Motion Detection, Letter Position Encoding, and Single Word Reading

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Recent research has shown that many people with dyslexia find it unusually difficult to detect flickering or moving visual stimuli, consistent with impaired processing in the magnocellular visual stream. Nonetheless, it remains controversial to suggest that reduced visual sensitivity of this kind might affect reading. We first show that the accuracy of letter position encoding may depend on input from the magnocellular pathway. We then suggest that when children read, impaired magnocellular function may degrade information about where letters are positioned with respect to each other, leading to reading errors which contain sounds not represented in the printed word. We call these orthographically inconsistent nonsense errors letter errors. In an unselected sample of primary school children, we show that the probability of children making "letter" errors in a single word reading task was best explained by independent contributions from motion detection (magnocellular function) and phonological awareness (assessed by a spoonerism task). This result held even when controlling for chronological age, reading ability, and IQ. Together, these findings suggest that impaired magnocellular visual function, as well as phonological deficits, may affect reading.

INTRODUCTION

Despite adequate educational opportunity and intellectual ability, somewhere between 3 and 15 percent of children fail to acquire competent reading skills (Rutter and Yule 1975). Such children are commonly described as having developmental dyslexia. Given that reading requires a rapid association of visual with linguistic information, it is natural to ask whether problems with either visual or language processing could cause these individuals' reading difficulties.

As far as language is concerned, two decades of research have firmly established that the poor reading of people with dyslexia is often correlated with phonological problems. Typically, their phonological difficulties are revealed by poor performance in a variety of phonological awareness tasks such as rhyme detection ("mat" is the odd man out in the sequence "mat", "had", "sad", "bad"), phoneme counting ("cat" has 3 phonemes: /k/, /æ/, and /t/), and phoneme deletion (saying "flin" without the /f/). This is thought to be due to "fuzzy" or underspecified phonological representations which lead to difficulties with mapping letters onto sounds (Bradley and Bryant 1983; Brady and Shankweiler 1991), and cause people with dyslexia to be extremely slow and inaccurate readers. Reading nonsense words aloud, where successful decoding depends on the use of letter-to-sound correspondence rules, is an extremely good demonstration of the weaknesses experienced by people with dyslexia (Snowling 1980).

Recent research has shown that many dyslexic individuals also may have specific and subtle visual problems. They find it unusually difficult to detect flickering or moving visual stimuli. This finding has been replicated in a variety of ways including psychophysical and electrophysiological techniques, as well as functional brain imaging (Martin and Lovegrove 1987; Brannan and Williams 1988; Mason, Cornelissen, Fowler, and Stein 1993; Waltherm, Iler 1995; Cornelissen, Richardson, Mason, and Stein 1995; Lehmkuhle, Garzia, Turner, Hash, and Baro 1993; Livingstone, Rosen, Drislane, and Galaburda 1991; Eden, VanMeter, Rumsey, Maisog, Woods, and Zeffiro 1996). To illustrate this phenomenon, figure 1 shows a diagrammatic representation of the kind of visual stimulus used to measure motion sensitivity. It is called a random dot kinematogram (RDK).

In this example, movement of the dots in the left-hand panel is random, similar to the snow storm on a "detuned" television screen. In the right-hand panel, half of the dots move randomly
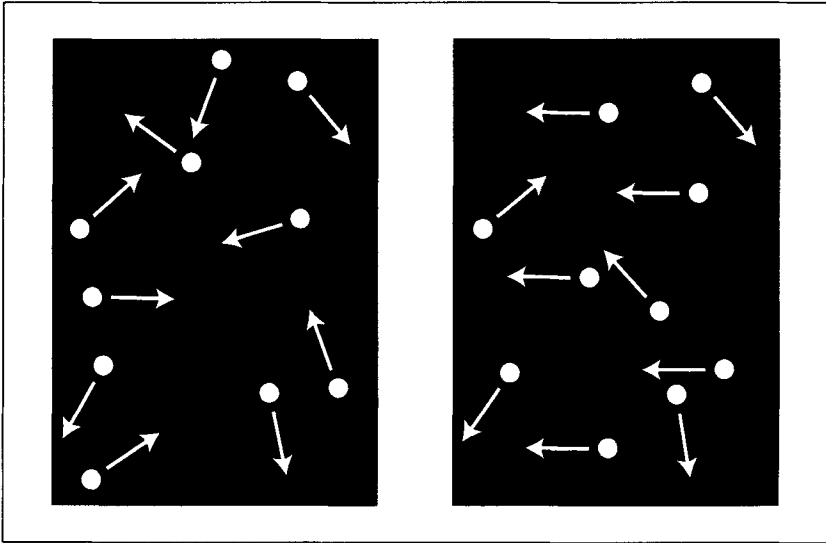
Figure 1. A diagrammatic representation of both patches of a coherent motion stimulus. Note that in reality, there might be as many as 300 dots per patch. Note also that each dot lives for only two consecutive animation frames. The arrows indicate the direction and extent of the movement of each dot from one animation frame to the next. In this example, the right-hand patch contains coherent movement toward the left of the page.

and half move in one direction. The presence of these so-called "coherent" dots induces the perception of global movement to the left. An important feature of RDKs is that each dot only stays on the screen for a very short time. Consequently, the viewer cannot detect which patch contains global motion simply by concentrating on just one or two dots on the screen. Instead, the visual system must integrate the local motion vectors of a much larger number of dots over two or more animation frames before the perception of global motion emerges (Smith and Snowden 1994).

In a previous study (Cornelissen et al. 1995), we used RDKs to measure motion sensitivity, both in people with dyslexia and in a nondyslexic comparison group of the same age. In that study, percentage coherence was systematically varied over a large number of trials. The goal was to find the minimum coherence necessary for individuals to be able to detect the presence of global motion (a higher coherence "threshold" indicates worse motion detection). Figure 2 shows the distributions of coherent motion thresholds in the samples of
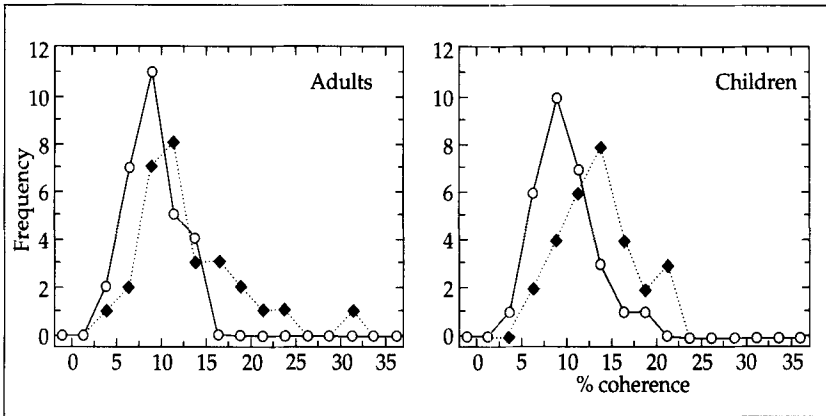
*Figure 2.   The frequency distributions for coherent motion thresholds
in 29 dyslexic adults (mean age 29:0), 29 dyslexic children
(mean age 9:11), 29 age-matched control adults (mean age
28:10), and 29 age-matched control children (mean age
9:9). In each plot, normal readers are represented by solid
lines with open circles. Dyslexic readers are represented
by dashed lines with solid diamonds.*

children and adults who have dyslexia together with the non-
dyslexic comparison groups. In both samples, the dyslexic in-
dividuals found it significantly harder to detect motion than
the nondyslexic individuals.

A MAGNOCELLULAR VISUAL DEFICIT IN
DEVELOPMENTAL DYSLEXIA?

One way to interpret results like these is to compare them with
behavioral studies of macaque monkeys with specific lesions to
the magno- or parvocellular visual pathways. The macaque
brain has similar neuroanatomical structures and is thought to
be sufficiently closely related to the human brain to justify ap-
plying anatomical and electrophysiological data from that
species to human vision.

In both macaques and humans, the visual information con-
tained in the output of the retina is derived from two kinds of gan-
glion cell: M cells and P cells. En route to the cortex, the axons of M
and P cells target the magnocellular and parvocellular layers of the
lateral geniculate nucleus (LGN) of the thalamus. At this subcorti-
cal stage of processing, information derived from M and P cells is
strictly segregated. Livingstone and colleagues made histological

comparisons of the LGN from five dyslexic and five normal brains (Livingstone et al. 1991). The study revealed that the ventral, magnocellular layers of the LGN (mLGN) from the dyslexic brains contained fewer, smaller cells than did the comparable layers in the normal brains. By contrast, no group differences were found in the cell sizes of the parvocellular layers of the LGN (pLGN). These findings suggested the existence of an anatomical abnormality of mLGN in people who have dyslexia. Further support is provided by the fact that lesions to mLGN (but not pLGN) cause motion-blindness in macaques (Schiller, Logothetis, and Charles 1990). When combined, these results suggest that the reduced motion sensitivity of people with dyslexia could be explained by a magnocellular system deficit which originates subcortically.

Whereas the anatomical segregation of magno- and parvo-streams from the LGN is maintained only as far as the input layers of the primary visual cortex (V1), the responses of cells beyond this point reflect the fact that information derived from M and P cells becomes increasingly mixed (see figure 3A). This
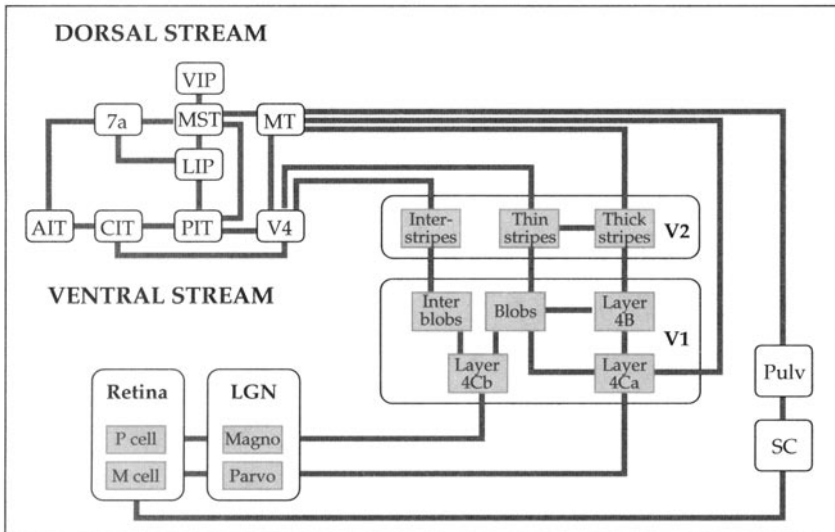

Figure 3A. A schematic diagram of the two streams of visual processing in primate cerebral cortex. LGN: lateral geniculate nucleus; SC: superior colliculus; Pulv: pulvinar; PIT: posterior inferotemporal cortex; CIT: central inferotemporal cortex; AIT: anterior inferotemporal cortex; MT: middle temporal area; MST: middle superior temporal area; LIP: lateral intraparietal sulcus; and VIP: ventral intraparietal sulcus. (Adapted from Goodale and Milner 1995.)

has been shown convincingly by inactivation of either pLGN or mLGN combined with simultaneous recordings in V1, middle temporal area (MT), and visual area 4 (V4). Magnocellular, rather than parvocellular blockade, was more detrimental to MT neuronal responses, reflecting a predominant input from M cells to the dorsal stream of visual processing. Blockade of both mLGN and pLGN, however, affected the responses of cells in V1 and V4 about equally, indicating mixed M and P cell input to the ventral stream of visual processing (Maunsell, Nealy, and DePriest 1990; see also Milner and Goodale 1995 for review). Figure 3B shows the approximate locations of V1, V4, and MT(V5) in the human brain, in addition to those of the dorsal (DS) and ventral (VS) visual streams.

Given the interaction between M and P information at the level of the cortex, how should we best interpret the reduced motion sensitivity shown by people with dyslexia? Lesions of human MT (sometimes referred to as V5) cause akinetopsia, an inability to see movement (Zihl, von Cramon, and Mai 1983). Recordings in macaque monkeys have shown that neuronal responses in MT can account for behavioral decisions during coherent motion detection tasks (Britten, Shalden, Newsome, and Movshon 1992; Shadlen, Britten, Newsome, and Movshon
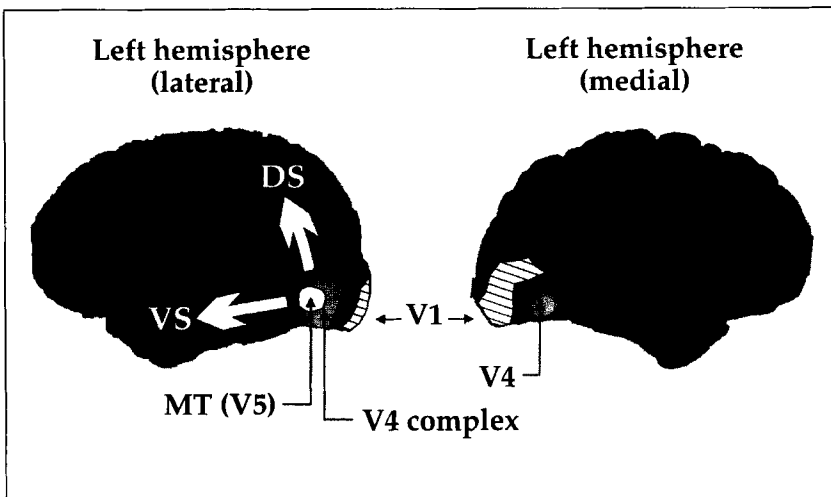

Figure 3B. The approximate locations of the human equivalents to V1, MT, V4, and V4 complex. The arrows marked DS and VS represent the dorsal stream (predominant magnocellular input) and ventral stream (mixed magno- and parvocellular input) of visual processing, respectively. (Adapted from Kaas 1995.)

1996). Since the predominant input to area MT is from the magnocellular system, we argue that reduced motion sensitivity in dyslexic people is consistent with impaired magnocellular function. Nevertheless, it remains to be seen whether the source of the problem is subcortical (cf. Livingstone et al. 1991), cortical, or possibly both. In the face of such uncertainty, we use the term "magnocellular impairment" to refer to degraded information processing in regions of the brain known to receive information which is derived anatomically from M ganglion cells.

How should the nonspecialist reader interpret these admittedly complex data? We think three points should be emphasized. First, we use motion detection as an indirect measure of magnocellular dependent processes (as a "magno-meter"). Second, in the same way that the phrase phonological deficit is used as an umbrella to describe the phonological difficulties of dyslexic people, the term magnocellular deficit tends to be used by researchers as a convenient shorthand for reduced visual sensitivity to flicker and motion. Third, the reader should bear in mind that the hypothesis that impaired motion and flicker sensitivity in people with dyslexia is caused by magnocellular dysfunction is still under investigation. Despite these caveats, the reader's attention should not be diverted from the crucial issue. The very existence of an association between developmental dyslexia and reduced motion sensitivity raises a clinically important question: does abnormal visual processing, independent of phonological problems, affect some children's reading? It should be noted, however, that this question does *not* imply a conflict between visual and phonological processing problems because both could exist independently.

THE PRESENT STUDY

Normally, information from the magnocellular system provides major input to those visual cortical areas responsible for analyzing object movement and location (Milner and Goodale 1995). It may be no coincidence that many poor readers complain that letters seem to "drift on the page" or "move over each other," as though their visual world becomes unstable when they read (Eden, Stein, Wood, and Wood 1994). Consequently, we propose that when some children read, impaired magnocellular function could lead to uncertainty about where letters and letter features are positioned with respect to each other, subsequently leading to predictable reading errors. This hypothesis, which we have tested in the two experiments reported here, is consistent both

with recent models of word recognition (Grainger and Dijkstra 1995) and with the suggestion that magnocellular input is likely to be important for encoding spatial position (Mishkin, Ungerlieder, and Macko 1983; Milner and Goodale 1995).

METHODOLOGICAL ISSUES

Figure 2 shows two trends commonly found in studies of visual processing and developmental dyslexia. First, the participants' performance on the motion detection task was quite variable within the comparison groups. Second, even though the differences between mean thresholds for the dyslexic and nondyslexic participants were statistically significant, the distributions overlap considerably and there seems to be a continuum of visual performance between persons with and without dyslexia. In light of such variability, how should one test whether reduced sensitivity of this kind might affect reading? One way is to avoid comparing groups of dyslexic and nondyslexic individuals altogether. Instead, we have investigated the relationship between motion detection and letter position encoding in the population at large, including some people conventionally regarded as having dyslexia. Similarly, we have looked at the correlation between motion detection and reading behavior in a sample of school children who were not preselected in any way. An advantage of this strategy is that it circumvents the difficult task of defining who is dyslexic, an issue that is sometimes difficult for researchers (Stanovich, Siegel, and Gottardo 1997), let alone clinicians.

EXPERIMENT 1: DOES LETTER POSITION ENCODING REQUIRE INPUT FROM THE MAGNOCELLULAR SYSTEM?

OBJECTIVE

In Experiment 1, we sought direct evidence linking motion detection with letter position encoding. We propose that people who are poor at motion detection should encode letter position less accurately than people who are good at motion detection. Therefore, poor motion detectors should be more likely to inadvertently unscramble briefly presented anagrams and respond to them as if they were words.

PARTICIPANTS

A total of 48 undergraduate students from Newcastle University took part in this study. Each student carried out a coherent-

motion detection task, two subtests (Similarities and Block Design), from the *Wechsler Adult Intelligence Scales–Revised* battery (Wechsler 1981), and two timed reading tests. The characteristics of the participants are described in table I. All of them had normal or corrected-to-normal visual acuity.

PSYCHOLOGICAL TEST BATTERY

All participants were given the WAIS-R subtests, similarities and block design, to assess verbal and nonverbal reasoning, respectively. Each participant was asked to read aloud all the items from the Schonell reading accuracy test (Schonell 1950), as well as a list of 30 nonwords (Castles and Coltheart 1993). In each case, we recorded the number of errors that participants made and the time it took them to complete the list.

COHERENT MOTION DETECTION

Participants sat 60 cm from a 17" computer monitor on which the random dot kinematograms were displayed. We used a two-alternative force-choice method (2AFC) to identify students' coherence thresholds. On each trial, which lasted 2300 msec, coherent motion appeared randomly in one of the two patches. The experimenter initiated each trial, and students

TABLE I. EXPERIMENT 1—PARTICIPANT CHARACTERISTICS.

n = 48

Variable	*M (SD)* range
Coherence at threshold (percentage)	21.3 (10.4) 8.5–45.8
Chronological age (years: months)	20:4 (1:4) 18:0–24:0
WAIS-R Block Design (scaled score, max = 19)	12.1 (2.3) 6–17
WAIS-R Similarities (scaled score, max = 19)	12.7 (1.5) 9–16
Schonell single word reading list errors (max = 110)	5.3 (3.7) 0–17
Time taken to read Schonell (seconds)	80.5 (19.7) 47–164
Nonword reading errors (max = 30)	2.2 (2.8) 0–14
Time to read nonword list (seconds)	24.6 (7.3) 14–52

were asked to indicate which panel contained coherent motion either by pointing or by naming the side (labeled 1 or 2) on which it appeared. Once the experimenter keyed in each response, the next trial started automatically one second later. Participants were encouraged to make sure that they had looked carefully at both panels before they made their decision. Coherence was varied according to a 1-up-1-down staircase procedure. The staircase procedure started well above threshold at 90 percent. Coherence was then adaptively decreased by a factor of 1.122 for every correct response, and increased by a factor of 1.412 for every incorrect response. These two factors are equivalent to changes of 1dB and 3dB respectively (dB = 10 . $\mathrm{Log}_{10}(k)^2$, where: k = percent coherence). Every staircase procedure was run for a total of ten reversals. Threshold was estimated as the geometric mean of the coherence levels at which the last eight reversals occurred. The geometric, rather than the arithmetic, mean was calculated to minimize the skewing effect of outlying data points. We obtained a total of three thresholds for each subject. The first threshold was discarded as a learning period and the remaining two thresholds were averaged together.

In this study, the motion detection task used was improved relative to the one used in Cornelissen et al. (1995). The most significant change was to reduce the lifetime of coherently moving dots to only two animation frames. As described in the introduction, this maneuver ensures that subjects cannot solve the task by concentrating on only a few dots at a time.

LEXICAL DECISION TASK

We used a lexical decision task in which participants were presented with five-letter words or five-letter anagrams with equal probability of occurrence. Anagrams were generated by swapping the positions of two of the internal letters contained in five-letter words:

    a) left anagrams (L): letter positions 2 and 3 were swapped (OCEAN > OECAN).

    b) right anagrams (R): letter positions 3 and 4 were swapped (OCEAN > OCAEN).

    c) far anagrams (F): letter positions 2 and 4 were swapped (OCEAN > OAECN).

One half of the word and anagram stimuli were based on high frequency words, whereas the other half of the stimuli were based on low frequency words. (Mean Kucera-Francis word frequencies: 192.8, $SD = 315.7$, and 2.8, $SD = 2.0$, respectively).

PROCEDURE

Using a counterbalanced design, participants were presented with a total of 144 five-letter stimuli for lexical decision (36 high frequency words, 36 anagrams based on a different set of high frequency words, 36 low frequency words, and 36 anagrams based on a different set of low frequency words). Each set of 36 anagrams was further divided into 12 L, 12 R, and 12 F anagrams such that the L, R, and F anagrams were based on different words.

Participants sat 60cm in front of a computer monitor. Upper case black letters and symbols were presented on a white background. Each trial comprised the following sequence of events which appeared in the middle of the monitor screen: fixation cross (300ms), blank screen (300ms), letter string target (43ms), pattern mask (100ms), and response prompt. At the end of each trial, participants were asked to respond as quickly as possible by pressing a "1" if they had seen a word and "0" if they had not. For example, if the stimulus OCAEN was presented, a *correct* response would have been to press "0" and an *incorrect* response to press "1" because "ocaen" is not a real word. However, if the stimulus had been OCEAN, a *correct* response would have been to press "1" and an *incorrect* response to press "0," because "ocean" is a real word. Participants' responses and reaction times were automatically recorded.

RESULTS

Table II shows participants' mean reaction times in the lexical decision task for words and L, R, and F anagrams. Although there is wide variability, table II suggests that participants reacted more quickly to high frequency anagrams than to low frequency ones.

This impression was confirmed by a two-way repeated measures ANOVA of participants' reaction times which showed significant main effects of both stimulus (word, L, R, and F anagram) and word frequency (high or low), $F(3,141) = 5.7$, $p = 0.001$ and $F(1,47) = 13.7$, $p < 0.0005$, respectively. The two-way interaction of *stimulus x word frequency* was not significant at $p < 0.05$.

We used multiple regression analysis to investigate the relationship between reaction time in the lexical decision task, motion detection, and word frequency. We ran the following model once for each stimulus type (word, and L, R, or F anagram):

$$y = b_1 x_1 + b_2 x_2 + e \quad \text{where: } y = \text{reaction time, } x_1 = \text{motion detection}$$
$$x_2 = \text{word frequency (high or low)}$$

Only the model for word stimuli was significant at $p < 0.05$ and only the main effect of word frequency in this model was

TABLE II. EXPERIMENT 1—REACTION TIMES (MS) FOR THE LEXICAL DECISION TASK.

n = 48	
Stimulus	*M (SD)*
High frequency	
Words	512 (198)
L anagrams	568 (221)
R anagrams	592 (314)
F anagrams	630 (249)
Low frequency	
Words	623 (263)
L anagrams	621 (251)
R anagrams	661 (303)
F anagrams	693 (364)

significant $F(1,93) = 5.5$, $p < 0.05$. Motion detection was not significantly associated with reaction time for any of the four stimulus types.

Table III shows the mean percentage errors that participants made in the lexical decision task. Overall, participants made fewer errors to words than to anagrams, and made more errors to high frequency anagrams than to low frequency anagrams.

This was confirmed by a two-way repeated measures ANOVA of the arcsine transformed proportions of participants' errors. Both

TABLE III. EXPERIMENT 1—PERCENTAGE ERRORS FOR THE LEXICAL DECISION TASK.

n = 48	
Stimulus	*M (SE)*
High frequency	
Words	11.4 (1.9)
L anagrams	53.6 (3.1)
R anagrams	62.4 (3.1)
F anagrams	29.8 (2.8)
Low frequency	
Words	30.3 (2.8)
L anagrams	37.2 (2.5)
R anagrams	36.0 (2.9)
F anagrams	24.3 (2.6)

main effects of word frequency (high or low) and stimulus (word and L, R, or F anagram) were significant, $F(1,47) = 19.3, p = 0.0001$ and $F(3,141) = 62.7, p = 0.0001$, respectively, as was the two-way interaction *frequency x stimulus*, $F(3,141) = 51.8, p = 0.0001$.

To investigate the relationship between motion detection and the kinds of errors made by participants, we carried out four multiple logistic regression analyses. For each of the four stimulus types (words and L, R, or F anagrams), we tested for an association between motion detection and the proportion of errors on the lexical decision task while controlling for any effects of word frequency, chronological age, WAIS-R Similarities, WAIS-R Block design, Nonword and Schonell reading errors, and time. We permitted differential effects of word frequency (coded 1 for high frequency or 0 for low frequency) by including the interaction term *motion detection x frequency*. This provides a convenient way of estimating separate regression lines and intercepts for high and low frequency stimuli in the same model, and means that we only had to run four models instead of eight. Because we were dealing with proportionate data with a binomial distribution, we applied the logit transform (log odds) to stabilize the variance in our multiple regression analyses (see Altman 1991). Regression coefficients are expressed as log odds ratios which can be converted to odds ratios ($p/1-p$), also known as risk values. Odds ratios greater than one represent increased risk; values less than one represent reduced risk.

We explored a variety of different methods for rejecting or retaining explanatory variables including fitting of the complete model, backward elimination, forward selection, and stepwise selection. Note that the output from these methods does not depend on the order in which explanatory variables are entered in the model. They merely represent different algorithms for finding a minimum set of explanatory variables, each of which satisfies the significance criterion ($p < 0.05$) for inclusion in the model. All four fitting procedures gave the same outcomes with goodness of fit measures (using the -2 log likelihood statistic) which were significant at $p < 0.0005$. We have reported the output from the stepwise procedure in table IV.

Table IV shows that a significant association exists between motion detection and the proportion of errors made in the lexical decision task for high frequency L and R anagrams and low frequency R anagrams, but not for F anagrams or words. Figure 4 illustrates these regression models. It shows a series of plots for the predicted probability of an error in the lexical decision task (y-axis in each case) as a function of motion detection

TABLE IV. EXPERIMENT 1—OUTPUT FROM
LOGISTIC REGRESSION MODELS.

Stimulus	Explanatory Variable	Regression Coefficient (logit)	SE	Change in χ^2 at 1 df	p value	Odds Ratio /unit
	Intercept	−0.51	0.086	36.1	p = 0.0001	
L anagrams	*Motion x Frequency*	0.029	0.0085	11.7	p = 0.0006	1.030
	Nonword time	0.027	0.0085	10.0	p = 0.002	1.027
	Word frequency	0.67	0.12	30.8	p = 0.0001	1.95
	Intercept	−0.57	0.087	44.0	p = 0.0001	
R anagrams	*Motion detection*	0.016	0.0061	6.6	p = 0.01	1.016
	Nonword time	0.029	0.0088	11.3	p = 0.0008	1.030
	Word frequency	1.10	0.12	80.8	p = 0.0001	3.002
	Intercept	−1.20	0.099	146.3	p = 0.0001	
F anagrams	Nonword errors	0.062	0.022	7.5	p = 0.006	1.064
	Schonell time	0.0099	0.0033	9.1	p = 0.002	1.010
	Chronological age	0.036	0.017	4.3	p = 0.04	0.037
	Word frequency	0.28	0.13	5.2	p = 0.02	1.326
	Intercept	−0.91	0.053	285.8	p = 0.0001	
Words	Schonell errors	0.07	0.011	38.3	p = 0.0001	1.073
	Chronological age	0.031	0.011	7.8	p = 0.005	1.031
	Word frequency	−1.23	0.092	180.0	p = 0.0001	0.291

(x-axis in each case) for each stimulus type. In each case, the effects of age, IQ, and reading have been taken into account.

Figure 4 shows that the effect for high frequency L anagrams was equivalent to a 36 percent increase (4.3 out of 12 stimuli) in the errors made in the lexical decision task over the motion coherence range of 8 percent to 45 percent. Students with the highest motion detection thresholds made the most errors. The effect for R anagrams was present for both high and low frequency stimuli, but was generally weaker, evidenced by an 11 percent increase in errors over the same motion detection range.

One possibility to account for the lack of an effect of motion detection on the errors made to F anagrams might be that these five-letter strings contain more unusual bigrams (e.g.,QI, PZ, and XM) than do L and R anagrams. To test this possibility, we extracted all the position-dependent token frequencies of bigrams from the CELEX psycholinguistic database (Centre for Lexical Information, Nijmegen, the Netherlands). We calculated a position sensitive bigram frequency score for each anagram,
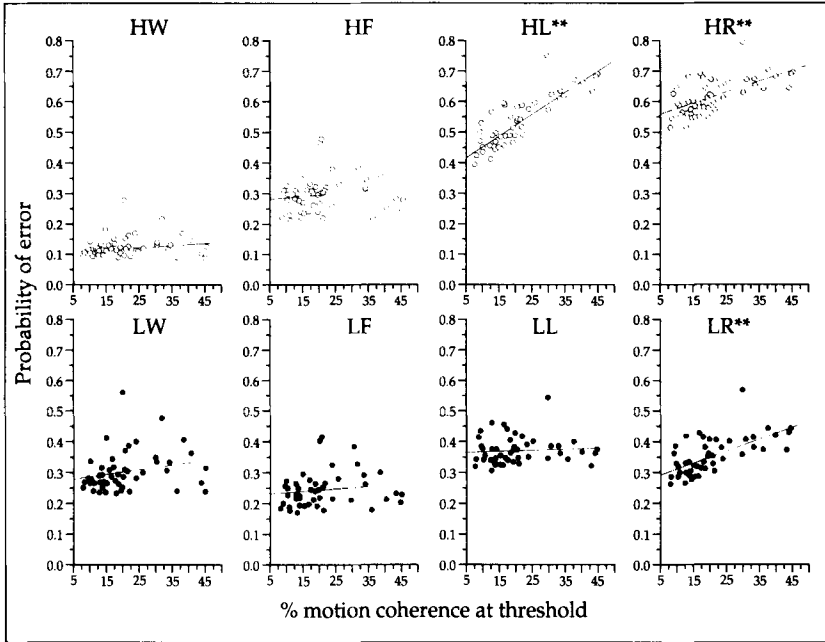
Figure 4. A series of plots for the predicted probability of an error in the lexical decision task (y-axis in each case) as a function of motion detection (x-axis in each case) for each stimulus type. HW: high frequency words; HF: high frequency F anagrams; HL: high frequency L anagrams; HR: high frequency R anagrams; LW: low frequency words; LF: low frequency F anagrams; LL: low frequency L anagrams; and LR: low frequency R anagrams. NB** = p < 0.005.

then compared these scores across the three kinds of anagrams. For example, the L anagram BRAON comprises four bigrams: BR, RA, AO, and ON, which have token frequency counts (in units of 10,000) of 4.8, 22.1, 1.8, and 22.3, respectively (total = 49.4). Since a one-factor ANOVA (anagram type L, R, or F) of the total bigram scores (L mean = 41.8, R mean = 39.6, F mean = 36.9) was not significant, $F(2,213) = 0.65$, $p = 0.5$, it is unlikely that bigram frequency can explain why there was no association between motion detection and errors made to F anagrams.

Finally, we wanted to exclude the possibility that participants may have traded speed of response for accuracy in the lexical decision task. Table V shows the correlations between reaction speed (1/reaction time) and percentage errors for the four stimulus types (words and L, R, and F anagrams) at high and low word frequency. None of the correlations was signifi-

TABLE V. EXPERIMENT 1—PEARSON CORRELATIONS
BETWEEN REACTION TIME AND PERCENTAGE ERRORS IN THE
LEXICAL DECISION TASK.

Stimulus	Correlation Coefficent (r)	p value
High Frequency		
Words	–0.37	$p < 0.005$
L anagrams	–0.08	$p > 0.5$
R anagrams	–0.19	$p > 0.1$
F anagrams	–0.12	$p > 0.1$
Low Frequency		
Words	–0.25	$p > 0.05$
L anagrams	0.005	$p > 0.5$
R anagrams	–0.25	$p > 0.05$
F anagrams	–0.14	$p > 0.1$

cant at $p < 0.05$ except the one for high frequency words. Even
in this situation we could not find evidence for a speed-
accuracy trade off. Faster responses were always associated
with more accurate responses.

DISCUSSION

The mean threshold coherence for the adults in this study (~21 per-
cent) was considerably higher than that for the normal reading
adults in our previous study, shown in figure 2 (~10 percent)
(Cornelissen et al. 1995). This is due to the fact that the coherently
moving dots in our previous study had longer lifetimes, compared
to only two animation frames in the current stimuli. Thus the mo-
tion detection task in the present study was more difficult.

Reaction time is probably the most common outcome measure
to be analyzed in lexical decision experiments and the fact that we
found no association between it and motion detection requires
some explanation. We suggest two factors that may account for
this result. First, when the lexical decision task was being ex-
plained to participants, accuracy, rather than speed of response,
was emphasized. Second, and probably more significantly, succes-
sive trials automatically followed each response. Subjectively, this
gave the task a natural rhythm that was easy to fall into; this
would have strongly encouraged participants to focus on accuracy
rather than on speed of reaction.

In Experiment 1, participants were considerably quicker and
more accurate at responding to words than to anagrams. This is

likely to have been due to the word-pseudoword advantage; when viewing tachistoscopic displays, people can correctly report words at shorter exposure times than pseudowords (Carr 1986; Henderson 1982). The main finding from Experiment 1 which supports our hypothesis is that participants who were poor at motion detection were also more likely to make errors on high frequency L and R anagrams as well as low frequency R anagrams. Research suggests that during the early visual analysis of text, the positions of the first and last letters of a word are rigidly encoded (Hammon and Green 1982; Mason 1982). However, internal letter position encoding is more flexible, and consequently more fallible (Humphreys, Evett, and Quinlan 1990; Mozer 1983). Therefore, it is plausible that errors in the anagram task could reflect some uncertainty about the positions of adjacent letters. Specifically, a participant might encode the stimulus OCAEN as O + C + E + A + N, and as a result, respond to it as if it was a word instead of an anagram. The fact that there was no effect of motion detection on error rates for F anagrams may also be explained in terms of letter position encoding. In order to unscramble an F anagram, letter positions 2 and 4 would have to be swapped around. When, in a lexical decision task, such a briefly presented (40ms) letter string is encoded by the visual system, we suggest that positional uncertainty would be much less likely to cause the large jumps of letter position necessary to unscramble F anagrams, as compared to merely shifting adjacent letter positions as required by L and R anagrams.

The overall error rates for the low frequency anagrams were smaller than those for the high frequency anagrams. It is plausible that the word frequency effect (Monsell 1991) could account for this result. All participants made more errors to low frequency words than to high frequency words; that is, they were more likely to respond to low frequency words as if they were nonwords. Therefore, presenting participants with anagrams based on the kind of words that were already being treated as nonwords was unlikely to have elicited anything other than a nonword response (an appropriate response to anagram stimuli), and would account for the lower error rates for the low frequency anagrams.

In this study of young adults, we have found an association between coherent motion detection and performance in a task in which optimal responses explicitly depend on accurate information about letter position. Our analyses suggest that neither reading ability, IQ, nor a speed-accuracy trade off can adequately explain this association. Nevertheless, there are still at

least two alternative explanations for it. The first we propose is a "bottom-up" process: variability in our motion detection task directly reflects abnormal magnocellular system function. Any process that requires input derived from the magnocellular system—such as position encoding and motion detection—would, therefore, be impaired. Alternatively, a "top-down" mechanism might affect performance in the motion detection tasks and the letter position tasks. A likely candidate for such a mechanism is attentional processing in which the magnocellular pathway has also been implicated (Steinman, Steinman, and Lehmkuhle 1997). Further research is required, either to rule out an attentional component, or to elucidate the nature of any interaction between attention, motion detection, and letter position coding.

In conclusion, the findings of Experiment 1 make an explicit, albeit tentative, link between motion detection and letter position encoding. (For further analysis and supportive experimental data see Cornelissen, Hansen, Gilchrist, Cormack, Essex, and Frankish 1998). In Experiment 2, we go on to explore whether motion detection predicts the pattern of children's reading errors.

EXPERIMENT 2: DOES REDUCED MAGNOCELLULAR FUNCTION AFFECT READING?

Fluent reading involves a rapid, alternating pattern of fixation and saccadic (jumping) eye movements. When we read, it is during these brief periods of fixation that our visual systems sample the text image projected onto our retinae. Unlike images from the natural world, printed words represent a very unusual visual stimulus. Specifically, all the information available in a page of text is compressed into three discrete spatial scales: coarse, intermediate, and fine. These scales approximate the average size of a word, the average size of a letter, and the average thickness of the lines that make up each letter. There is no other useful information at intermediate spatial scales. This contrasts with natural images which contain a smooth continuum of information across all spatial scales. Figure 5 illustrates this situation for text, with the three discrete spatial scales represented by the three degrees of blur. (Although the three spatial scales are placed under each other in figure 5, in reality they would effectively be superimposed.)

We have printed the two words in figure 5 in a stylized font using simple, discrete features: long and short horizontal or ver-
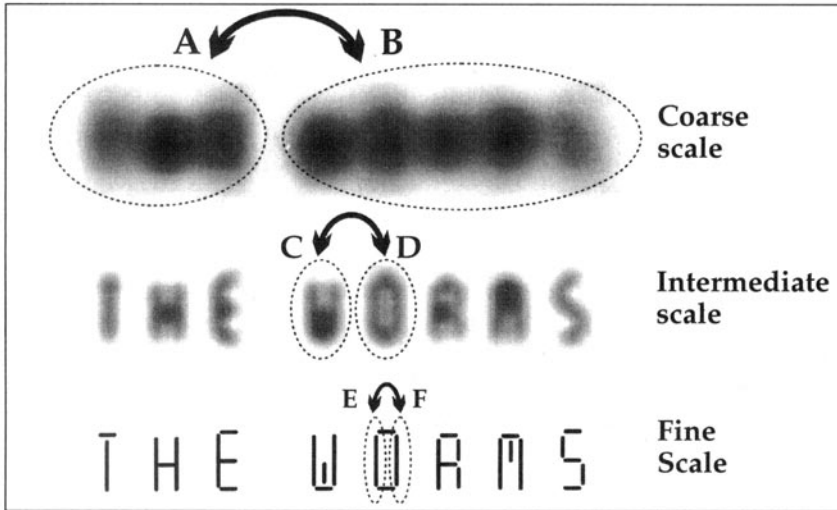
Figure 5. *Information available in the phrase THE WORMS at three discrete spatial scales. The double-headed arrows represent examples of feature mislocations at each scale which could be caused by positional uncertainty. See text for details.*

tical bars. This is meant to emphasize the fact that the identity of a particular letter is determined by the combination of *what* features are *where*. The visual system must reliably extract information about both *shape* and *position* of features.

Our brains are thought to process visual information by using a coarse-to-fine strategy. First, large objects (A and B in figure 5) and their relative positions are detected at the coarsest spatial scales. Coarse scale information not only confirms that object A is to the left of object B but also constrains the location of objects at the next, finer scale. For example, the two objects C and D in figure 5 are associated with object B at the coarsest scale, but not with object A. Position information at the intermediate scale also shows that object C is to the left of object D. At the finest scale, a similar argument applies. The two vertical features (marked E and F in figure 5) belong to the "O" in "Worms" and are associated with object C at the intermediate scale. In addition, position information at this scale determines where horizontal and vertical features are located with respect to one another.

We suggest that poor magnocellular function—revealed by high motion detection thresholds—is associated with poor position coding. In terms of figure 5, we argue that this positional uncertainty acts both within and between the three spatial scales.

Consequently, positional uncertainty could cause letter clusters, individual letters, or even parts of letters to be lost, duplicated, or even incorrectly bound together, leading to a scrambled or non-sense version of what is actually printed on the page. This is especially likely when two or more fixations are required per word. When children try to read aloud what they see under these circumstances, we predict that their utterances should contain sounds not represented in the printed word. It is as if they literally translate visual garbage into spoken garbage. For convenience, we refer to such orthographically inconsistent nonsense responses as letter errors. In Experiment 2, we investigated whether the probability of children making letter errors during reading was predictable from their motion detection thresholds.

PARTICIPANTS

Fifty-eight children were chosen from a Newcastle primary school to take part in this study. They represented all of the 33 boys and 25 girls in the two most senior classes of the school (mean age 10:5). All children had normal or corrected-to-normal visual acuity. The characteristics of the sample are described in table VI.

TABLE VI. EXPERIMENT 2—PARTICIPANT CHARACTERISTICS.		
n = 58		
Variable (units)	*M* range	(*SD*)
Chronological Age (years: months)	10:5 9:4–11:5	(0:6)
Reading Age (years: months)	9:11 6:5–14:5	(2:1)
Nonverbal IQ (number correct / 48)	27.9 11–42	(7.6)
Verbal IQ (quotient: 70–130)	96.8 83–118	(8.9)
Rhyme Detection (PhAB) (number correct / 21)	17.1 8–21	(3.2)
Spoonerism (PhAB) (number correct / 40)	23.3 2–39	(9.7)
Motion Detection (percent coherence at threshold)	17.2 7.1–42.8	(8.4)
Letter Errors in Experimental Word lists (max = 45)	6.2 0–16	(4.3)
Total Errors in Experimental Word lists (max = 45)	19.2 8–34.5	(6.5)

PSYCHOLOGICAL TEST BATTERY.

Nonverbal IQ. *AH1 X and Y Group Tests of Perceptual Reasoning* (Heim, Watts, and Simmonds 1977).

Verbal IQ. *Non-Reading Intelligence Tests* (NRIT), level 3, (Young 1996).

Reading Age. Children's reading ages were assessed using the *British Ability Scales* (BAS) single word reading accuracy test.

Phonological Awareness. We administered two subtests of the *Phonological Awareness Battery* (1995) including rhyme detection and a set of three spoonerism tasks. In part 1 of the spoonerism test the child is asked to replace the first sound of a word with a new sound ("cot" with a /g/ results in "got"). Part 2 also involves semispoonerisms, but here the child replaces the first sound of the first word with the first sound of the second word ("die" with "pack" results in "pie"). Part 3 is a full spoonerism measure in which the child is asked to exchange initial sounds in two words ("sad cat" becomes "cad sat").

EXPERIMENTAL WORD LISTS AND ADMINISTRATION

At the beginning of each assessment, children were given the BAS single word reading test. Next, they were asked to read 45 regularly spelled words selected on the basis of their BAS reading age. The task difficulty was adjusted individually so that all children made 30 to 50 percent errors. (Details of the experimental word lists can be obtained from Cornelissen, Bradley, Fowler, and Stein 1991; Cornelissen 1992). All children's responses were tape recorded for later analysis. The scorer listened for the *first complete utterance* in response to a target word; partial responses were ignored. Errors were subsequently classified as real words, orthographically consistent nonsense errors, or orthographically inconsistent nonsense errors (equivalent to the letter errors defined above). Examples of children's errors are shown in table VII. Finally, the proportion of letter errors that each child made was calculated, where $p = total\ number\ of\ letter\ errors/total\ number\ of\ errors$.

COHERENT MOTION THRESHOLDS

We used the same method described earlier to obtain four motion detection thresholds from each participant. The first was discarded as a learning period; the remaining three thresholds were averaged together for further analysis.

TABLE VII. EXPERIMENT 2—EXAMPLES OF CHILDREN'S READING ERRORS.

Error Category	Target Word	Error
Real Word	fool	floor
	banker	blanket
	feeling	flooding
	contents	constant
	seduction	suggestion
Orthographically Consistent Nonsense Error	leap	lep
	perish	purrish
	fever	fevver
	wither	whyther
	prosper	pro-spur
Orthographically Inonsistent Nonsense Letter Error	victim	vikim
	garden	grandeen
	suspect	subpact
	temper	templay

STATISTICAL MODELING OF THE DATA

We used multiple logistic regression to examine the relationship between the proportion of letter errors that children made and their motion detection thresholds, while controlling for any effect due to IQ, chronological age, reading ability, and phonological awareness.

We carried out multiple regression analyses in two phases. In the first phase, we included all explanatory variables in the linear model below to elucidate only those factors which had a significant effect on the proportion of letter errors that children made. The phase one model was as follows:

Model: $\log_e(p/[1-p]) = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + b_7x_7$

where: p = (letter errors)/(total error) x_5 = rhyme detection
           x_1 = chronological age x_6 = spoonerism task
           x_2 = reading age x_7 = motion detection
           x_3 = non-verbal IQ
           x_4 = verbal IQ

In the second phase, we explored a variety of methods to optimize a model which was built from the significant explanatory variables identified in phase one.

RESULTS

Univariate Statistics. Table VIII shows the matrix of Pearson correlations between the psychological measures. Motion detection is also included. As would be expected, we found significant positive correlations among reading ability, both IQ measures, and both phonological awareness tasks. Motion detection did not correlate with any measure except for verbal IQ. We suggest that brighter children obtained lower coherent motion thresholds, either because they learned the task more quickly, or because they were better able to discover optimal viewing strategies during the task.

First phase of logistic regression modeling. Table IX shows the output of the first regression model, predicting letter errors as described above. It is clear that the only factors accounting for significant changes in χ^2 were reading ability, phonological awareness measured by the spoonerism task, and motion detection. The fact that there was no effect of rhyme detection when both phonological tasks were included in the same model is probably because of the high correlation between rhyme detection and the spoonerism task (see table VIII). Henceforth, chronological age, rhyme detection, and both IQ measures are excluded from the analyses.

Second phase of logistic regression modeling. Figures 6A, 6B, and 6C show plots of the proportion of letter errors that the children made as a function of motion detection, reading age, and the spoonerism task, respectively.

TABLE VIII. EXPERIMENT 2—PEARSON CORRELATIONS BETWEEN PSYCHOLOGICAL MEASURES, INCLUDING MOTION DETECTION.
$*p < 0.05,\ **p < 0.005,\ ***p < 0.0005$

	1	2	3	4	5	6	7
1. Age							
2. Reading Ability	–0.018						
3. Nonverbal IQ	0.20	0.41**					
4. Verbal IQ	–0.23	0.36**	0.51***				
5. Rhyme Detection	–0.12	0.40**	0.51***	0.44*			
6. Spoonerism Task	–0.0098	0.57***	0.47***	0.42**	0.58***		
7. Motion Detection	0.018	–0.19	–0.093	–0.28*	–0.064	–0.053	

TABLE IX. EXPERIMENT 2—OUTPUT FROM PHASE ONE LOGISTIC REGRESSION MODEL.

Explanatory Variable units	Regression Coefficient (logit)	SE	Change in χ^2 at 1 df	p value	Odds Ratio /unit
Intercept	1.69	2.35	0.52	$p > 0.1$	
Chronological Age months	–0.0057	0.015	0.15	$p > 0.5$	1.06
Reading Age months	–0.01	0.0039	6.38	$p < 0.05$	0.99
Nonverbal IQ number correct / 48	0.056	0.11	0.24	$p > 0.5$	1.058
Verbal IQ quotient	–0.0087	0.012	0.53	$p > 0.1$	0.991
Rhyme Detection number correct / 21	0.0048	0.033	0.021	$p > 0.5$	1.005
Spoonerism Task number correct / 40	0.019	0.011	4.13	$p < 0.05$	1.02
Motion Detection percent coherence	0.024	0.0093	6.89	$p < 0.005$	1.025

In support of our hypothesis, figure 6A shows that children who perform well on the motion detection task (low percent coherence at threshold) made appropriately less letter errors than those who performed poorly at this task (high percent coherence at threshold). However, this relationship is nonlinear in that the proportion of letter errors asymptotes above 20 percent coherence. Figure 6B also reveals a nonlinear relationship between the proportion of letter errors and level of phonological awareness. These results can be explained by data from a small number of participants who obtained either very low or very high scores on the spoonerism task, causing the proportion of letter errors to alternately rise and fall as values along the x-axis increase.

In view of figures 6A and 6B, we felt we should take these nonlinearities into account when optimizing the final model. However, there are many functions which could, in principle, be used to achieve this. Since our analysis was post hoc and exploratory, we chose to use the simplest approach possible by including second order terms (see Altman 1991). We included the three explanatory variables which survived the first phase: reading ability, the spoonerism task, and coherent motion detection. To account for the nonlinearities shown in figure 6, we
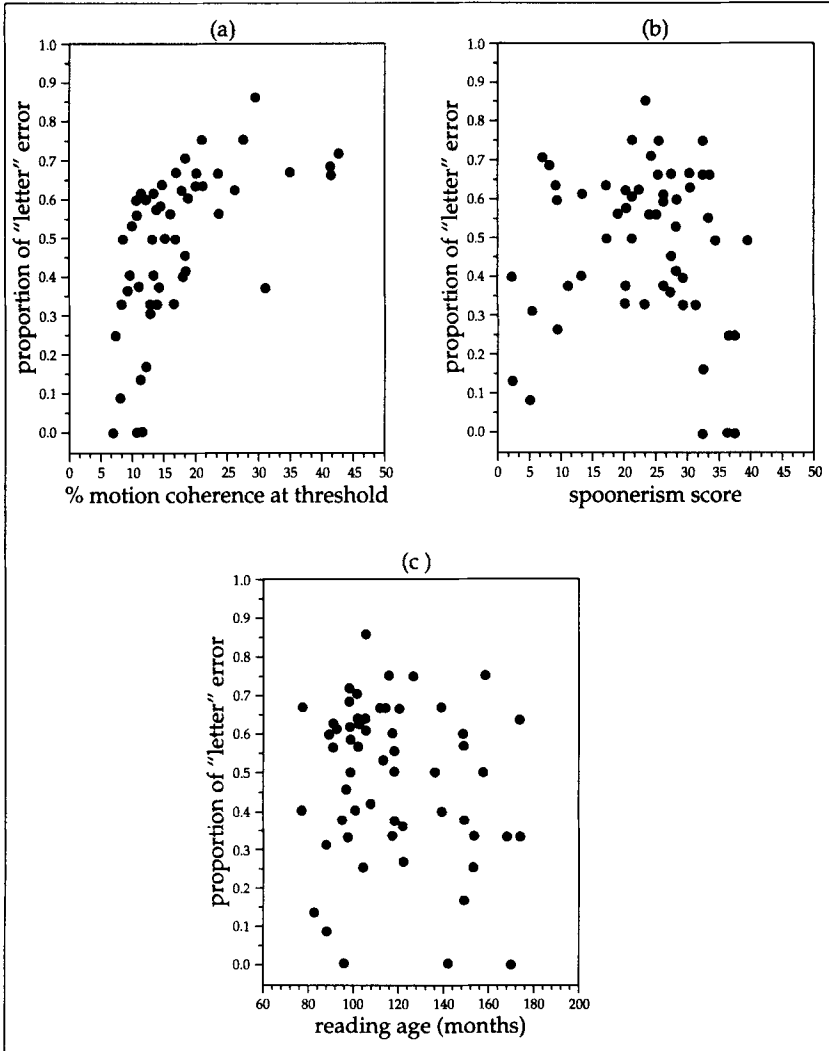
Figure 6.   *Scatter plots of the relationship between the proportion of letter errors and (A) motion detection (percent coherence at threshold), (B) phonological awareness (spoonerism task), and (C) reading age.*

then added the squared terms: (reading ability)^2, (spoonerism task)^2, and (motion detection)^2. There appears to be little justification in the physiological or psychological literature for fitting a more complex function. The second phase regression model is shown below:

Model: $\log_e(p/[1-p]) = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6$

where: p = (letter errors)/(total error)

x_1 = reading age $\qquad\qquad$ x_4 = (reading age)^2
x_2 = spoonerism $\qquad\qquad$ x_5 = (spoonerism)^2
x_3 = motion detection $\qquad$ x_6 = (motion detection)^2

We first compared the residual scaled deviance for the poly-nomial model above using all the variables $x_1 \ldots x_6$ (residual χ^2 = 46.69 at 51df) with a linear model which excluded variables $x_4 \ldots x_6$ (residual χ^2 = 64.47 at 54df). The difference in residual χ^2 of 17.78 at 3df between the two models is significant at $p < 0.0005$ and strongly supports the inclusion of the quadratic terms. We then explored a variety of different methods for re-jecting or retaining explanatory variables to derive our optimal model which is shown below:

$\log_e(p/[1-p]) = -0.37 + 0.11.x_1 + 0.04.x_2 - 0.0027.x_3 - 0.0019.x_4$

where: p = (letter errors)/(total errors)

x_1 = spoonerism task $\qquad$ x_3 = (spoonerism task)^2
x_2 = motion detection $\qquad$ x_4 = (motion detection)^2

The regression coefficients, their χ^2 values, and associated significance levels are given in table X. We should emphasize that the equation above represents the best statistical descrip-tion of our data that we could produce. To illustrate this model, we have plotted the probability of the occurrence of letter errors (z-axis) as a function of both phonological awareness (x-axis) and motion detection (y-axis) (see figure 7).

TABLE X. EXPERIMENT 2—OUTPUT FROM SECOND PHASE
LOGISTIC REGRESSION MODEL.

| Explanatory Variable *units*	Regression Coefficient *(logit)*	*SE*	Change in χ^2 at 1 *df*	*p* value	Odds Ratio */unit*
Intercept	−0.37	0.37	0.99	$p > 0.1$	
Spoonerism Task *number correct/40*	0.11	0.036	9.21	$p < 0.005$	1.12
Motion Detection *percent coherence*	0.041	0.0090	20.26	$p < 0.0005$	1.042
(Spoonerism Task)^2 *number correct/40*	−0.0027	0.00095	7.97	$p < 0.005$	0.997
(Motion Detection)^2 *percent coherence*	−0.0019	0.00088	4.50	$p < 0.05$	0.998
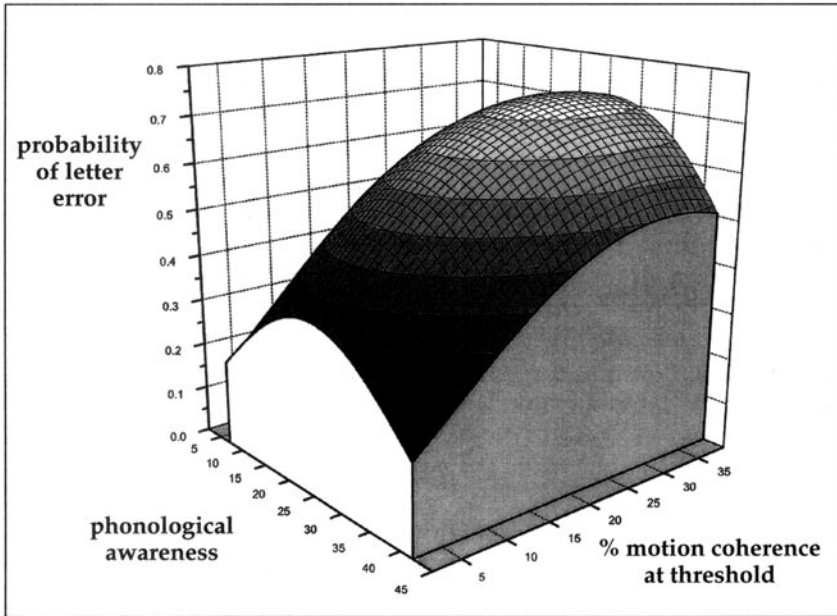
Figure 7.   A 3-dimensional surface plot in which the probability of the occurrence of letter errors (z-axis) is shown as a function of both phonological awareness (x-axis) and motion detection (y-axis).

Probability values are calculated from logits such that if $l = logit(p)$, then $p = e^l/(1+e^l)$. Figure 7 shows that the likelihood of letter errors increases sharply with poorer performance on the motion task, but that the rate of increase tails off above 20 percent coherence. The effect of phonological awareness (spoonerism task) is clearly nonlinear; the children most likely to make letter errors are those with *intermediate* phonological skills, whereas children with either very poor or very good phonological skills have a much lower incidence of letter error. It should be emphasized, however, that the nonlinear relationship between letter errors and phonological skills is caused in our data by a small number of children who obtained extreme scores on the spoonerism task. Therefore, further samples of children would be required to confirm this finding.

Exclusion of reading disabled participants.   In the current study, we tested an unselected sample of primary school children on the grounds that our previous study (Cornelissen et al. 1995) suggested a continuum of performance at coherent motion detection. Therefore, if our sample was representative of

school children at large, it should have contained anywhere be-
tween 5 and 15 percent reading disabled individuals. To exclude
the possibility that our results depended exclusively on such in-
dividuals, we carried out one final analysis. We defined as read-
ing disabled anyone whose reading age was two or more years
below their chronological age and excluded them from the study
(cf. Williams, May, Solman, and Zhou 1995). Even when these 17
reading disabled individuals were excluded, we still found that
both motion detection thresholds and spoonerism task scores
were significantly correlated with the proportion of letter errors
that children made ($r = 0.56$, $p < 0.0005$; $r = -0.36$, $p = 0.01$, respec-
tively). The fact that the correlation between letter errors and the
spoonerism task became negative when reading disabled indi-
viduals were excluded (as opposed to the nonlinear relationship
for the whole sample) suggests strongly that it was these very in-
dividuals who had some of the worst phonological skills, as
would be predicted. A t-test comparison between the spoonerism
scores obtained by children who did and did not qualify as read-
ing disabled confirmed this (mean scores: 15.8 and 26.5, respec-
tively; $t(56) = -4.34$, $p < 0.0005$).

DISCUSSION

We found a positive relationship, albeit a nonlinear one, be-
tween children's motion detection thresholds and the likelihood
of them making letter errors. This result held when chronologi-
cal age, IQ, reading age, and phonological awareness were
taken into account. This result supports the hypothesis that
poor motion sensitivity (reflecting poor magnocellular function)
leads to greater uncertainty about letter position and conse-
quently, an increase in the chances of children making letter er-
rors. It should be noted (table VIII) that children's motion
detection thresholds were not correlated with their reading abil-
ities, as assessed by an untimed single word reading task (the
BAS word reading accuracy test). This suggests that when chil-
dren are reading single words in the absence of time con-
straints—as in Experiment 2—magnocellular function appears
to predict only the pattern of errors that they make rather than
the overall number of errors. However, in a recent functional
imaging (fMRI) study, Demb, Boynton, and Heeger (1997)
showed that participants' reading rate for prose was correlated
with a measure of magnocellular function calculated from the
fMR signals. Therefore, time pressure may be needed in single
word reading tasks before motion detection is observed to cor-
relate not only with the pattern of reading errors but also with

the total number of errors that children make. Future research is necessary to clarify this important issue.

In Experiment 2, we found that phonological factors also played an important part in explaining children's letter errors. Those individuals with intermediate phonological skills (assessed by the spoonerism task) were much more likely to make letter errors than children who had either very poor or very good phonological skills. Since there was very little correlation between children's motion detection thresholds and their performance on the phonological tasks (see table VIII), this effect must have been independent of motion detection and requires a separate explanation.

Gough and Walsh (1991) and Baldwin (1990) have described how children can make nonsense errors for phonological reasons alone. This is easily predicted if we consider children who misapply letter-sound conversion rules. For example, if asked to read the word PERISH, they may accurately identify two graphemic units (PER- and -ISH). But they might incorrectly translate the first unit as PURR, leading to the nonsense error PURRISH. This kind of error is consistent with the printed orthography and was deliberately excluded from our analysis. However, children who apply letter-sound conversion rules imperfectly, and who would arguably be the same children who had intermediate scores in the spoonerism task, may also make letter errors for phonological reasons. For example, when such children see PERISH, they may associate at least one letter/letter cluster with an incorrect sound/sound cluster, thereby mistaking /p/ for /b/ and resulting in BERRISH; or /ɪ/ for /ɛ/, resulting in PERESH. According to our definition, since either response would constitute a letter error, such a mechanism could certainly account for children making some letter errors for phonological reasons. By contrast, children with the highest scores on the spoonerism task may have such good phonological skills that they can apply letter-sound correspondences faultlessly and not make this kind of mistake. At the opposite extreme, children who score particularly poorly on the spoonerism task may not yet have developed the kind of fine-grained, analytical strategy which, when applied incorrectly, could lead to phonologically based letter errors. In this respect, their reading strategy may be comparable to Frith's logographic stage of reading development (Frith 1985).

At this point in the discussion, we have accounted for children's letter errors in terms of motion detection. We also have suggested that children can make letter errors for phonological

reasons. So have we created a dilemma? We propose an explanation which reconciles these two possibilities in a complementary way.

Multiple-level models of reading. The visual analysis of print makes available orthographic information at a variety of scales from single letters to syllables (Prinzmetal, Trieman, and Rho 1986; Treiman and Zukowszki 1988). In order that words can be read aloud, however, this multiscale orthographic activity must be associated with appropriate phonological output. Shallice, Warrington, and McCarthy (1983) proposed a solution to this problem in which multiple parallel correspondences are allowed between orthographic and phonological units of varying sizes. Their scheme comprised seven levels: initial consonant clusters, vowels, syllable-final consonant clusters, initial cluster plus vowel, rimes, syllables, and morphemes. Recently, this multiple-levels approach has been successfully implemented in artificial neural network models of reading aloud (Norris 1994; Brown 1987). Since orthographic units are directly connected to phonological units in parallel, it is plausible that distortion at either the orthographic or the phonological ends of these connections could have similar effects. Thus, while the presence of magnocellular impairment need not necessarily be associated with a phonological deficit in the same individual (the two can be independent of each other), the effects of damage in either domain could produce the same errors in letter/letter cluster to sound/sound cluster mapping; both could result in letter errors. Ideas like these are consistent with the present findings, but further experiments are clearly required to test them. In particular, it would be interesting to try to dissociate phonological from visual effects, perhaps by manipulating the spelling-sound consistency of target words, as well as the physical appearance of text. In addition, we need to control explicitly for visual attentional factors.

Developmental dyslexia and the magnocellular deficit hypothesis. The correlational design of the experiments described here, and the nature of the participant samples, make it difficult to relate our findings directly to the comparison between children who have dyslexia and those who do not. Nevertheless, it is possible to offer some speculations. A key observation is the continuum of visual performance between the dyslexic and nondyslexic comparison groups shown in figure 2. This finding is reminiscent of Seymour's (1986) serial case studies of reading disabled individuals which suggested that many of the component skills in reading are distributed continuously

in the population. If we accept this idea, children's reading problems can be considered within the following information processing framework. Let us assume, for the sake of simplicity, that reading can be described by a multi-channel model in which, for example, visual processing, phonological processing, and short-term memory are all necessary components. The amount of information which can flow through each channel can vary continuously between a minimum and maximum value. Since reading requires several channels, the net flow of information through the model can be described by some function of these channels (linear or otherwise). If an individual's information processing capacity falls below some critical value, then they may experience difficulty with reading. In this view, a critical reduction in information flow could be caused either by a restriction within a single channel, or by a variable combination of restrictions across two or more channels. Clearly, this model avoids the problem of forcing a division between phonological and visual impairments when trying to explain children's reading problems. It allows variable contributions from several factors in different individuals and is consistent with the interrelationships we found between motion detection and phonological awareness in primary-school children.

In conclusion, we have identified a novel association which suggests that motion sensitivity statistically predicts the pattern of children's reading errors when they read regularly spelled words. We argue that this is caused by positional uncertainty. We have also shown that while the magnitude of this effect depends on children's phonological skills, these two factors seem to be independent from one another—at least in this sample of children. The framework we have used to interpret our results is open to further experimental testing, but our results do suggest that both visual and phonological problems may contribute to children's reading problems.

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