

Visual processing deficits

Visual processing deficits in children with slow RAN performance

Keywords: Visual feature discrimination; Rapid automatized naming; reading development; speed of processing

## Visual processing deficits

Slow performance on rapid automatized naming tasks has long been known to be associated with poor reading performance (Denckla & Rudel, 1974, 1976; Spring & Capps, 1974), with RAN performance of children with dyslexia differing from that of age-matched average readers (Bowers, Steffy & Tate, 1998), ‘garden-variety’ poor readers (Badian, 1994; Wolf & Obregon, 1992) and readers with other learning disabilities (Ackerman & Dykman, 1993).

In recent years, various explanatory accounts of this relationship have been advanced: that both slow RAN and poor reading index an underlying problem in phonological processing (Wagner & Torgesen, 1987; Wagner, Torgesen, et al., 1997; Torgesen, Wagner, et al., 1997); that slow RAN is an index of generally slow processing speed that also affects the development of reading skills (Kail, 1991; Kail & Hall, 1994; Kail, Hall & Caskey, 1999); and that slow RAN indexes a deficit in non-phonological processes, possibly a problem with orthographic processing (Bowers & Wolf, 1993; Wolf & Bowers, 1999; Ackerman & Dykman, 1993; Badian, 1993; Blachman, 1984; Felton & Brown, 1990; Manis, Seidenberg, & Doi, 1999). This latter view has come to be known as the double deficit theory of dyslexia, which proposes that children with dyslexia can be assigned to one of three subgroups: those with a phonological deficit, those with a RAN deficit, and those (the most severely affected) with deficits in both phonological processing and RAN. Bowers (1995), Bowers and Wolf (1993), and Powell, Stainthorp, Stuart, Garwood and Quinlan (2007) all provide evidence of the existence of these three postulated subgroups in typically developing populations and those with dyslexia.

Bowers and Newby-Clark (2002) have suggested that poor RAN performance may have a negative impact on the integration of the visual information relating to the sequence of letters in

## Visual processing deficits

words which may then result in limitations on the development of an extended orthographic lexicon.

Despite the many studies that have been carried out to demonstrate and investigate the nature of the relationship between RAN performance and reading, relatively few studies have sought to investigate the cognitive processes that are involved in performing RAN tasks. A number of studies (Cobbold, Passenger & Terrell, 2003; Georgiou, Parrila & Kirby, 2006; Neuhaus, Foorman, Francis & Carlson, 2001) separated RAN response times into two components, articulation time and pause time, and showed that it is the latter, pause time, component that relates most closely to reading levels. Pause time is interpreted as a measure of retrieval time from phonological memory. However, Clarke, Hulme and Snowling (2005) failed to replicate this result when the reading measure used was exception word reading. Clarke et al. noted that better readers paused more strategically (i.e. more often at the ends of lines) than poorer readers, and they suggested that differences in RAN may in part reflect differences in strategic control that result from differences in reading practice and experience.

Of the four RAN tasks (picture naming, color naming, digit naming, letter naming) it is the alphanumeric tasks (RAN letters and digits), which are most strongly associated with reading performance (Neuhaus & Swank, 2002). The letter and number stimuli differ from the color and picture stimuli in being selected from a closed set of items all of which are composed from a small set of visual features, that is, lines and curves in different orientations. The RAN letter task would appear to have a more direct relationship with reading because both involve the processing of letters per se. The flowchart (see figure 1) provided by Wolf, Bowers and Biddle (2000) of the processes that are likely to be involved in RAN proposes that one of the first stages in RAN performance involves visual processing. However, possibly because of the impact of

## Visual processing deficits

Vellutino's devastating critique of studies investigating visual perceptual processing deficits in dyslexia (Vellutino, 1979), until recently there have been fewer investigations of prelexical visual processing in children with dyslexia or those showing typical development. This despite Venezky's point that the fact that "... the reader interacts with the text, integrates previously acquired knowledge with local text information, and generates hypotheses about what might occur next in the text does not negate the critical initiation role played by the letters, words, punctuation, and other graphic characteristics of the page." (Venezky, 1993, p.3). Lackmann and van Leeuwen (2007) have recently argued that many of the tasks used to investigate visual processing deficits in children with dyslexia may not be sufficiently sensitive to detect anomalies. To our knowledge there is no research as yet that has focused specifically on letter identification processes in children identified as having RAN deficits. That is, it is simply not known whether or not children with RAN deficits have problems with the early visual processing of letters.

Insert figure 1 about here

Vellutino (1979) made a systematic review of the published research which implicated a visuo-perceptual deficit in dyslexia. He found that much of the research up to that time was flawed because of poor methodology. For example, few studies included a control group and little attention was paid to matching for socioeconomic status or cultural background. Groups of poor readers often included children with low IQ, neurological problems or emotional problems which rendered conclusions about a visuo-perceptual deficit which was specific to poor reading performance unreliable. The majority of the studies reviewed by Vellutino used tasks of

## Visual processing deficits

matching to standard and figure drawing such as the Bender Visual Motor Gestalt Task (Bender, 1938) as indices of a perceptual deficit. It is questionable whether such tasks are able to assess performance at the very first stage of visual processing since they clearly involve a degree of higher-level cognitive processing. Vellutino argued that because of flawed methodology, claims that a visuo-perceptual deficit was implicated in poor reading performance had to be treated with caution. His laboratory therefore instigated a systematic experimental investigation of the perceptual deficit hypothesis using carefully controlled stimuli with appropriate control of participants. In this series of experiments no significant differences were found between participants with and without dyslexia on tasks involving the processing of visual stimuli such as words, scrambled letters, items composed of Hebrew letters, and geometric designs. It was therefore concluded that visuo-perceptual difficulties were not implicated in dyslexia. However, the tasks used in these experiments (including copying and copying from memory) required much more than visual perception. Because no differences were found in performance across groups on these tasks Vellutino concluded that visual perception in children with dyslexia must be intact. However, this conclusion needs to be treated with some caution because of the rather complex nature of the tasks used and the failure to measure response times.

Vellutino's critique notwithstanding, there is more recent evidence suggesting that children with dyslexia do show visual and visual- attentional deficits. For example, Lovegrove, Martin and Slaghuis (1986) proposed that a large percentage of disabled readers had a low-level visual deficit. While they acknowledged that the impact of this deficit on reading was not known, they argued that its association with reading disability merited further investigation.

In a developmental experimental study, Willows, Kruk and Corcos (1993) found that younger children with a reading disability were slower and less accurate at deciding whether two

## Visual processing deficits

unfamiliar letters (Hebrew for non-Hebrew speakers) were the same or different. Stein and Walsh (1997) argue from their studies that children with developmental dyslexia may have deficits in the adequate processing of fast incoming sensory information across all modalities. They suggest that the underlying cause of such deficits may be found at a lower level than the perceptual and cognitive systems that have been investigated in psychological research.

Additionally, Hari and Renvall (2001) propose that the observed deficits may be the result of children with dyslexia having sluggish attentional shift which can impair rapid stimulus sequence processing regardless of the modality. However, Bosse, Tanturier and Valdois (2007) have recently suggested that the visual attention span disorder is not a universal characteristic and might be a separate, independent cognitive disorder leading to word reading difficulties.

Additionally, Pammer and Kevan (2007) have proposed that low-level visual sensitivity is a significant contributor to word reading with the possible result some children with dyslexia may show impaired visual sensitivity. However, in their study investigating this they measured phonological processing but not RAN performance.

In short, though a phonological deficit has been firmly established as a cause of some children's dyslexia, there is now sufficient evidence to hypothesize that early visual perceptual processes may also be implicated in word reading difficulties. The rapid naming deficit associated with dyslexia is well established, and though we cannot gainsay that phonological processes are involved in RAN performance, the potential role that visual perceptual processes may play remains largely uninvestigated. This is therefore a potentially fruitful area for research, especially as the cognitive processes which Wolf et al. (2000) propose operate in performing the RAN letter naming task can be directly related to the cognitive processes proposed to operate in the lexical reading route of the Dual Route Cascade model of visual word recognition (see figure

Visual processing deficits

2 – RAN and DRC lexical processes). Given this direct relationship, an understanding of the sources of difficulty underlying slow performance on the RAN letter naming task might transfer directly to related reading difficulties.

Insert figure 2 about here

The DRC model incorporates the McClelland and Rumelhart (1981) model of lexical access. This proposes three levels of representation: visual features, letters and words. Lexical access is achieved through processes of activation and inhibition between and within these three levels. If we adopt this model, then the first stage in processing letters in both reading and RAN alphanumeric tasks is visual feature identification.

In this study we report the data from four experiments designed to investigate whether children with a single RAN deficit showed compromised performance when processing visual stimuli relative to children who showed normal performance on RAN tasks. We also report the data from control measures of visual and auditory reaction time tasks.

## Experiment 1: Simple Reaction Time

### Method

#### Participants

In order to select criterion groups for the study, the Comprehensive Test of Phonological Processing (CTOPP) (Wagner, Torgesen, & Rashotte, 1999) and the British Ability Scales Word reading test was administered to a total of 1010 children in Years 3 and 4 (equivalent to US Grades 2 and 3) in nine state funded primary schools in an urban area to the west of London, UK (Powell, Stainthorp, Stuart, Garwood & Quinlan, 2007).

## Visual processing deficits

The RAN letters and RAN digits subtests from the CTOPP were administered to assess naming speed. Both these two subtests require participants to name as quickly as possible two 4 x 9 arrays containing repetitions of 6 letters or digits. Phonological awareness was assessed using the elision and blending subtests of the CTOPP. Elision requires the participant to say out loud the word that results from the deletion of a designated sound (e.g., “Say *cup* without saying /k/”). Blending requires the participant to combine a sequence of discrete phonemes to form a word (e.g., “What word do these sounds make? m-ă-d”). Phonological memory was assessed using the memory for digits subtest and the nonword repetition subtest. The CTOPP manual gives procedures for calculating composite scores for RAN, PM and PA by summing the standard scores for the two measures of each construct. However, because the instrument was not standardized on a UK population composite scores for RAN, PM and PA were calculated by summing the raw rather than the standard scores.

Word reading ability was assessed using the BAS single word reading task (Elliot, Murray & Pearson, 1983). This task requires the participants to read aloud single words of increasing difficulty. Only correct pronunciations of words were accepted, and testing was abandoned if the children made more than 10 successive errors as detailed in the manual.

These data were used to select 154 children to form two groups: a Low RAN group and a group of matched control children. The 75 children comprising the Low RAN group were further subdivided into a younger and an older group: 36 younger children in Year 4 (equivalent to US Grade 3) and 39 older children in Year 5 (equivalent to US Grade 4). They were identified as having a RAN deficit (defined as RAN performance of at least one standard deviation below the mean) and normal phonological awareness (defined as performance not less than one standard deviation below the mean). The control group was also further subdivided into a younger and an



## Visual processing deficits

older group consisting of 36 children in Year 4 and 43 in Year 5. They were selected to show normal phonological awareness as defined above and normal RAN performance (defined as scores not less than one standard deviation below the mean). In addition each child in each of these two control groups was selected as a match for a Low RAN child in the respective younger and older groups on the basis of age, verbal and non-verbal ability as measured respectively by the vocabulary and the block design subtests of the WISC-III-R (Wechsler, 1992), and on visual acuity as measured on the Freiburg Visual Acuity Test (Bach, 1996).

Table 1 shows the mean performance of the 4 groups on these tests. These data were analyzed using independent t tests to verify the accuracy of the matching procedure. No significant differences were found between groups on any of these control measures. There were differences on British Ability Scales word reading; for the younger groups  $t(70) = 2.55, p = .03$  and for the older groups  $t(80) = 2.79, p = .007$ . In each case the control children were significantly better readers than the low RAN children.

Table 1 about here

## Materials and measures

As we intended to measure both speed and accuracy in later visual feature judgment experiments (see below), and as there have been suggestions that slow RAN is an index of generally slow speed of processing (Kail, 1991), we first administered a simple reaction time task to all children. Any observed simple reaction time differences between groups could then be statistically controlled in subsequent data analysis. A computerized test of simple reaction time was developed using E-prime experiment presentation software (Schneider, Eschman & Zuccolotto, 2002). The task was presented using a Dell Latitude D800 laptop computer with an Intel Pentium processor (1400MHz) and a 15" color screen. The children were required to make

## Visual processing deficits

a key-press response following the appearance of a target stimulus on the screen and the time taken to do this was measured. The target stimuli were six color drawings of monsters.

### Procedure

The ethics committee of the School of Psychology and Human Development, Institute of Education scrutinized and passed the project. Informed parental consent was obtained from the parents via letters sent out from the schools. The children were told that they were free to withdraw at any time. No child chose to do so.

Each participant saw a welcome screen displaying the six pictures of monsters that acted as target stimuli and the following instructions, “Hello. When you see one of these monsters, press the spacebar as quick as you can”. After ensuring that the child understood the instructions, the experimenter initiated a block of six practice trials, followed by two blocks of experimental trials. For both practice and experimental blocks, each trial began with the presentation of a black fixation cross in the center of a white screen for 500 ms, followed by a lag, followed by the appearance of the target stimulus. The duration of the lag was varied to prevent the children anticipating the moment when the stimulus appeared on the screen and was either 300, 600 or 900 ms. Each lag duration occurred equally often and in random order, as did each of the six target stimuli. The target remained in the center of the screen until the participant made a spacebar response, which initiated the next trial. There was a short break of approximately 1000 ms between trials. There were 18 trials in each of the two experimental blocks.

### Results and discussion

Raw scores for the simple reaction time task are given in Table 2.

Table 2 about here

## Visual processing deficits

Simple reaction time task data were analyzed in a two-way ANOVA, with Group and Year as between-group factors, and mean RT as the dependent variable. There was a significant main effect of Group, with the low RAN group being significantly slower than the controls,  $F(1, 150) = 4.25, p < 0.05, \eta^2 = .028$ . There was also a significant main effect of Year, with significantly slower RTs in Year 4 than Year 5,  $F(1, 150) = 7.02, p < 0.02, \eta^2 = .039$ . The interaction between Group and Year was not significant,  $F(1, 150) < 1, ns$ . These data show that the children with a single RAN deficit had significantly slower response times when they were required to detect the appearance of a stimulus. This finding would appear to be in accord with Kail's position that RAN performance may index a general speed of processing deficit. Because of this difference in the groups it was necessary to control for simple reaction time when analyzing the reaction time data from subsequent experiments.

Experiment 2: Visual features same/different judgment task (parts a, b, & c).

### Method

#### Participants

The participants in this experiment were the same children who took part in the simple reaction time experiment reported above. The experiment was carried out at the beginning of the following academic year: thus the younger groups were in Year 4 (equivalent to US Grade 3) and the older groups were in Year 5 (equivalent to US Grade 4).

#### Materials and measures

A computerized visual feature discrimination experiment was developed using the E-prime software and presented using the laptop computer described above. This was in three parts (a, b and c). Pairs of stimuli were presented on the screen and the children were required to

## Visual processing deficits

decide whether the stimuli were the same or different. The stimuli stayed on the screen until a key-press response was made. Speed and accuracy data were collected.

The stimuli for experiment 2(a) (see figure 3) were simple visual features of which letters are composed. Sixty pairs of stimuli were prepared, thirty of which were ‘same’ trials (five for each stimulus), and thirty were ‘different’ trials (each combination of the six stimuli, with each combination occurring twice to allow for both possible left-right positions of the two stimuli).

Insert Figure 3 about here

The seven stimuli for experiment 2(b) (see figure 4) were based on the letter-like forms designed by Gibson, Gibson, Pick and Osser (1962) and included transformations that were letter-like i.e. horizontal and vertical flips, forms with an add-on feature, and forms that involved open or closed elements.


Insert Figure 4 about here

Eighty-four pairs of stimuli were prepared as target stimuli. There were 42 ‘same’ trials, involving six pairs of each of the seven letter-like forms, and 42 ‘different’ trials, involving each combination of all forms, with each combination occurring twice to allow for both possible left-right positions of each pair.

The seven stimuli for experiment 2(c) were real letters. The lower case letters b d p n m c and o were selected. These shared similar characteristics to the letter-like forms used as stimuli in experiment 2(b). There were reversals (b d p), add-ons (n m) and open and closed curves (c o). Eighty-four pairs of letters were prepared as target stimuli. There were 42 ‘same’ trials, involving six pairs of each of the seven letters, and 42 ‘different’ trials, involving each combination of all letters, with each combination occurring twice to allow for both possible left-right positions of each pair.



## Visual processing deficits

### Procedure

The procedure was the same for each part of the experiment. For 2(a) the children saw a welcome screen with the instructions “You are about to see a screen with 2 pictures on it like this: . If the two pictures are the same, press the blue key. If they are different, press the red key.” The experimenter determined that the children understood the task, pointing out that to be considered the same, the two pictures comprising each pair “had to be not just the same shape but also pointing in the same direction”, a constraint that was further reinforced by the experimenter during the practice trials. There were ten practice trials, selected at random for each individual participant from the total sixty stimulus pairs, each of which was followed by encouraging corrective feedback. There followed three blocks of twenty experimental trials, allowing for the presentation of all sixty stimulus pairs, in random order, with feedback (percentage correct, and mean reaction time) given at the end of each experimental block. (Ten of the items were therefore presented once in practice and once in the experiment, though since these ten items were randomly selected they differed for each participant.) Each trial commenced with the presentation of a fixation cross for 500ms followed by a pair of stimuli, which remained visible until a key-press response was made. Children pressed the blue key (the L key covered with a blue sticker and presented as the ‘blue key’) if they thought the 2 features were the same, and the red key (the A key covered with a red sticker and presented as the ‘red key’) if they thought they were different. For left-handers the required key-press response was reversed (red, A key for ‘same’ responses; blue, L key for ‘different’ responses) so that all participants responded ‘same’ with their dominant hand. Speed and accuracy measures were recorded.

The procedure was the same for 2(b) and 2(c) with the exception that the initial welcome screen for part b had the instructions “You are about to see a screen with two pictures on it like

## Visual processing deficits

this:  . If the two pictures are the same, press the blue key. If the two pictures are different, press the red key”. For 2(c), the word “letters” was substituted for “pictures” and two letters replaced the letter-like forms.

## Results and discussion

Accuracy and latency scores and adjusted RT scores after controlling for simple reaction time (SRT) scores are given in table 3.

Insert Table 3 about here

We initially present the results for each part of this experiment separately.

A two-way ANOVA was carried out on the accuracy data for experiment 2(a) (simple visual features), with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There were no main effects of Group or Year and no interaction,  $F(1,150) = 0.53, 1.36$  and  $0.78$  respectively.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate and mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was still a main effect of Group,  $F(1,149) = 9.62, p < .01, \eta^2 = .06$ . There was no main effect of Year,  $F(1,149) = 3.22, p = .08$ , and no interaction between Group and Year,  $F(1,149) < 1, ns$ .

The accuracy data from this part of the experiment showed that there were no differences between the groups in their ability to make an accurate decision as to whether the pairs of stimuli were the same or different. This would appear to be a task which demanded very little processing capacity and indeed the performance of all groups was close to ceiling. On the surface these data support Vellutino’s claims that individual differences in visual perception do not have an impact on reading performance. However, as we noted above, Vellutino did not

## Visual processing deficits

include any speeded performance measures. The analysis of the RT data (for correct responses only) showed that, even after controlling for SRT, the children in the Low RAN groups were still taking longer to make their decisions about the identity of the pairs of stimuli. These data suggest that a characteristic of this group was that, though they were just as accurate in discriminating between stimuli composed of single basic visual features, they required significantly longer (on average 115 ms) to make that decision after controlling for differences in SRT. The children in the Low RAN groups had been selected because they had a significant deficit in RAN performance. These results suggest that over and above a general speed deficit, these children had a particular problem with speeded discrimination, which could possibly result from a deficit in this aspect of visual perception.

A two-way ANOVA was carried out on the accuracy data for experiment 2(b) (letter-like forms), with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There were no main effects of Group or Year and no interaction, all  $F_s$  (1,150) < 1, ns.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate and mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was a main effect of Group,  $F(1,149) = 4.37$ ,  $p = .04$ ,  $\eta^2 = .038$ . The children in the Low RAN groups were significantly slower to make a decision about the letter-like forms even after controlling for their slower simple reaction time performance. There was a marginally significant main effect of Year,  $F(1,149) = 3.71$ ,  $p = .056$ ,  $\eta^2 = .024$ . There was a tendency for Year 4 children to be slower than Year 5 children. There was no significant interaction,  $F(1,149) < 1$ , ns.

## Visual processing deficits

A further ANCOVA was carried out on these data with RTs for experiment 2(a) (simple visual features) added as a further covariate. When these data were added as a covariate, the effects of both Group and Year were no longer significant,  $F_s(1,148) = 0.63$  and  $= 1.57$  respectively. The adjusted means and standard errors are presented in table 4.

Table 4 about here

As with Experiment 2(a), there were no differences between the groups in their accuracy levels. However, when responding at speed the Low RAN groups were again significantly slower to discriminate this time between the more complex unfamiliar non-nameable stimuli than the control groups even after controlling for SRT. These results would again seem to confirm Kail's position. Nevertheless, when RTs for simple visual feature discrimination obtained from experiment 2(a) were entered as a covariate there were no longer any significant differences between the groups. This suggests that the between group differences in discrimination between the more complex, non-nameable letter-like forms were accounted for by differences in discriminating between the stimuli composed of very basic visual features since the group differences on the more complex measure became non significant when visual feature discrimination speed was covaried.

A further two-way ANOVA was carried out on the accuracy data for experiment 2(c), with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There was no main effect of Group or Year,  $F_s(1,150) = .001$  and  $1.114$ , ns, and no interaction,  $F(1,150) = .694$ , ns.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate and mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was a main effect of



## Visual processing deficits

Group,  $F(1,149) = 7.65$ ,  $p = .006$ ,  $\eta^2 = 0.049$ . The Low RAN groups were significantly slower to make a decision about the letters even after controlling for their slower simple reaction time performance. There was no main effect of Year,  $F(1,149) = 1.92$ ,  $p > .05$ . There was no interaction,  $F(1,149) < 1$ , ns.

A further ANCOVA was carried out on these data with RTs for experiment 2(a) (simple visual features) added as a further covariate. When these data were added as a covariate, the difference between the groups was no longer significant,  $F(1,148) = 1.14$ , ns.

The accuracy data showed that there were no group or age differences when judging whether two letters were the same or different. These data suggest that the differences between the groups in their performance on the RAN task were not due to a priori differences in letter identification per se. Given that these children were in either their fourth or fifth year of reading instruction and had not been identified as having any specific problem this is not a surprising finding. The letters were familiar nameable stimuli. Nevertheless, as with the results from the earlier parts of the experiment, the Low RAN groups were significantly slower to judge whether the two letters were the same or different. However, again this difference was no longer significant when the RT performance for experiment 2(a) was controlled for. These results suggest that the Low RAN children do have a difficulty in discriminating between the basic visual features which make up letters which is not accentuated by added complexity nor compensated for by familiarity or nameability.

## Further analyses

As will be noted from table 1, though the Low RAN children were in mainstream schools and not identified as having any specific problems with reading, nevertheless their mean word reading was significantly poorer than that of the control group. Therefore it remains a possibility

## Visual processing deficits

that their slowness in discriminating between simple visual features might be the result of their poorer word reading. We therefore decided to conduct a further two way ANCOVA with SRT and BAS word reading raw scores as the covariates and the RTs for experiment 2(a) (simple visual feature discrimination) as the dependent variable. The adjusted mean RTs and standard errors after controlling for BAS word reading performance are shown in table 5.

Table 5 about here

There was a main effect of group after controlling for SRT and BAS word reading,  $F(1,148) = 7.53, p = .007, \eta^2 = .074$ .

This analysis suggests that the Low RAN groups had a significant specific weakness in processing the non-nameable visual features of which letters are composed, which is not accounted for by differences in their reading ability.

### Experiment 3: Letter-like shapes same/different judgment task with memory component

This experiment was designed to investigate whether there was an extra cost to the Low RAN children if a memory component was added to the discrimination task.

#### Participants.



The participants were the same as for the previous experiments.

#### Materials and measures

The materials and measures were the same as for experiment 2b and involved the identical 42 stimulus pairs for the ‘same’ trials, involving six pairs of each of the seven letter-like forms, and 42 stimulus pairs for the ‘different’ trials, involving each combination of all forms, with each combination occurring twice to allow for both possible sequential ordering of each pair.

## Visual processing deficits

### Procedure

This experiment involved the sequential presentation of the same 82 pairs of letter-like forms that were used in experiment 2(b), and required the children to decide whether each pair of letter-like forms were the same or different. The children saw a welcome screen with the instructions “You are about to see a screen with 1 picture on it like this: , followed by a screen like this: #####, followed by a screen like this . Press blue if the two pictures are exactly the same. Press red if the two pictures are different”. The experimenter determined that the children understood the task and pointed out that to be considered the same, the pictures had to be not just the same shape, but also pointing in the same direction. There were ten practice trials, each of which were followed by encouraging corrective feedback, followed by 4 blocks of 21 experimental trials, with feedback (percent correct and mean reaction time) given at the end of each block. Each trial began with a fixation point which stayed on the screen for 500ms. The first of the stimulus pair then appeared on the screen for a duration of 1000ms, and was then replaced by a pattern mask of ##### for a further 1000ms. Then the second of the stimulus pair was displayed and remained on the screen until the child made a key press. As before red was for a “same” response and blue was for a “different” response. In order to control for order effects, both possible orders for each stimulus pairing were presented. RT and accuracy measures were recorded.

### Results and discussion

The mean accuracy and RT scores are given in table 6. This table includes the adjusted means after controlling for simple reaction time scores and also after controlling for both SRT (experiment 1) and simple visual feature discrimination RT scores from experiment 2(a).

Table 6 about here

## Visual processing deficits

A two-way ANOVA was carried out on the accuracy data, with Group and Year as between-group factors, and proportion correct responses as the dependent variable. There was no main effect of Group,  $F(1,150) = 1.93$ , ns. There was a significant main effect of Year,  $F(1,150) = 4.24$ ,  $p = 0.04$ . There was no significant Group by Year interaction.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors, SRT as the covariate and mean RTs for the correct responses as the dependent variable. Analysis revealed that after controlling for SRT there was a main effect of Group,  $F(1,149) = 10.50$ ,  $p < .001$ ,  $\eta^2 = .066$ . The Low RAN groups were significantly slower to make a decision about the letter-like forms even after controlling for their slower simple reaction time performance. There was no main effect of Year,  $F(1,149) = 2.17$ ,  $p > .05$ . There was no interaction,  $F(1,149) < 1$ , ns.

A further ANCOVA was carried out on these data with RTs for experiment 2(a) (simple visual feature discrimination) added as a further covariate. When these data were added as a covariate, the differences between the groups were no longer significant,  $F(1,148) = 2.39$ , ns.

The accuracy data again showed no significant differences between groups for this task. However, there was a main effect of year group. The younger groups made on average two more errors than the older groups. These results reflect an expected modest rise in immediate memory efficiency due to age but do not indicate that the performance of the Low RAN groups was compromised by specific limitations in visual short term memory. The group differences in RTs, which were again not significant when controlling for RTs in experiment 2(a), reflect and confirm the findings from parts (b) and (c).

## Experiment 4 Auditory Reaction time

## Visual processing deficits

All the experiments in this study reported so far involved performance when making judgments about visual stimuli. Our analyses led us to conclude that the Low RAN groups showed a consistent speed of decision deficit relative to the control children even when controlling for simple reaction time and word reading accuracy. However, it could be argued, as Kail has done, that poor performance on RAN tasks relates to a general speed of processing deficit. We therefore decided to investigate whether the general group differences we had seen in the visual simple reaction time experiment generalized to the auditory modality. To do this we designed an auditory simple reaction time experiment and an auditory same/different judgment experiment using non linguistic sounds generated by the computer. Non linguistic auditory stimuli were chosen to be appropriate analogs for the very basic visual stimuli used in experimental 2(a) and ensured that no semantic elements would be involved in the responses.

### Experiment 4(a) Auditory simple reaction time

#### Participants

The same children participated in these experiments, which were carried out while the children were in the spring term of Year 4 and 5 of primary school. One child from the older control group was not available to complete this task.

#### Materials and measures

A computerized test of auditory simple reaction time was developed using E-prime experiment software (Schneider et al. 2002). A Dell Latitude D800 laptop computer with an Intel Pentium processor (1400 MHz) and a 15" color screen were used to present the task. Six different non-linguistic sounds were used as test stimuli.

#### Procedure

## Visual processing deficits

The procedure was analogous to that of visual reaction time task (experiment 1). The participants were told that this task involved sounds. They would see a welcome screen and sounds would be played via the computer. The instructions were “Hello, when you hear one of these sounds [6 in all] press the space bar as quickly as you can.” After ensuring that the child understood the instructions, the experimenter initiated a block of 6 practice trials followed by 2 blocks of experimental trials. For both practice and experimental blocks, each trial began with the presentation of a black fixation cross in the centre of a white screen. The non-linguistic sound was presented in random order, with lags of either 300, 600 or 900 ms, selected randomly, between fixation and presentation of the sound.

### Results and discussion

The mean auditory RTs are given in table 7.

Table 7 about here

A two-way ANOVA was carried out on the data, with Group and Year as between-group factors, and mean response time as the dependent variable. There was no main effect of Group or Year,  $F_s(1,149) = .49$  and  $2.21$ , ns, and no interaction,  $F(1,149) = 1.79$ , ns.

These results led us to conclude that the speed deficit we had observed in the visual tasks did not generalize to the auditory modality. In the light of these data we would argue that, contrary to Kail’s position, poor performance on RAN tasks is not simply an index of a general speed of processing deficit. From the data presented here, the children who were identified as having a RAN deficit only showed a speed deficit when responding to visual stimuli but not when responding to auditory stimuli.

Experiment 4(b) Auditory same/different judgment task

## Visual processing deficits

Having established that the Low RAN children did not show significantly slower auditory RTs than the control children, we had to further address the possibility that they were generally slower to make a same/different judgment than the control children regardless of modality. In order to investigate this we developed an auditory analog of the visual simple features task (experiment 2(a)). The stimuli selected were computer-generated tones with no semantic element, which varied in frequency, as described below.

### Method

#### Materials

The stimuli for this experiment were non-speech tones presented through headphones with a 1000Hz stimulus as the base tone and stimuli of 1015, 1017, 1019, 1021, 1023, 1025, 1027, 1029, 1031, 1033 Hz as the comparison tones

#### Procedure

The procedure was analogous to that of experiment 2(a) but with the pairs of stimuli being presented sequentially. Each stimulus pair started with a base tone of 1000HZ that lasted for 300 ms. This was followed by an inter-stimulus gap of 300 ms before the 2nd tone, which also had a duration of 300 ms, was presented. The second tone was either the same as the base (1000 Hz) or it differed in frequency in various increments. In order to identify a suitable level of difficulty, pilot work was carried out to find the most appropriate comparison tones. As with the visual experiments, the children pressed the blue key if they thought the 2 tones were the same and the red key, if different, though this was again reversed for left-handers.

### Results and discussion

The mean proportion correct responses and the response times to correct responses are given in table 8.

## Visual processing deficits

Table 8 about here

A two-way ANOVA was carried out on the data, with Group and Year as between-group factors, and proportion of total responses that were correct as the dependent variable. There were no significant main effects of Group or Year,  $F_s(1,149) < 1$ , ns. There were no significant interactions.

A two-way ANCOVA was carried out on the RT data, with Group and Year as the between-group factors and auditory SRT as the covariate. In the RT analysis there were also no significant main effects of Group or Year,  $F_s(1,148) = 3.17$ , ns and  $< 1$ , ns. There were no significant interactions.

These results suggest that the Low RAN children may not differ from the control children in their accuracy or speed to make a decision per se. They did not appear to have a deficit in their speed of response to stimuli presented in the auditory modality, unlike their slower responding to analogous tasks in the visual modality. These findings should be treated with caution because in order to identify sufficient participants for the Low RAN groups and appropriately matched members of the control groups we used the cut-off point of below minus one standard deviation below the mean for RAN and above minus one standard deviation below the mean for phonological awareness. A buffer zone between the experimental and control groups would have added strength to this no difference finding. However, this would have meant at least doubling the screening population.

### Regression of RAN, SRT and visual feature discrimination on word reading

Having established that the Low RAN groups were significantly slower than controls to make visual discriminations, our final aim was to examine more generally the degree to which



## Visual processing deficits

performance on our visual discrimination task predicted word reading, and whether visual discrimination, along with SRT, mediated the relationship between RAN and reading in our sample. To do this we conducted a hierarchical regression analysis.

Table 9 about here

Table 9 shows the correlations between the variables, the unstandardized regression coefficients (B), the standardized regression coefficients ( $\beta$ ), change in  $R^2$  after each variable was entered into the regression analysis as a separate step, and  $R$ ,  $R^2$  and adjusted  $R^2$  after entry of all three independent variables. After step 1, with SRT in the equation,  $R^2 = .16$ ,  $F_{inc}(1, 152) = 2.434$ , NS. After step 2, with visual discrimination added to the equation,  $R^2 = .040$ ,  $F_{inc}(1, 151) = 3.891$ ,  $p < .05$ . The addition of visual discrimination resulted in a significant increment in  $R^2$ . After the final step with RAN added to the equation,  $R^2 = .230$ ,  $F_{inc}(1, 150)$ ,  $p < .001$ . Addition of RAN to the equation resulted in a significant increment in  $R^2$ . Visual discrimination was no longer significant in the final regression equation.

To summarize, simple reaction time did not predict unique variance in word reading, though interestingly, performance on the visual discrimination task did at step 2 in the equation. Furthermore when entered last into the regression, RAN still predicted unique variance in word reading, suggesting that the relationship between RAN and reading is not entirely mediated by simple reaction time and performance on the visual discrimination task, but involves a large number of other possible processes which also need to be dissected out carefully in order to be understood.

These data show that the contribution of RAN performance to word reading is indexing more than just speed.

## Discussion

The data from this series of experiments provide compelling evidence of a deficit in speed of discriminating simple visual features in children with slow rapid automatized naming. This deficit cannot be accounted for by differences in general speed of processing, because 1) the difference between the Low RAN and control groups remained when differences in simple visual reaction time were controlled for and 2) no differences in speed of processing were found in the auditory modality. Thus the speed of processing deficit was specific to the visual modality in the tasks we administered<sup>1</sup>. Nor can the deficit be accounted for by differences in reading ability because the between group differences in speed of visual feature discrimination persisted when differences in reading ability were controlled. Neither does it appear to result from a general slowness in discrimination because no significant between group differences were found in an auditory discrimination task.

Differences in speed of letter identification were no longer significant once visual feature discrimination speed was controlled suggesting that any differences in speed of letter identification could be explained by the deficit in visual feature processing speed. This is an important new finding, which might have implications for the ease with which young children learn to identify letters: letter knowledge is consistently one of the strongest predictors of early reading skill. However, it is not just letter knowledge that is an important predictor of word reading skills; so is phonemic awareness. Both these combine to support knowledge of grapheme-phoneme correspondences. This possible deficit in the speed of letter identification, potentially related to early visual discrimination deficits, may inhibit the ability to map the letter-sound correspondences in the early stages of learning to read. This deficit might also

---

<sup>1</sup> Following a suggestion by a reviewer we checked whether the RAN effect remained after also controlling for the nonsignificant auditory RT differences. This was the case  $F(1, 147) = 9.375, p < .01$

## Visual processing deficits

subsequently affect the ease with which children set up representations of words in the orthographic lexicon. This argument is compatible with that of Willows et al. (1993). Both these proposals require further investigation.

For example, Breznitz (2002) suggested that children with deficits in RAN performance take a sequential approach to processing the letters in words which impacts negatively on the speed with which they can integrate the individual letters into an orthographic unit. This proposal depended on findings from ERP data that the latencies of both P200 and P300 components were slower in auditory-phonological tasks than visual-orthographic tasks in both typically and atypically developing child readers of Hebrew, with the latency difference significantly more pronounced in the children with dyslexia. This led Breznitz to propose that in children with dyslexia visual information has already deteriorated by the time auditory information is available to the system, leading to an impairment in the cross modal integration necessary for word recognition. Their findings were not inconsistent with earlier work with adults by Holmes and Ng (1993) who reported that poor spellers showed inefficient processing related to orthographically structured stimuli. However, recently Moll, Fussenegger, Wilburger and Landerl (2009) challenged the view that the RAN-reading association is mediated by orthographic processing. Their argument depends on the finding that once nonword reading fluency was entered into regression analysis, the relationship between RAN and word reading fluency was no longer significant. This suggests that it may be the early visual processing of orthography (a necessary stage in both word and nonword reading) which is impaired in children with slow RAN. Our findings that performance on the visual discrimination task predicted unique variance in word reading, over and above any variance due to simple reaction time are consistent with Moll et al.'s account. However, this finding should be treated cautiously,

## Visual processing deficits

because the proportion of the variance in reading accounted for by performance on the discrimination task, while significant, was extremely small (see table 9). In addition, the contribution of visual discrimination to word reading was no longer significant after RAN was entered into the equation, indicating that visual discrimination and RAN share common variance in the prediction of word reading.

It is important that other possible component processes be identified and investigated in order properly to understand the relationship between RAN and reading. Furthermore, our results cannot answer questions about causality: at least two causal accounts are feasible. One possibility is that an early problem with visual discrimination leads to deficits in learning to identify and discriminate letters when first learning to read. On the other hand, it could be that early experiences with letters drive visual discrimination ability, particularly of the kind of abstract visual stimuli of which letters are formed and which were utilized in the current research. Further, longitudinal research is necessary to resolve this issue.

An additional issue that should be investigated is the possibility that a visual discrimination problem occurring very early on in the children's educational lives may have resolved by the time children reach the age of our sample, and thus while visual discrimination problems per se are no longer evidenced to any substantial degree, the consequences of early difficulties may be seen in the children's performance on other letter and reading-related tasks. Again, further longitudinal research is required fully to address this possibility.

The results of our experiments also point to the importance of measuring speed as well as accuracy when investigating component processes of word reading skill, as no group differences in accuracy were found in any of the experiments reported here. As we commented above, a weakness of Vellutino's conclusion that there is not a visuo-perceptual deficit in dyslexia related

## Visual processing deficits

to the lack of any measurement of response times. Clearly this study did not investigate performance of children with dyslexia so we can make no claims about such children's performance.

Investigation of the processes involved in identifying letters is a promising area for further work to elucidate the relationship between slow RAN and word reading skill. In this connection Brundson, Coltheart and Nickels (2006) present a useful and detailed letter processing framework in which initial visual analysis gives sequential access to two levels of abstract letter identification comprising separable font-free representations and case-free representations. This is the level of detail necessary to design experimental investigations of processes involved in slow RAN letter performance which appear to impact on the development of word reading skills.

This study began investigating the relation between possible visual processing deficits and RAN performance when the participants had received a minimum of two years reading instruction. They were therefore no longer novice readers. To understand fully the direction of causality between these various skills there is a need for much wider longitudinal studies, which would enable an investigation of RAN performance and visual processing before reading instruction. At such a point performance on color and object naming would have to be included. Furthermore, though the participants were making good progress in their word reading skills, word reading accuracy was the only measure used in this study. Since speed has been identified as an important factor, it might be interesting to investigate the contribution of word reading speed as well as accuracy and additionally to study the contribution of these processes to comprehension of written texts. Verification of a role for early visual discrimination difficulties

Visual processing deficits

in later reading, not only at the single word but also the text level, would have important theoretical and educational implications.

#### Acknowledgements

The research described in this paper was supported by ESRC grant number RES-000-23-0699.

We thank the participants and their teachers for enabling us to conduct this research.

#### References

- Ackerman, P. T., & Dykman, R. A. (1993). Phonological processes, confrontation naming and immediate memory in dyslexia. *Journal of Learning Disabilities, 26*, 597-690.
- Bach, M. (1996). The “Freiburg visual acuity test”: automatic measurement of visual acuity. *Optometry and Vision Science, 73*, 49-53.
- Badian, N. A. (1993). Phonemic awareness, naming, visual symbol processing, and reading. *Reading and Writing: an Interdisciplinary Journal, 5*, 87-100.
- Badian, N. A. (1994). Preschool prediction: Orthographic and phonological skills and reading. *Annals of Dyslexia, 44*, 3-25.
- Bender, L. A. (1938). *Visual-motor gestalt test and its clinical use*. Research monograph no. 3, New York: American Orthopsychiatric Association.
- Blachman, B. A. (1984). Relationship of rapid naming ability and language analysis skills to kindergarten and first-grade reading achievement. *Journal of Educational Psychology, 76*, 610-622.
- Bosse, M-L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition, 104*, 198-230.

## Visual processing deficits

- Bowers, P. G. (1995). Tracing symbol naming speed's unique contributions to reading disabilities over time. *Reading and Writing: an Interdisciplinary Journal*, 7, 189-216.
- Bowers, P. G. & Newby-Clark, E. (2002). The Role of Naming Speed within a Model of Reading Acquisition. *Reading and Writing: An Interdisciplinary Journal*, 15, 109-26.
- Bowers, P. G., Steffy, R., & Tate, E. (1998). Comparison of the effects of IQ control methods on memory and naming speed predictors of reading disability. *Reading Research Quarterly*, 23, 304-309.
- Bowers, P. G., & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing: An Interdisciplinary Journal*, 5, 69-85.
- Breznitz, Z. (2002). Asynchrony of visual-orthographic and auditory-phonological word recognition processes: An underlying factor in dyslexia. *Reading and Writing: An Interdisciplinary Journal*, 15, 15-42.
- Brunsdon, R., Coltheart, M., & Nickels, L. (2006). Severe developmental letter-processing impairment: a treatment case study. *Cognitive Neuropsychology*, 23, 795-821.
- Clarke, P., Hulme, C., & Snowling, M. (2005). Individual differences in RAN and reading: a response timing analysis. *Journal of Research in Reading*, 28, 73-86.
- Cobbold, S., Passenger, T., & Terrell, C. (2003). Serial naming speed and the component elements of speech time and pause time: relationships with the development of word-level reading in children aged four to five years . *Journal of Research in Reading*, 26, 165-176.
- Denckla, M. B., & Rudel, R. G. (1974). Rapid 'automatized' naming of pictured objects, colors, letters and numbers by normal children. *Cortex*, 10, 186-202.

## Visual processing deficits

- Denckla, M. B., & Rudel, R. G. (1976). Rapid automatized naming (RAN) - Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, *14*, 471-479.
- Elliot, C. D., Murray, D. J., & Pearson, L. S. (1983). *British Ability Scales*. Windsor UK: NFER-Nelson.
- Felton, R. H., & Brown, I. S. (1990). Phonological processes as predictors of specific reading skills in children at risk for reading failure. *Reading and Writing: an Interdisciplinary Journal*, *2*, 39-59.
- Georgiou, G. K., Parrila, R., & Kirby, J. (2006). Rapid naming speed components and early reading acquisition. *Scientific Studies of Reading*, *10*, 199-220.
- Gibson, E. J., Gibson, J. J., Pick, A. D., & Osser, H. (1962). A developmental study of the discrimination of letter-like forms. *Journal of Comparative and Physiological Psychology*, *55*, 897-906.
- Hari, R., & Revall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trend in Cognitive Sciences*, *5*, 525-532.
- Holmes, V., & Ng, E. (1993). Word specific knowledge, word-recognition strategies, and spelling ability. *Journal of Memory and Language*, *32*, 230-257.
- Kail, R. (1991). Development of processing speed in childhood and adolescence. *Advances in Child Development and Behavior*, *23*, 151-185.
- Kail, R., & Hall, L. K. (1994). Processing speed, naming speed, and reading. *Developmental Psychology*, *30*, 949-954.
- Kail, R., Hall, L. K., & Caskey, B. J. (1999). Processing speed, exposure to print, and naming speed. *Applied Psycholinguistics*, *20*, 303-314.



## Visual processing deficits

- Lachmann, T., & van Leeuwen, C. (2007). Paradoxical enhancement of letter recognition in developmental dyslexia. *Developmental Neuropsychology, 3*, 61-77.
- Lovegrove, W., Martin, F. & Slaghuis, W. (1986). A theoretical and experimental case for a visual deficit in specific reading disability. *Cognitive Neuropsychology, 3*, 225-267.
- Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: Rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading, 3*, 129-157.
- McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception, 1: An account of basic findings. *Psychological Review, 88*, 375-407.
- Moll, K., Fussenegger, B., Willburger, E. & Landerl, K. (2009) RAN is not a measure of orthographic processing. Evidence from the asymmetric German orthography. *Scientific Studies of Reading, 13*, 1-25.
- Neuhaus, G., Foorman, B. R., Francis, D. J. & Carlson, C. D. (2001). Measures of information processing in Rapid Automated Naming (RAN) and their relation to reading. *Journal of Experimental Child Psychology, 78*, 359-373.
- Neuhaus, G. F., & Swank, P. R. (2002). Understanding the relations between RAN letter subtest components and word reading in first-grade students. *Journal of Learning Disabilities, 35*, 158-74.
- Powell, D., Stainthorp, R., Stuart, M., Garwood, H., & Quinlan, P. (2007). An experimental comparison between rival theories of Rapid Automated Naming (RAN) performance and its relationship to reading. *Journal of Experimental Child Psychology, 96*, 46-68.
- Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime User's Guide*. Pittsburgh: Psychology Software.

## Visual processing deficits

- Spring, C., & Capps, C. (1974). Encoding Speed, Rehearsal, and Probed Recall of Dyslexic Boys. *Journal of Educational Psychology, 66*, 780-786.
- Stein, J., & Walsh, V. (1997). To see but not to read: The magnocellular theory of dyslexia. *Trends in Neuroscience, 20*, 147-152.
- Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., & Hecht, S. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word-reading skills in second- to fifth-grade children. *Scientific Studies of Reading, 1*, 161-185.
- Vellutino, F. R. (1979). *Dyslexia: theory and research*. Cambridge, Mass.: MIT Press.
- Venezky, R. (1993). History of interest in the visual component of reading. In D. M. Willows, R. S. Kruk & E. Corcos (Eds.), *Visual processing in reading and reading disabilities*. (pp 3 – 30). Hillsdale NJ: Lawrence Erlbaum Associates
- Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*, 192-212.
- Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive test of phonological processing*. Austin, TX: PRO-ED.
- Wagner, R. K., Torgesen, J. K., Rashotte, C. A., Hecht, S. A., Barker, T. A., Burgess, S. R., et al. (1997). Changing relations between phonological processing abilities and word-level reading as children develop from beginning to skilled readers: a 5-year longitudinal study. *Developmental Psychology, 33*, 468-479.
- Wechsler, D. (1992). *Wechsler intelligence scale for children. 3<sup>rd</sup>. edition*. New York: Psychological Corporation.
- Willows, D. M., Kruk, R., & Corcos, E. (1993). Are there differences between disabled and normal readers in their processing of visual information? In D. M. Willows, R. Kruk & E.

## Visual processing deficits

Corcos (Eds.). *Visual Processing in Reading and Reading Disabilities*. Hillsdale, NJ.: Lawrence Erlbaum Publishers.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*, 415-438.

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities, 33*, 387-407.

Wolf, M., & Obregon, M. (1992). Early naming deficit, developmental dyslexia and a specific deficit hypothesis. *Brain and Language, 42*, 219-247.

Visual processing deficits

Table 1

Mean (and standard deviation) raw scores on Phonological Awareness (PA), Phonological Memory (PM) and RAN core subtests of the CTOPP, chronological age, scaled scores on the Block Design and Vocabulary subtests of the WISC III-R, and British Ability Scales (BAS) Word Reading standard scores and raw scores for Low RAN and Controls groups

	Younger (Year 4)		Older (Year 5)	
	Low RAN (n = 36)	Controls (n = 36)	Low RAN (n = 39)	Controls (n = 43)
PA (raw score)	20.285 (4.89)	20.47 (5.24)	20.41 (4.82)	19.93 (4.45)
PM (raw score)	18.92 (3.76)	18.86 (2.69)	20.51 (3.52)	20.14 (2.88)
RAN (raw score in ms)	117.07 (15.01)	78.67 (12.95)	102.79 (15.26)	70.74 (10.14)
Age at initial screening (Years 3 and 4)	7:12 (0:15)	7:21 (0:23)	8:22 (0:25)	8:20 (0:23)
WISC-III-R				
Block Design (s.s.)	9.06 (4.06)	8.69 (3.98)	9.15 (3.93)	8.40 (3.49)
Vocabulary (s.s.)	11.19 (3.47)	10.86 (3.21)	10.54 (3.56)	9.98 (3.04)
Visual acuity	16.33	17.97	18.50	16.93

Visual processing deficits

---

	(6.37)	(5.260	(5.07)	(4.16)
BAS Word Reading (s.s.)	118.42	135.56	134.15	149.46
	(32.04)	(26.43)	(30.41)	(26.62)
Range	58-172	69-188	49-199	72-184
BAS Word Reading (raw	52.64	62.72	61.67	70.44
scores)	(18.80)	(14.47)	(16.26)	(12.07)

---

## Visual processing deficits

Table 2

Mean (and standard deviation) reaction times (ms) for Experiment 1 (simple reaction time).

	Younger (Year 4)	Older (Year 5)
Low RAN	370.68 (77.40)	337.24 (58.57)
Control	341.33 (59.01)	323.64 (62.04)

Table 3

Mean (and standard deviation) accuracy scores (proportion correct), mean reaction times for correct responses (ms) and adjusted means (and standard errors) after controlling for simple reaction time (SRT) measures (Experiment 1) for Experiment 2 Same/different judgment task: (a) Simple Visual Features, (b) Letter-like forms and (c) Letters.

	Younger (Year 4)		Older (Year 5)	
	Low RAN	Control	Low RAN	Control
<b>Simple Visual Features</b>				
(Expt.2(a))				
Proportion correct	0.92 (0.06)	0.92 (0.06)	0.94 (0.04)	0.93 (0.06)
RTs to correct responses (ms)	1083.61 (262.79)	960.76 (208.47)	1002.87 (255.19)	856.87 (204.50)
Mean (SE) after controlling for SRT (Expt. 1) (ms)	1055.59 (38.21)	960.15 (37.35)	1007.77 (35.91)	875.46 (34.58)
<b>Letter-like forms (Expt. 2(b))</b>				
Proportion correct	0.92 (0.06)	0.92 (0.05)	0.91 (0.08)	0.93 (0.07)
RTs to correct responses (ms)	1120.12 (461.97)	980.56 (210.95)	985.86 (240.72)	897.40 (244.79)
RTs (SE) after controlling for SRT (ms)	1104.30 (51.33)	981.05 (50.17)	988.62 (48.24)	905.69 (46.45)
<b>Letters (Expt. 2(c))</b>				
Proportion correct	.94 (.05)	.94 (.03)	.93 (.06)	.93 (.07)
RTs to correct responses (ms)	938.69	959.20	1028.40	911.31

Visual processing deficits

---

	(194.76)	(41.23)	(39.65)	(39.59)
RTs (SE) after controlling for				
SRT (ms)	921.45	855.33	895.79	798.65
	(30.71)	(30.01)	(28.86)	(27.79)

---



## Visual processing deficits

Table 4

Adjusted mean reaction times (and standard errors) for correct responses (ms) for visual discrimination of letter-like forms (Experiment 2(b)) and visual discrimination of letters (Experiment 2(c)) after controlling for simple reaction time (SRT), and RTs for discrimination of simple visual features (Experiment 2(a)).

	Younger (Year 4)		Older (Year 5)	
	Low RAN	Control	Low RAN	Control
<b>Letter-like forms</b>				
RTs (SE) after controlling for				
SRT and RTs for Expt.2(a) (ms)	1054.83	987.32	967.08	961.42
	(47.14)	(45.34)	(43.74)	(43.03)
<b>Letters</b>				
RTs (SE) after controlling for				
SRT and RTs for Expt. 2(a) (ms)	1023.67	965.93	1003.01	961.90
	(32.76)	(31.51)	(30.40)	(29.90)

## Visual processing deficits

Table 5

Adjusted mean (and standard errors) reaction times for Experiment 2(a) after controlling for simple reaction time (SRT) and British Ability Scales (BAS) Word Reading raw scores.

	Younger (Year 4)		Older (Year 5)	
	Low RAN	Controls	Low RAN	Controls
RTs (SE) after controlling for SRT and	1046.91	960.57	1007.19	882.89
BAS word reading	(39.85)	(37.40)	(35.97)	(35.91)

Visual processing deficits

Table 6

Mean (and standard deviation) accuracy scores (proportion correct), adjusted mean reaction times (and standard errors) for correct responses (ms) for visual discrimination of letter-like forms with a memory component (Experiment 3) (after controlling for simple reaction time (SRT) (Experiment 1) and adjusted means (and standard errors) after controlling for SRT and RTs for discrimination of simple visual features (Experiment 2(a)).

	Year 4		Year 5	
	Low RAN	Control	Low RAN	Control
Proportion correct	.87	.88	.88	.90
	(.09)	(.06)	(.07)	(.06)
RTs to correct responses (ms)	1103.51	957.57	1026.66	880.61
	(242.21)	(243.36)	(277.19)	(241.84)
RTs (SE) after controlling for SRT (Expt.1) (ms)	1085.29	958.13	1029.85	892.50
	(42.48)	(41.52)	(39.92)	(38.44)
RTs (SE) after controlling for SRT and RTs for Expt. 2(a) (ms)	1023.67	965.93	1003.01	961.90
	(32.76)	(31.51)	(30.40)	(29.90)

Visual processing deficits

Table 7

Mean (and standard deviation) reaction times (ms) for the auditory reaction time task

(Experiment 4a) .

	Younger (Year 4)	Older (Year 5)
Low RAN	554.16 (257.46)	466.73 (170.59)
Control	490.98 (152.77)	486.32 (171.30)

## Visual processing deficits

Table 8

Mean (and standard deviation) accuracy scores (proportion correct) and adjusted mean reaction times for correct responses (ms) (and standard errors) for the auditory same/different judgment task (Experiment 4b) after controlling for auditory simple RT (Experiment 4a).

	Younger (Year 4)		Older (Year 5)	
	Low RAN	Control	Low RAN	Control
Proportion correct	.67	.70	.72	.68
	(.17)	(.18)	(.18)	(.20)
RTs for correct responses	1649.90	1550.58	1628.27	1536.90
	(55.56)	(55.01)	(53.03)	(50.95)

Visual processing deficits

Table 9

Hierarchical regression analysis of simple reaction time (SRT), visual discrimination, and RAN on British Ability Scales (BAS) word reading showing first order correlations between all variables, standardized and unstandardized coefficients (at the final step), and change in  $R^2$  as well as  $R$ ,  $R^2$  and adjusted  $R^2$  (at the final step).

Variables	BAS reading (DV)	SRT	Vis discrim	B	SE B	$\beta$ at entry	$\beta$ (in final regression equation)	$\Delta R^2$
SRT (entered at step 1)	-.126			.001	.019	.005		.16
Vis Discrim (entered at step 2)	-.190*	.329***		-.001	.005	-.167*	-.017	.025*
RAN	-.479***	.264**	.369***	-.341	.056	-.475		.190***

## Visual processing deficits

(entered at  
step 3)

$R^2$  = .230

Adjusted  $R^2$  = .215

R = .480

---

SRT = Simple Reaction Time

Vis discrim = visual discrimination task

B = unstandardized beta

SE B = standard error of beta

$\beta$  = standardized beta

$\Delta R^2$  = change in  $R^2$

\*  $p < .05$

\*\*  $p < .01$

Visual processing deficits

\*\*\* $p < .001$



## Visual processing deficits

## Visual processing deficits

Figure 1. Wolf, Bowers and Biddle (2000).

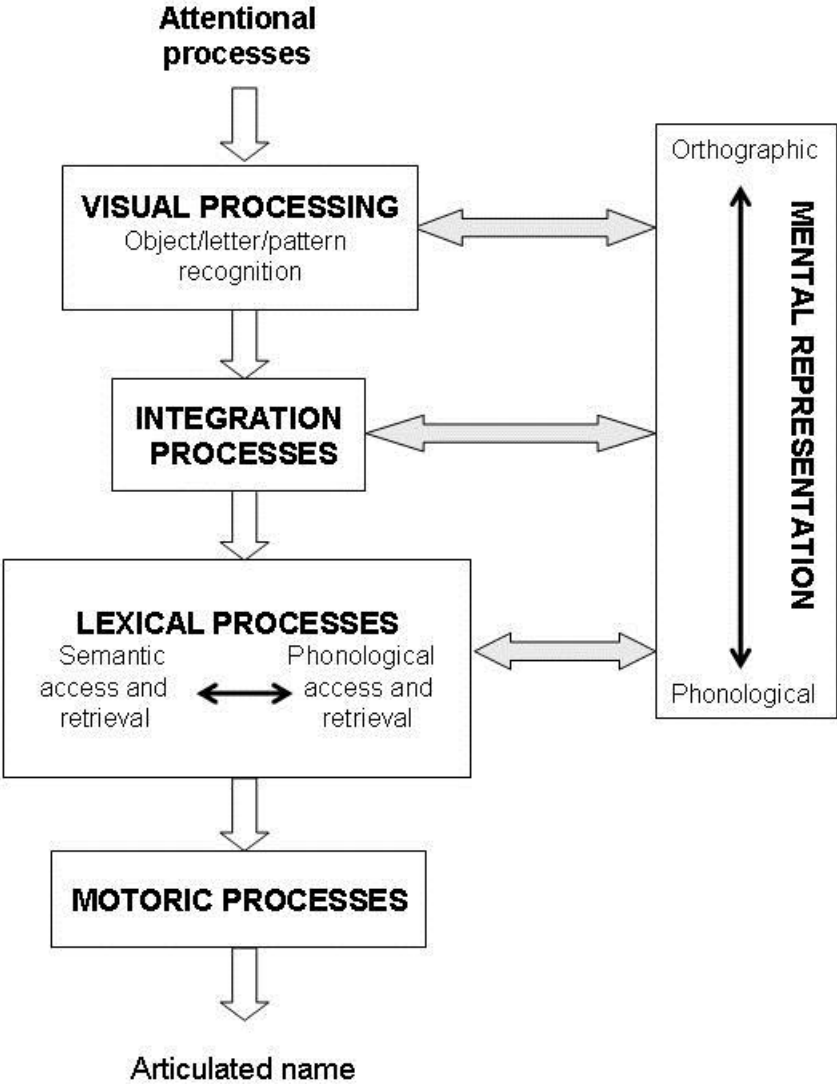
Figure 2. RAN processes compared with the DRC model.

Figure 3. Simple visual features stimuli used in experiment 2(a).

Figure 4. Letter-like form stimuli used in experiments 2(b) and 3 (from Gibson et al., 1962).

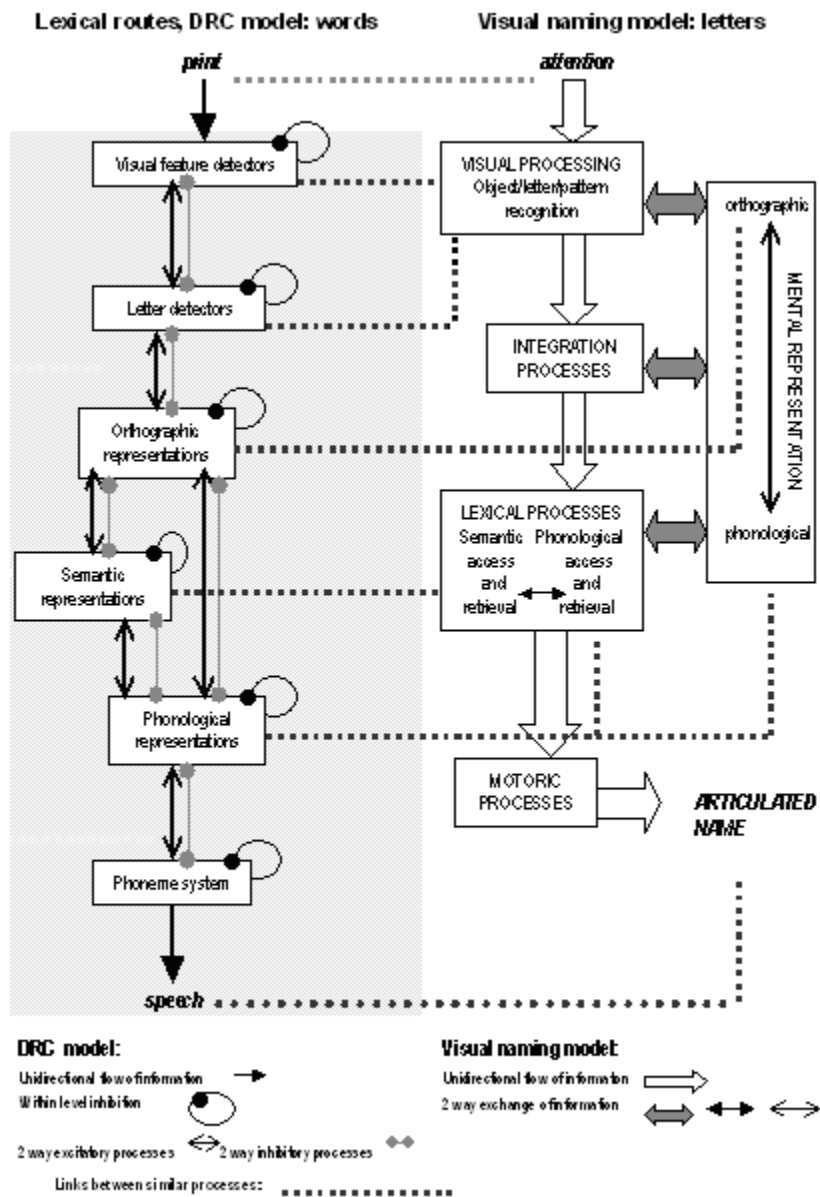
Figure 1

Letter stimulus to be named



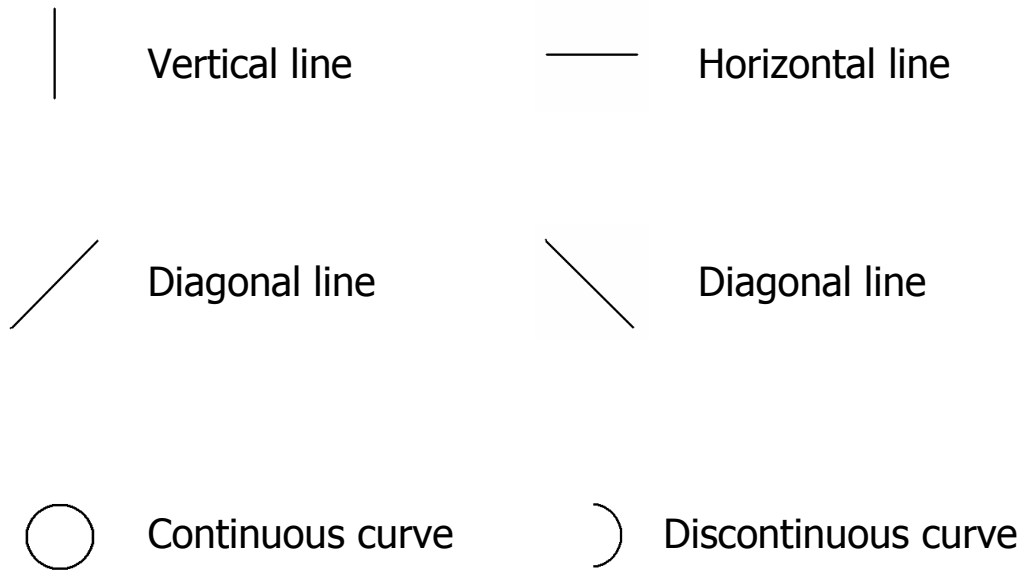
# Visual processing deficits

Figure 2



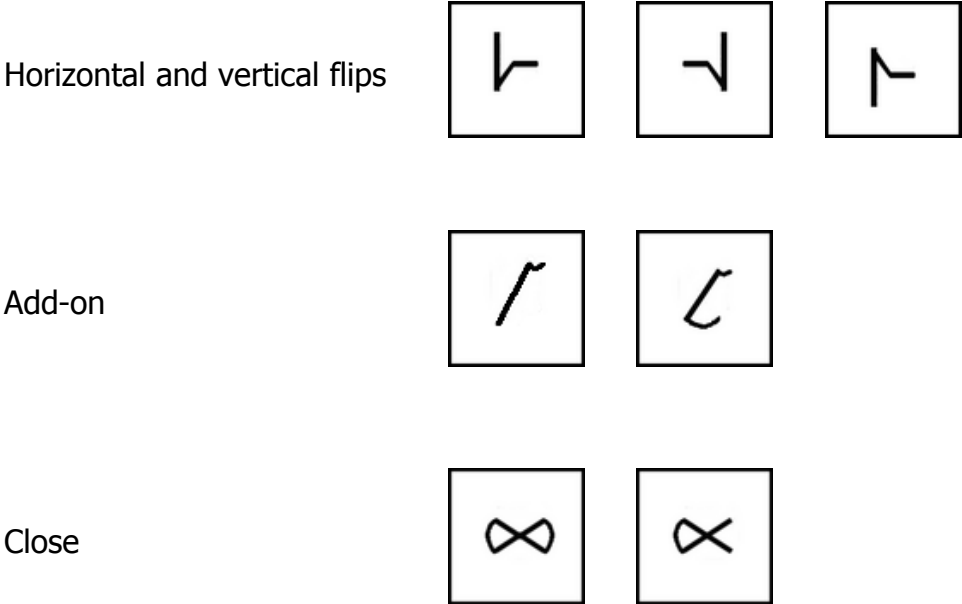
Visual processing deficits

Figure 3



Visual processing deficits

Figure 4



## Visual processing deficits