point scale by making a check mark under the headings ''never,'' ''sometimes,'' ''often'' or ''very often.'' The items were derived from the DSM-IV diagnostic criteria for attention deficit/hyperactivity disorder. Each item was scored from 0 to 3, with 0 indicating a response of "never" and 3 indicating a response of "very often."

Scores ranged from 0 to 24 (mean = 5.5, SD = 4.7) on the parent hyperactivity ratings, 0–20 (mean = 4.3, SD = 5.8) on the teacher hyperactivity ratings, 0–23 (mean = 8.1, SD = 4.8) on the parent inattentive ratings, and 0 to 26 (mean = 7.1, SD = 6.5) on the teacher inattentive ratings. A potential diagnosis would require a score of at least 27 in two settings. No child in the sample met diagnostic criteria for ADHD. Scores from parent and teacher rating forms were summed to give scores incorporating reports from both sources.

Procedure

The tasks were individually administered in a session that lasted approximately one hour. The tasks were presented in the following order: RAN Letters, RAN Numbers, Stroop Task, Trailmaking (parts A and B), Sentence Span, WRAT-3 Reading subtest, WRAT-3 Spelling subtest, WISC-III Vocabulary subtest, and WISC-III Block Design. Occasional deviations from this order were necessitated due to time constraints; for example, shorter tasks were administered first if limited time remained for testing before recess. The CSI-4 Checklists were sent home to parents with the consent forms, and teachers were asked to complete the checklists after testing with the students was completed. Five teacher behaviour checklists were not returned and one child did not complete the Stroop interference condition.

Results

Descriptive statistics

Grade three and four participants did not differ on estimated IQ, $t(54) = -0.23$, n.s., on WRAT-3 reading raw scores, $t(54) = 0.56$, n.s., WRAT-3 spelling raw scores, $t(54) = 1.90$, n.s., WRAT-3 reading standard scores, $t(54) = 1.36$, n.s., or on WRAT-3 spelling standard scores, $t(54) = -0.06$, n.s. They differed significantly only in age, with the grade three children being, on average, 12.5 months younger than the grade four children, $t(54) = 11.34$, $P < 0.001$. Descriptive statistics for our participants and their performance on the various experimental measures are displayed in Table 1. The only statistically significant difference on the experimental tasks between the two grades was on the

Colour Naming task, where the grade four children performed the task, on average, about 5.8 s more quickly than did the grade three children, $t(54) = 2.79$, $P < 0.01$. Because we were interested in looking at performance over a normal continuum, we combined the two grades into a single group for statistical analyses and used only raw scores. Subsequent correlations are thus reported after partialling out the effects due to age (which has, in fact, only minor consequences).

Correlations and composite scores

Correlations between the variables of interest are shown in Table 1. Note that the effect of age has been partialled out of all correlations. The correlations for the timed executive function variables (Stroop Interference and Trailmaking part B) have been reflected so that they are in the same direction as those for Working Memory, so that better performance on these variables is correlated positively with better performance on untimed variables (WRAT-3 reading and spelling, Rosner AAT) and negatively correlated with better performance on other timed variables (RAND, RANL, Word Naming, Colour Naming).

Participants' times for RANL and RAND correlated at $r = 0.607$, $P < 0.05$. Both RAND ($r = -0.296$, $P < 0.05$) and RANL ($r = -0.384$, $P < 0.05$) were significantly correlated with WRAT-3 reading scores. Neither RAND nor RANL were significantly correlated with CSI-4 inattentive (RAND : $r = 0.022$, n.s.; RANL: $r = 0.013$, n.s.) or hyperactive (RAND: $r = 0.050$, n.s.; RANL: $r = -0.028$, n.s.) behaviour rating scores. Colour naming time was not significantly related to WRAT-3 reading scores ($r = -0.060$, n.s.), though it was significantly correlated with both CSI-4 inattentive behaviour rating ($r = 0.406$, $P < 0.05$) and hyperactive behaviour rating ($r = 0.310$, $P < 0.05$) scores.

The mean correlation amongst the three executive function measures (Stroop Interference Time, Working Memory, Trailmaking Task, Part B) was 0.454. While these variables are hypthesised to tap different aspects of executive function, the pre-theoretical categorization of these variables as all belonging to a single construct, executive function, was largely borne out. We, therefore, constructed two composite measures as more powerful indicators of the key constructs. Each component score was standardized (z-transformation) so that they would all be in the same metric and then the components were summed. The RAN composite represents the naming times for both RAND and RANL. The Executive Function composite was composed of times for the

Table 1. Correlations, means and standard deviations

Variable	Vocab	BlockDes	Read	Spell	AAT	RAND	RANL	WrdNm	ColNm	SInt	Trails	WM	Bin	BHy
Vocab														
BlockDes	**0.378**													
Read	**0.583**	**0.292**												
Spell	**0.541**	**0.350**	**0.659**											
AAT	0.255	**0.281**	**0.318**	**0.399**										
RAND	−0.175	−0.106	**−0.296**	**−0.300**	0.035									
RANL	**−0.286**	−0.070	**−0.384**	−0.221	0.079	**0.607**								
WrdNm	**−0.317**	−0.260	**−0.427**	**−0.405**	−0.148	**0.439**	**0.607**							
ColNm	−0.124	−0.162	−0.060	−0.135	0.178	**0.356**	**0.453**	**0.410**						
SInt	**0.291**	0.261	0.263	**0.317**	**0.300**	**−0.321**	**−0.426**	**−0.511**	**−0.778**					
Trails	**0.433**	**0.439**	0.235	**0.286**	**0.462**	−0.136	−0.250	**−0.290**	**−0.411**	**−0.450**				
WM	**0.527**	**0.411**	**0.425**	**0.353**	**0.345**	−0.166	−0.317	**−0.383**	**−0.299**	**−0.478**	**−0.435**			
Bin	**−0.302**	−0.166	−0.066	−0.272	**−0.431**	0.022	0.013	0.191	**0.406**	**0.310**	**0.574**	**−0.273**		
BHy	−0.183	−0.004	0.040	−0.065	−0.145	0.050	−0.028	−0.053	**0.310**	0.199	**0.379**	−0.212	**0.680**	
Mean	9.95	11.43	32.37	28.68	28.48	24.32	29.63	26.66	47.64	78.62	109.38	16.11	15.18	9.37
SD	3.62	3.25	4.50	4.26	7.01	4.49	4.74	4.17	7.98	15.64	42.47	4.41	10.49	8.18
Minimum	3	4	20	17	12	17	21	19	32	50	29	8	0	0
Maximum	19	19	45	41	39	39	44	40	63	111	200	27	44	34

Notes: $N = 56$, SInt $N = 55$, BIn BHy $N = 51$.
Correlations in bold are statistically significant, $P < 0.05$, two-tailed.
Read: WRAT-3 Reading raw score; Spell: WRAT-3 spelling raw scores; AAT: Rosner AAT raw scores; RAND: Rapid automatised naming, digit stimuli time; RANL: Rapid automatised naming, letter stimuli time; WrdNm: Stroop word naming time; ColNm: Stroop colour naming time; Sint: Stroop interference condition time; Trails: Trailmaking B time; WM: Sentence span, number of words recalled; BHy: Hyperactive behaviour, total score; Bln: Inattentive behaviour, total score.

Values for timed executive function tasks (Sint, Trails) have been reflected so that better performances on these tasks are positively associated with better performance on untimed tasks.

Table 2. Correlations and adjusted coefficients of variation for composite variables

Variable	Colour naming	RAN composite
WRAT-3 Reading ($N = 56$)	−0.060	**−0.379**
	(−0.02)	(0.13)
Executive Function Composite ($N = 56$)	**0.575**	0.213
	(0.32)	(−0.03)
Inattentive Behaviour Ratings ($N = 51$)	**0.406**	0.020
	(0.15)	(−0.02)
Hyperactive Behaviour Rating ($N = 51$)	**0.310**	0.012
	(0.08)	(−0.02)

Notes: Correlations in bold are statistically significant, $P < 0.01$, two-tailed.

Stroop interference condition, the Trailmaking Task, Part B, and the mean recall scores on the Working Memory task.

Table 2 shows the correlations of direct significance to our hypotheses. In Table 2, we see that the RAN composite, while it shows a significant, moderate correlation with the WRAT-3 reading score ($r = -0.379$, $P < 0.05$), has no significant correlation with the Executive Function composite ($r = 0.213$, n.s.) or with children's scores on the behaviour rating scales for either Inattentive ($r = 0.020$, n.s.) or Hyperactive ($r = 0.012$, n.s.) behaviour rating scores. The Colour Naming task, however, shows no significant correlation with the WRAT-3 reading scores ($r = -0.060$, n.s.), but does show significant, moderate correlations with the Executive Function composite ($r = 0.575$, $P < 0.05$) and with both inattentive ($r = 0.406$, $P < 0.05$) and hyperactive ($r = 0.310$, $P < 0.05$) behaviour ratings.

Also in Table 2 are the adjusted coefficients of determination for each correlation. These represent the proportion of variance accounted for by the relationship, after adjusting for sample size (the adjustment can result in small, negative values). The RAN composite measure accounts for about 13% of the variance in WRAT-3 reading raw scores, but less than one percent of the variance in the Executive Function composite measure, or the Inattentive or Hyperactive behaviour ratings. Colour naming speed accounts for less than 1% of the variance in WRAT-3 reading raw scores, but 32% of the variance in the Executive Function composite measure, 15% in the Inattentive behaviour ratings and 8% in the Hyperactive behaviour ratings. The statistical significance of the findings are thus largely reflected in the relative sizes of the effects.

Discussion

Consistent with the RAN literature, rapid naming of digits and letters was a reasonably good predictor of single-word reading scores. Colour naming showed no correlation with our reading measure and this suggests that any linguistic/phonological component necessary to its performance is probably insignificant in terms of the overall speed of naming. That is, the cognitive demands of retrieving and articulating the colour names must pale beside the demands of classifying and identifying the colours. Neither RANL nor RAND, singly or in composite, correlated significantly with either of the behaviour rating measures. Only the Colour Naming task showed moderate, significant correlations with both inattentive and hyperactive behaviour ratings. Neither RANL, RAND, nor the RAN composite showed a significant correlation with the executive function composite. The Colour Naming task showed a moderate, significant correlation with the executive function composite. These results were reflected in effect size measures. It would seem clear that the data reveal the hypothesized double dissociation.

Geschwind, in discussing performance on the colour naming task by patients with alexia (Geschwind, 1965) notes that colours have no associates other than their verbal labels, and thus performance on colour naming tasks should reflect only the strength of visual-auditory associations. Tannock, (Martinussen, and Frijters 2000), however, in explaining the results of their study in which they found slower colour naming performance by ADHD children, refer to a study entitled ‘‘Why is colour naming difficult?’’ (Braisby & Duckrell, 1999). Braisby and Dockrell hypothesize that children may have trouble with colour terms because of the ‘‘conceptual structure of the colour domain’’. To illustrate their point, Braisby and Dockrell (1999) contrast colour naming with naming ‘‘natural kinds,’’ such as animals and plants. They argue, and present evidence in support, that colour naming differs from ‘‘natural kind’’ categorization in two major ways. Natural kind categories have sharp, clear boundaries, while colours have vague, even variable boundaries. Moreover, colour categories, unlike natural kinds, do not exist in a hierarchical semantic organization. For example, the relationship between the colours ‘‘red’’ and ‘‘burgundy’’ does not invoke the same relationship as between ‘‘bird’’ and ‘‘chicken.’’ The process to identify a colour, then, is likely more complex and takes longer than the processing to identify a natural kind. The structure of the category ‘‘letters’’, by contrast, is simple and clear. The study by Neuhaus et al. (2001), proposed that the pause time between individual RAN stimuli (which is the major component of naming time) reflects the time taken to process the stimuli. It is worth noting, perhaps, that in both the Neuhaus et al. (2001) and Tannock et al. (2000) studies, RANL is accomplished much more quickly than RANO or RANC, indicating that the processing of object or colour stimuli is more involved than the processing of letter or digit stimuli (there is an extensive, historical discussion in the literature regarding the differences between the processing of letters and digits vs. colours and objects – book-ended by Cattell, 1886; Wolf & Bowers, 1999).

The question of why colour naming is difficult becomes more complex with the discovery of this double dissociation. That is, it was found that colour naming was difficult specifically for children with behavioural/attentional and/or executive processing problems, but not reading problems. Moreover, the correlational relationships obtained suggest that letter and digit naming is difficult specifically for children with reading problems, but not behavioural/attentional or executive processing difficulties. However, while the question is a little more complex, answers may be found in the similarities and differences between the tasks. Neither letters, digits nor colours are similar to "natural kind" categories, in that none of them are represented in hierarchical semantic structures. What does differ between letters and colours is the clarity of the category. For a normally achieving child, both the orthographic and phonological categories that accrue to a letter are so clear and overlearned that there is no question of difficulty in identifying that letter. Even for the child with reading problems, the orthographic categorization is so clear that they make virtually no errors. What does present a problem for the child with reading problems is, perhaps, the fuzziness of the phonological categorization, and the assigning of a verbal label to the orthographic stimulus. The clarity of phonological categories is a known problem for most children with reading problems (Brady, 1997; Cornelissen, Hansen, Bradley, & Stein, 1996; Elbro, 1996; Elbro, Borstrom, & Petersen, 1998; Fowler, 1991; Hulme & Snowling, 1992; McBridge-Chang, 1996; Metsala, Stanovich, & Brown, 1998; Mody, Studdert-Kennedy, & Brady, 1997; Swan & Goswami, 1997; Walley, 1993), though there does appear to be a group of individuals who have no obvious phonological processing problems yet who do have naming speed deficits (Wolf & Bowers, 1999, Wolf, Bowers, & Biddle, 2000). We can assume that, while problems with phonological boundaries would also have an impact on creating the phonological output for the colour names, the variance in naming speed due to this rather subtle problem will be obscured by the relatively lengthy time taken to identify the appropriate colour category. For children without phonological processing difficulties but who have behavioural/

attentional and/or executive function difficulties, however, phonological, orthographic and colour category boundaries are probably the same as for any other child. The category boundaries of the colours used in this study, red, orange, blue and green, were probably somewhat less clear than for the more "prototypical" colours often used in RAN tasks. This may have made the categorization process more complex. What seems probable, however, from the data we have reviewed, is that coming up with a proper categorization simply takes longer for these children, for reasons having to do with executive function processes.

It may be worthwhile, here, to speculate briefly on what might have been the case with RAN Objects. We did not include such a task in this battery, but one might wonder where it would have stood in terms of its correlations with either reading or executive function/behaviour measures. Typically, object naming tends to be slower than naming letters and digits, roughly the same speed as naming colours. Like naming colours, naming objects is inconsistently related to reading ability (Anderson, Podwall, & Jaffee, 1984; Neuhaus, Foorman, Francis, & Carlson, 2001; Obrégon, 1994). However, it would seem that objects can tap a variety of category structures, flat and clear like letters and digits, hierarchical like fruit or furniture, or fuzzy like cups and mugs. It is probable that the relationship between object naming and reading, or object naming and executive function, would vary depending upon the type of stimuli used and the category structures they evoked.

On this note, Cutting, Carlisle and Denckla (1998) propose that RAN can be seen as the intersection of two sets of processes, one set being the phonological processing components of the task and a second set reflecting the processing speed/executive function aspects of the task. Unfortunately for the apparent simplicity of the model, each of these two domains (which together still do not specify all of the variance in RAN performance) covers a potentially large variety of more specific processes. Processing speed is conceptualized by Kail and Salthouse (1994) as a basic cognitive "primitive," that is, a more or less fixed attribute of the cognitive system(s) that cannot be conceptually reduced. Processing speed would thus be inextricably linked to the overall cognitive ability of individuals.[4] This link is reflected in some models of intelligence, for instance the Carroll-Horn-Cattell (CHC) model on which the Woodcock-Johnson III cognitive abilities test (Woodcock, McGrew, & Mather, 2003) is based, in which processing speed is reflected in the "*Gs*" index, or in the fourth factor of the Wechsler intelligence scales (Wechsler, 1991; labeled "Processing Speed"). This could, theoretically, lead to artifactual differences between IQ-discrepant and non-discrepant readers on RAN performance, depending on whether the processing speed aspect of intelligence is tapped in defining the groups. In models such as the one proposed by Kail and Salthouse (1994), or the CHC model, processing speed is seen as an inextricable attribute of executive and other functions. Kail et al. (Kail & Hall, 1994; Kail, Hall, & Caskey, 1999) have shown that processing speed is related to reading ability through rapid naming performance, while Carver (Carver, 1997) includes processing speed (*Gs*, measured partly by RAN) in his "rauding" model, as a supporting factor for reading rate. While there seems to be little doubt that processing speed is an important factor in RAN performance, it is still unclear which processes lack speed. The results of this study would seem to indicate that whether or not the implicated processes are executive in nature could be dependant upon the stimuli being processed.

This study implies an even more complex model in which different versions of the RAN, or perhaps even different stimuli within a single version, draw on different specific executive processes. It is important to note that these differences exist between children along the normal continuum of RAN and executive function performance. It is not necessary to look at children diagnosed with RD or ADHD, to find these effects. The effects are not functions of clinical severity. This opens the field of study much wider and to more researchers. These findings also underscore the importance of observing all of these constructs – both cognitive and behavioural – across a continuum of performance. It is both theoretically interesting and clinically relevant to observe these patterns in normal samples of children. This method of examining the problems of written language, attention, behaviour, executive functions and the various forms of rapid automatised naming, can also provide a productive structure to frame future research questions. It would be interesting to know, for instance, whether a second, critical domain in RAN, beyond phonological processing, might indeed be executive function. It would be interesting to see what would happen if one varied the categorical clarity of RAN stimuli, perhaps by using different or degraded fonts, or primary versus secondary colours.

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Note

4. See, for instance, Jensen and Munro (1979). While Jensen repeatedly found relationships between reaction time and intelligence, he saw the relationship as being between IQ and the slope of the reaction time curve as the complexity of the task increased. Current research (for instance, Deary, Der, & Ford, 2001) indicate that the situation might be much more simple, with clear relationships existing between IQ and the magnitude of the simple RT.

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