Coherent motion detection and letter position encoding

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Abstract

We identified 24 'good' and 24 'poor' coherent motion detectors from an unselected sample of young adults. The two groups were matched for reading ability, age and IQ. All subjects carried out two tasks in which optimal performance depended on accurate letter position encoding: a lexical decision task and a primed reaction time task. We found that accurate letter position encoding was predicted by performance in the motion detection task. Since coherent motion detection depends on input from the magnocellular pathway, these findings suggest that information carried by the magnocellular system may be required for encoding letter position. Furthermore, these results may have implications for reading disability which is said to be associated with magnocellular dysfunction. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The Diagnostic and Statistical Manual of Mental Disorder [1] defines reading disability (reading disorder) as "reading achievement … substantially below that expected, given the person's chronological age, measured intelligence, and age-appropriate education". Although there is debate about whether reading disability should best be defined by examining achievement discrepancy with respect to IQ [2], it is well established that a major cause of such individuals' reading problems lies in the phonological domain [3,4]. It is thought that 'fuzzy' or 'underspecified' phonological representations lead to difficulties with mapping letters onto sounds. Consequently, reading disabled people often find it particularly hard to read nonsense words [5].

Reading disabled individuals also show abnormal responses to a variety of dynamic visual stimuli. For example, there are functional MRI [6], electrophysiological [7,8] and psychophysical studies which suggest that disabled readers find it abnormally difficult to detect coherent motion in random dot kinematograms [9], uniform field flicker [10] and flickering sinewave gratings [11,12]. These findings have been interpreted as evidence for a 'magnocellular deficit' in reading disabled people, a hypothesis which is still under investigation (For a fuller discussion see Refs [13] and [14]). However, the very existence of an association between reading disability and performance on visual tasks like motion detection raises a clinically important question: does abnormal visual processing, independent of phonological problems, affect some children's reading?

To address this issue, we first argued on the basis of earlier studies [9] for a continuum of performance on motion detection tasks in the population at large. This methodological simplification allowed us to investigate the relationship between motion detection and reading behaviour in general, thereby avoiding the problems caused by imprecise definitions of 'reading disability'. Accordingly, we measured coherent motion detection in a sample of 58 unselected primary school children. In a single word reading task, we found that 'poor' motion detectors were more likely than 'good' motion detectors to make 'letter' errors. 'Letter' errors were orthographically inconsistent nonsense responses, e.g. misreading VICTIM as VIKIM, or GARDEN as GRANDEEN. This result held even when chronological age, reading

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Table 1
Subject characteristics comparing 'good' and 'poor' motion detectors

Variable	'Good' motion detectors (n = 24) mean (S.D.)	'Poor' motion detectors (n = 24) mean (S.D.)	P value for t-test comparison
Coherence at threshold (percentage)	13.7(3.0)	29.0(9.1)	$P < 0.0001$
Chronological age(years: months)	20.0(11.3)	20.8(1.4)	$P > 0.05$
WAIS-R block design (scaled score, max = 19)	12.6(2.1)	11.5(2.3)	$P > 0.05$
WAIS-R similarities (scaled score, max = 19)	13.0(1.4)	12.3(1.6)	$P > 0.05$
Schonell single word reading list errors (max = 110)	4.4(2.9)	6.25(4.2)	$P > 0.05$
Time taken to read Schonell (sec)	75.3(15.3)	85.7(22.4)	$P > 0.5$
Nonword reading errors (max = 30)	1.9(1.6)	2.4(3.6)	$P > 0.1$
Time to read nonword list (sec)	23.8(7.2)	25.4(7.4)	$P > 0.1$

ability, IQ, and phonological processing were controlled [14]. To explain this effect, we proposed that 'poor' motion detectors might not encode letter position as accurately as 'good' motion detectors. We envisage that positional uncertainty of this kind could lead to scrambled or nonsense versions of what was actually printed on the page, hence the increased risk of 'letter' errors during reading.

1.1. The present study

In the present study, we sought direct evidence linking coherent motion detection with letter position encoding in the general population. The rationale behind our experiments was to compare a group of 'poor' motion detectors with a group of 'good' motion detectors on two tasks in which optimal performance explicitly depended on accurate letter position encoding. 'Good' and 'poor' motion detectors were drawn from an unselected sample of young adults and they were matched as closely as possible across a number of variables known to affect reading. In this situation, we argue that when 'good' and 'poor' motion detectors are compared, any difference in the experimental tasks may then be attributable to the group difference in performance on the motion detection task [15].

2. General methods

2.1. Subjects

A total of 58 undergraduate students from Newcastle University were pre-tested as potential participants in this study. Each student carried out a coherent motion detection task, two sub-tests from the WAIS-R IQ battery (similarities and block design) and two timed reading tests. We then used a 'median split' to divide the sample into one group of 29 'good' and another group of 29 'poor' motion detectors (median motion

threshold for the sample was 19.0%). Next, we removed five subjects from each group to match individuals as best we could for chronological age, both IQ sub-tests and both reading tests. This procedure resulted in 24 'good' and 24 'poor' motion detectors who carried out both Experiments 1 and 2; their characteristics are described in Table 1. All subjects had normal or corrected to normal visual acuity.

2.2. Psychological test battery

All subjects were given two sub-tests from the WAIS-R IQ test battery: similarities and block design, to assess verbal and non-verbal reasoning respectively. Each subject was asked to read aloud all the items from the Schonell reading accuracy test [16] as well as a list of 30 nonwords [17]. When the reading tests were being explained to the subjects, it was emphasized that even though they were being timed, they were encouraged to read words as accurately as possible [18].

2.3. Coherent motion detection

Subjects sat 60 cm from an Iiyama Vision Master Pro-17 monitor (70 Hz vertical refresh) on which the random dot kinematograms were displayed. The stimuli were generated by a PC and comprised two rectangular patches each containing 300 randomly arranged white dots on a dark background. At 60 cm each patch of dots subtended $8.8 \times 12.4°$. The patches were separated by a horizontal distance subtending 4.3°. The luminance of each white dot was 94.7 cd/m² while the luminance of the darker background was set to 0.9 cd/m² (measured with an OptiCal digital photometer), giving a Michelson contrast of 98%. The room was illuminated by strip lights alone, producing a room illuminance of approximately 700 lux. The appearance of the stimuli is shown in Fig. 1

We used a two alternative force choice method (2AFC) to identify subjects' coherence thresholds. On
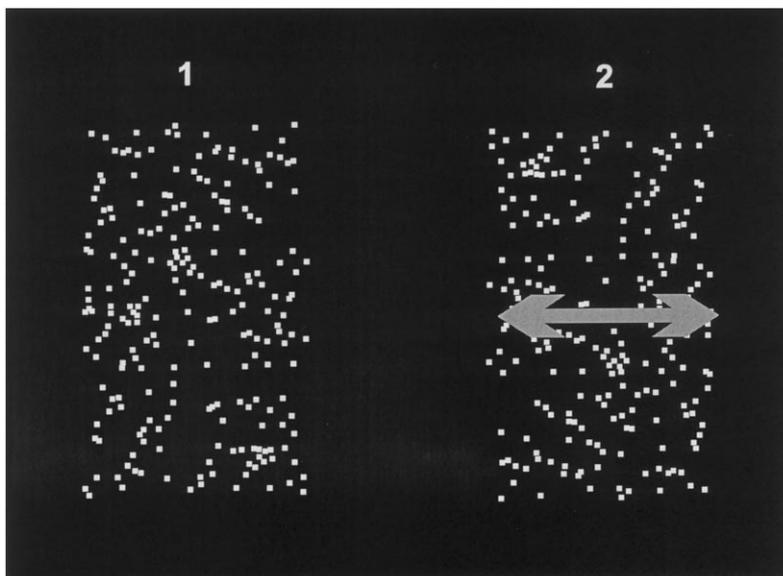
Fig. 1. Diagrammatic representation of both patches of the motion stimulus. In this example patch 2 is shown with coherent side to side movement.

each trial, which lasted 2300 ms, coherent motion appeared randomly in one of the two patches. Coherence was varied according to a '1-up-1-down staircase procedure' (for further stimulus details see ref. [14]). The experimenter initiated each trial and subjects 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 subject's response the next trial started automatically one second later. Subjects were encouraged to make sure that they had looked carefully at both panels before they made their decision. 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.

3. Experiment 1: lexical decision task

3.1. Objective

We propose that 'poor' motion detectors should encode letter position less accurately than 'good' motion detectors. Therefore, 'poor' motion detectors should be more likely to 'unscramble' briefly presented anagrams and respond to them as if they were words.

3.2. Methods

We used a lexical decision task in which subjects were presented 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:

1. 'Left anagrams' (L): letter positions 2 and 3 were swapped (OCEAN > OECAN).
2. 'Right anagrams' (R): letter positions 3 and 4 were swapped (OCEAN > OCAEN).
3. '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, while the other half of the stimuli were based on low frequency words.

We treated words as foils because peoples' reaction times in lexical decision tasks are known to be quicker, and their responses more accurate for words than pseudowords or random letter strings [19,20]. This 'word superiority effect' (WSE) is thought to be due to a top-down influence from whole words. Since our subjects were skilled readers attending university, we expected that the WSE would be more than likely to overwhelm any potential differences in response to accuracy for words when 'good' and 'poor' motion detectors were compared. We also expected both groups of subjects to show the word frequency effect' for word stimuli; i.e. reduced accuracy for low frequency words compared to high frequency words [21].

3.3. Stimuli

Using a counterbalanced design, subjects were presented a total of 144 five letter stimuli for lexical decision. The stimuli comprised: 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.

The words used in the experiment were selected from the Oxford Psycholinguistic Database [22]. Half of them were high word frequency and half were low frequency. The means of the Kucera-Francis word frequencies were 192.8 (S.D. = 315.7, range = 13–1815) and 2.8 (S.D. = 2.0, range = 1–10) respectively. High and low frequency words were of comparable imageability (mean 437.5 and 439.5, S.D. 123.0 and 100.1 respectively). Table 2 shows examples of the high and low frequency word and anagram stimuli.

3.4. Procedure

Subjects sat 60 cm from the same VDU display described above. Stimuli were presented under computer control. Black letters and symbols were presented on a white background (Michelson contrast = 98%, as above). Each trial comprised the following sequence of events which appeared in the middle of the monitor screen: fixation cross (300 ms), blank screen (300 ms), letter string target (43 ms), pattern mask (100 ms) and response prompt illustrated in Fig. 2.

All letter strings were presented in upper case, each letter subtending 0.4° vertically. At the end of each trial a prompt appeared asking the subject to press 'one' if they thought they had seen a word and 'zero' if not. Subjects' responses were automatically recorded as correct or incorrect: for example, if the stimulus was a word then 'one' is counted as a correct response; if the stimulus was an anagram, 'one' is counted as an incorrect response. The computer also logged how long subjects took to make their responses.

3.5. Results

Table 3 shows the mean reaction times in the lexical decision task for words and L, R and F anagrams.

As expected on the basis of both the word superiority and word frequency effects, subjects' response times were quicker for word stimuli than for anagrams (with the exception of low frequency words for 'good' motion detectors) and were also quicker for those stimuli based on high frequency words than low frequency words.
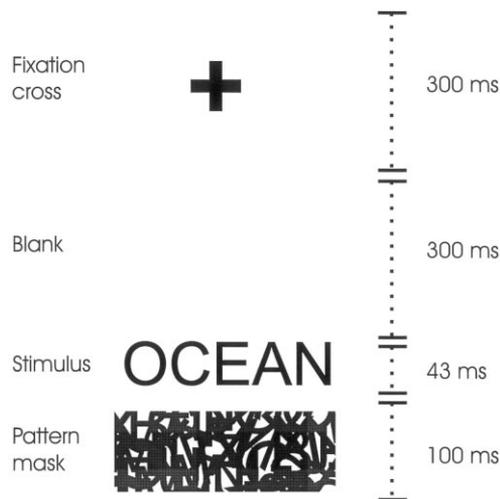

Fig. 2. Shows a schematic representation of the sequence of events in each trial of Experiment 1. All events appeared centred on the middle of the display monitor. The pattern masks were generated by randomly rotating, chopping up and then scattering pieces of actual letters to compile the mask images.

These findings were confirmed quantitatively by a one between groups, two repeated measures analysis of variance (ANOVA). The main effects of stimulus type and word frequency were significant at $P < 0.05$ ($F_{3,138} = 5.7$, $P = 0.001$; $F_{1,46} = 13.4$, $P = 0.0006$ respectively). Neither the main effect of group, nor any interaction terms were significant at $P < 0.05$.

Table 4 and Fig. 3 show the mean percentage errors that subjects made in the lexical decision task when responding to words and L, R and F anagrams.

Both groups of subjects made more errors (i.e. inappropriate 'no' responses) to anagrams than to words for the high frequency stimuli, but this difference between words and anagrams disappeared for low frequency stimuli. The main result which supports our hypothesis is that 'poor' motion detectors made more errors on the

Table 2
Examples of word and anagram stimuli from Experiment 1

Frequency	Words	L anagrams	R anagrams	F anagrams
High	FINAL	FNIAL	FIANL	FANIL
	TITLE	TTILE	TILTE	TLTIE
	EQUAL	EUQAL	EUAUL	EAUQL
	REPLY	RPELY	RELPY	RLPEY
Low	PROXY	PORXY	PRXOY	PXORY
	ABYSS	AYBSS	ABSYS	ASYBS
	MURAL	MRUAL	MUARL	MARUL
	STOIC	SOTIC	STIOC	SIOTC

Table 3
Reaction times for the lexical decision task in Experiment 1.

Stimulus	'Good' motion detectors (n = 24)	'Poor' motion detectors (n = 24)
	Reaction time (mins) mean (S.D.)	Reaction time (mins) mean (S.D.)
High frequency		
Words	543(218)	480(174)
L anagrams	599(256)	537(180)
R anagrams	672(398)	512(176)
F anagrams	629(271)	632(230)
Low frequency		
Words	672(323)	575(180)
L anagrams	652(311)	591(175)
R anagrams	691(357)	632(242)
F anagrams	740(426)	647(293)

anagram stimuli than 'good' motion detectors did. Moreover, it is clear from Fig. 3 and Table 4, that this 'unscrambling' effect for high frequency stimuli was bigger for L and R anagrams than it was for F anagrams.
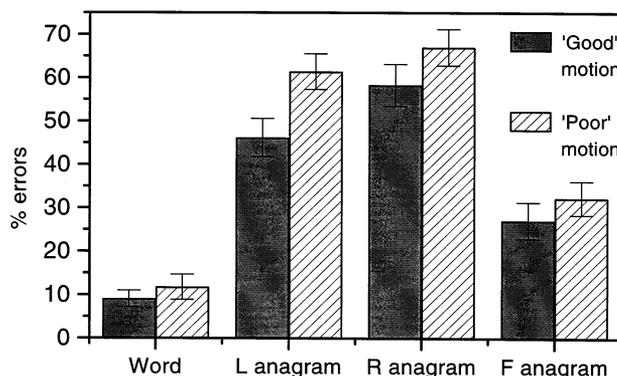
We carried out a one between groups, two repeated measures ANOVA of subjects' percentage errors. Error percentages were arcsine transformed prior to analysis [23]. The main effects of motion detection, frequency and stimulus were all significant at $P < 0.05$ ($F_{1,46} = 4.3$, $P < 0.05$; $F_{1,46} = 19.1$, $P < 0.0005$; $F_{3,138} = 61.5$, $P < 0.0005$). The two way interaction stimulus x frequency was also significant ($F_{3,138} = 53.1$, $P < 0.0005$). No other two or three-way interactions were significant at $P < 0.05$. Note: one sample t-tests showed that while the scores for 'good' motion detectors on high frequency L and R anagrams were not significantly different from 50% ($t = -0.87$, $P > 0.1$; $t = 1.73$, $P > 0.05$), the scores for 'poor' motion detectors were ($t = 2.77$, $P = 0.01$; $t = 4.0$, $P < 0.001$). Therefore, it is impossible to tell whether or not 'good' motion detectors were guessing when they responded to high frequency L and R anagrams. However, 'poor' motion detectors performed significantly worse than chance on these stimuli. Since their responses were also faster than those of 'good' motion detectors, this suggests that 'poor' motion detectors genuinely did treat high frequency L and R anagrams as words.

As can be seen in Table 1, 'good' and 'poor' motion detectors were not perfectly matched across all eight psychometric variables. Therefore, to take account of these residual differences, we carried out a multiple logistic regression analysis in which we tested whether the association between motion detection and performance on the lexical decision task held up, even when chronological age, IQ and reading ability were con-

HIGH WORD FREQUENCY STIMULI

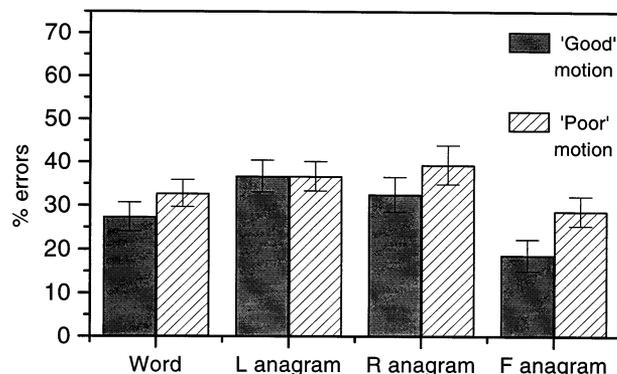### LOW WORD FREQUENCY STIMULI

Fig. 3. Shows bar charts of the mean percentage errors that 'good' (gray) and 'poor' (hatched) motion detectors made when presented with Words, L anagrams, R anagrams and F anagrams in Experiment one. Error bars = ± one standard error of the mean. Results are shown separately for stimuli based on high or low word frequency.

Table 4
Mean percentage errors made by 'good' and 'poor' motion detectors in the lexical decision task in Experiment 1

Stimulus	'Good' motion detectors ($n = 24$)	'Poor' motion detectors ($n = 24$)
	% Errors mean (S.E.)	% Errors mean (S.E.)
High frequency		
Words	9.10% (1.9)	11.8% (2.9)
L anagrams	46.2% (4.4)	61.4% (4.1)
R anagrams	58.3% (4.8)	67.0% (4.2)
F anagrams	27.1% (4.2)	32.3% (3.9)
Low frequency		
Words	27.4% (3.3)	32.8% (3.1)
L anagrams	36.8% (3.7)	36.8% (3.4)
R anagrams	32.6% (4.0)	39.5% (4.5)
F anagrams	18.7% (3.6)	28.8% (3.4)

trolled for. Since we treated motion detection as a continuous variable, no information about subject performance was thrown away. We applied the logit transform (i.e. log odds) to stabilize the variance in our multiple regression analyses [24]. Regression coefficients are expressed as log odds ratios which can be converted to odds ratios (i.e. $P/1 - P$), also known as risk values. Odds ratios greater than one represent increased risk; values less than one represent reduced risk. We carried out three separate multiple regression analyses, one for each anagram type (L, R and F). The regression model we used was:

Model: $\log e(P/(1 - P)) = b_1x_1 + b_2x_2 + b_3x_3$

$+ b_4x_4 + b_5x_5 + b_6x_6 + b_7x_7 + b_8x_8 + b_9x_9$

where P is (anagram errors)/12; x_1 is chronological age; x_2 is block design; x_3 is similarities; x_4 is word frequency; x_5 is Schonell reading errors; x_6 is Schonell reading time; x_7 is nonword reading errors; x_8 is nonword reading time; x_9 is motion detection

Table 5
Output from logistic regression models in Experiment 1

Anagram stimulus	Explanatory variable units	Regression coefficient (logit)	Standard error	Change in Chi^2 at 1df	P value	Odds ratio / unit
L	Intercept	−1.62	0.26	39.3	$P = 0.0001$	.
	Motion detection	0.020	0.0059	10.8	$P = 0.001$	1.020
	Nonword time	0.027	0.0086	9.7	$P = 0.002$	1.027
	Word frequency	0.71	0.12	33.9	$P = 0.0001$	2.029
R	Intercept	−1.64	0.26	38.4	$P = 0.0001$	.
	Motion detection	0.016	0.0061	6.5	$P = 0.01$	1.016
	Nonword time	0.029	0.0088	11.3	$P = 0.0008$	1.030
	Word frequency	1.10	0.12	79.4	$P = 0.0001$	3.0006
F	Intercept	−2.15	0.29	52.5	$P = 0.0001$	.
	Nonword errors	00.063	0.022	7.8	$P = 0.005$	1.065
	Schonell time	0.010	0.0033	9.6	$P = 0.002$	1.010
	Word frequency	0.31	0.13	5.2	$P = 0.02$	1.359

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. All four fitting procedures gave goodness of fit measures (i.e. the − 2 log likelihood statistic) which were significant at $P < 0.0005$. Since there was little to choose between them, we have reported the simplest models in Table 5.

Table 5 confirms that a significant association exists between motion detection and the proportion of errors made in the lexical decision task for L and R anagrams, but not F anagrams. This result held even when the other psychological variables were controlled for and provides further support for our hypothesis. The frequency of the words from which anagrams were created also played a significant role; subjects made more errors on high frequency stimuli.

One possibility to account for the lack of an effect of motion detection on the errors made to F anagrams might be that these 5-letter strings contain more unusual bigrams (e.g. QI, PZ and XM) than L and R anagrams do. 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). This database of approximately 440000 English words contains 61158 bigram types and 11507,291 bigram tokens. We calculated a position sensitive bigram frequency score for each anagram and then compared these scores across the three kinds of anagram. For example, the L anagram BRAON comprises four bigrams: BR, RA, AO and ON, which have token frequency counts of 48158, 220655, 1773 and 223725 respectively (total = 494311). A one factor ANOVA (anagram type: L, R or F) of the total bigram scores (L mean = 417887.2; R mean = 396204.4; F mean = 368848.3) was not significant at $P < 0.05$ ($F_{2,213} = 0.65$, $P = 0.5$). Tukey HS.D. post-hoc multiple comparisons confirmed the absence of any significant differences between pairs of means

($a = 0.05$, minimum significant difference = 101357). Therefore it is unlikely that bigram frequency can explain why there was no association between motion detection and errors made to F anagrams.

3.6. Discussion

The main finding from Experiment one was that 'poor' motion detectors made more errors on high frequency L and R anagrams than 'good' motion detectors did. Research suggests that, during the early visual analysis of text, the positions of the first and last letters of a word are rigidly encoded [25,26]. However, internal letter position encoding is more flexible, and consequently more fallible [27,28]. Therefore, it is plausible that errors in the anagram task could reflect some uncertainty about the positions of adjacent letters. Specifically, a subject 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. Because of our experimental design, since 'poor' motion detectors made more slips of this kind than 'good' motion detectors did, this difference may be attributed to the one main difference between the groups; namely performance on the motion detection task. This interpretation is given further weight by the multiple regression analyses. Even when we removed any confounding influence of age, IQ and reading ability we still showed a positive relationship between motion detection and error rates in the lexical decision task for L and R anagrams. Thus, we argue that the results from Experiment 1 support the idea that there is an association between motion detection and letter position encoding. The fact that there was no effect of motion detection on error rates for high frequency F anagrams may also be explained in terms letter position encoding. In order to unscramble an F anagram, letter positions two and four would have to be swapped around. When such a 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 in the case of L and R anagrams.

The overall error rates for low frequency anagrams were smaller than those for the high frequency anagrams, and this effect was similar for both 'good' and 'poor' motion detectors. It is likely that the word frequency effect [21] could account for this result. All subjects made more errors to low frequency words than to high frequency words; i.e. they were more likely to respond to low frequency words as if they were non-words. Therefore, presenting subjects with anagrams based on the kind of words that subjects were already treating as non-words was unlikely to have elicited anything other than a non-word response (i.e. an appropriate response to anagram stimuli) and would account for the lower error rates for the low frequency anagrams.

4. Experiment 2: multiple alphabetic decision task

4.1. Objective

In Experiment 1, by using a lexical decision task, we could not prevent top-down influences from real words affecting subjects' performance. Computational models of visual word recognition suggest that whole word based information must be included to provide adequate simulations of performance in lexical decision tasks [29]. Therefore, despite the fact that we interpreted Experiment 1 in terms of letter position encoding, we can not discount a significant influence from whole words.

In Experiment 2 we addressed this problem by using a 'multiple alphabetic decision task' [30] to look for an association between motion detection and letter position encoding. Since the target stimuli in this task are random consonant strings which do not exist in the lexicon, there can be no top-down influence from words. The 'multiple alphabetic decision task' is a primed reaction time task. Subjects are asked to respond as rapidly as possible when presented with a target made up entirely of letters (a positive trial), but not to respond when the target contains a non-alphabetic symbol (a foil trial). All targets are preceded by a briefly presented prime sequence. The degree to which letter-position information is shared between prime and target is systematically varied. Priming effects in this task are thought to reflect immediate and automatic encoding of letter position during visual word recognition. We predicted that 'poor' motion detectors ought to be less sensitive to priming than 'good' motion detectors.

4.2. Stimuli

All the prime and target stimuli appeared in upper case black Arial font on the same white background as experiment 1 (Michelson contrast = 98%). Both the prime and mask were half the size of the target string, each letter subtending 0.4° vertically. The mask consisted of four hash marks (# # # #) [30]. Each letter in the target stimuli subtended 0.8° vertically, minimising any spatial overlap between prime and target. Positive targets were made up of four consonants randomly selected from B C D F G H K L M N P Q R S T V X Z. Foil targets were three consonants from the above set and a non alphabetic symbol from ?! < > [ ]% + .

There four categories of positive trial as follows:

1. Absent Prime (AP): no letters in common between the prime and target (prime = MDQV, target = PLTB), giving minimal shared information.
2. Same position (SP): all the letters in the prime appeared in an identical position in the target (prime = PLTB, target = PLTB), giving maximal shared information.
3. Displaced Position (DP): the same letters appeared in both prime and target, but half of them in a different position (prime = LPTB, target = PLTB), giving 50% positional similarity but 100% similarity for identity.
4. Changed Position (CP): all the same letters appeared in the prime and target, but with a complete change in position (prime = BPLT, target = PLTB), giving 0% similarity in position, but 100% similarity for identity.

DP trials could be generated in six different ways: exchanging 1st and 2nd letters; 1st and 3rd; 1st and 4th; 2nd and 3rd; 2nd and 4th; or 3rd and 4th. These different permutations were counterbalanced across all DP trials. For each of the four conditions AP, DP, CP and SP, 18 different prime/target pairs were generated, giving a total of 72 positive trials with four levels of similarity between prime and target. The 72 foil trials comprised three letters and a symbol. The position in which the symbol appeared (whether 1st, 2nd, 3rd, or 4th), was counterbalanced, with 18 stimuli in each condition. The foils were also preceded by a prime which contained no letters in common with the target, but which was taken from those which preceded the positive targets. Thus every prime appeared twice: once before a positive target, and once before a foil target.

4.3. Procedure

The same subjects, monitor, computer and viewing conditions were used as in Experiment 1. At the start of Experiment 2, subjects were shown an instruction sheet which explained the procedure. Next they carried out 24 practise trials to familiarise themselves with the

procedure and minimise any potential learning effects. This was followed by three blocks of 144 trials (432 in total). Positive and foil trials were randomly interleaved with 50% chance of occurrence. Each trial consisted of the following sequence of events all of which were centred on the middle of the monitor screen: fixation cross (1000 ms), prime (43 ms), mask (28 ms), target (800 ms, or until the subject responded by pressing the space bar-whichever was soonest), blank screen (2000 ms), after which the cycle was repeated again with a different stimulus). Reaction times were recorded to the nearest millisecond.

4.4. Results

Table 6 shows the mean reaction times for each experimental condition, comparing 'good' with 'poor' motion detectors.

It is clear from Table 6 that for both groups of subjects, the rank ordering of reaction times was the same: $AP > CP > DP > SP$, and replicates the findings of Peressotti and Grainger [30]. Moreover the range of reaction times was comparable to these authors' data, the biggest difference in reaction times between conditions being of the order of tens of milliseconds. Table 6 also shows that 'good' motion detectors consistently reacted more quickly than 'poor' motion detectors.

We carried out a one between groups, one repeated measures ANOVA of subjects' reaction times. Both main effects of group and condition were significant at $P < 0.05$ ($F_{1,46} = 10.34$, $P = 0.002$; $F_{3,138} = 7.25$, $P < 0.0005$ respectively). The interaction term between group x condition was not significant at $P < 0.05$. We then carried out multiple pair-wise comparisons of the mean reaction times for the four experimental conditions. For 'good' motion detectors, Tukey's HSD revealed three main groupings such that AP was

Table 6
Mean reaction times to priming task in Experiment 2, comparing 'good' with 'poor' motion detectors

Stimulus	'Good' motion detectors	'Poor' motion detectors
	Reaction time (ms) mean (S.E.)	Reaction time (ms) mean (S.E.)
AP (MDQV > PLTB)	410.1 (9.9)	452.5 (9.6)
CP (BPLT > PLTB)	407.8 (9.5)	449.2 (8.5)
DP (LPTB > PLTB)	402.7 (9.2)	443.9 (8.7)
SP (PLTB > PLTB)	400.8 (10.6)	444.1 (9.3)

Table 7
Mean reaction times for DP experimental condition, comparing 'good' and 'poor' motion detectors in Experiment 2

Stimulus	'Good' motion detectors (n = 24)	'Poor' motion detectors (n = 24)
	Reaction time (mins) mean (S.E.)	Reaction time (mins) mean (S.E.)
DP 'Adjacent' (LPTB > PLTB)	395.8(9.8)	442.5(9.2)
DP 'Distant' (BLTP > PLTB)	408.9(9.3)	445.1(8.4)

significantly slower than both DP and SP, while CP was significantly slower than SP alone ($a = 0.05$, Minimum significant difference $= 6.76$). There were no significant differences between AP and CP, or between DP and SP. The Tukey HSD groupings for 'poor' motion detectors showed that no pair-wise comparisons reached significance ($a = 0.05$, Minimum significant difference $= 9.61$).

Since the potential differences in positional information comparing SP trials (all the same: prime = PLTB, target = PLTB) with CP trials (all different: prime = BPLT, target = PLTB) are quite extreme, we carried out a further analysis of subjects' reaction times in the DP condition. DP trials were counterbalanced such that the two letters which were shifted with respect to the target were either 'adjacent' (e.g. prime = LPTB, target = PLTB) or two or more letters 'distant' (e.g. prime = BLTP, target = PLTB). In this respect, DP trials were comparable to the L, R and F anagrams of Experiment 1. Table 7, shows that while 'good' motion detectors reacted more promptly to 'adjacent' DP trials than to 'distant' DP trials (a difference of 13 ms), this difference was negligible for 'poor' motion detectors (a difference of 3 ms).

We confirmed this result by a one between groups, one repeated measures ANOVA of subjects' reaction times. The main effects of group and stimulus condition ('adjacent' versus 'distant' DP trials) were both significant at $P < 0.05$ ($F_{1,46} = 10.5$, $P = 0.002$; $F_{1,46} = 9.0$, $P = 0.004$). In addition the two-way interaction group x stimulus was significant ($F_{1,46} = 4.0$, $P = 0.05$). A post-hoc Tukey HSD showed that the difference between 'adjacent' and 'distant' DP trials was significant for 'good' motion detectors ($a = 0.05$, Minimum significant difference $= 8.92$) but not for 'poor' motion detectors ($a = 0.05$, Minimum significant difference $= 6.25$). Finally, as is shown in Table 8, there were no statistically significant differences between the two groups in either false positive (i.e. pressing the space bar to foil stimuli) or false negative (failing to press the space bar during a positive trial) response rates.

Table 8
False positive and false negative error rates for 'good' and 'poor' motion detectors in Experiment 2

Error type	'Good' motion detectors ($n = 24$) Errors mean (S.D.)	'Poor' motion detectors ($n = 24$) Errors mean (S.D.)	P value for T-test comparison between 'good' and 'poor' motion detectors
False positive	7.6(11.0)	8.0(7.6)	$P > 0.5$
False negative	3.9(7.1)	1.2(1.8)	$P > 0.05$

4.5. Discussion

The 'multiple alphabetic decision task' generates small differences between stimulus conditions which are of the order of tens of milliseconds at most. We argue that using a reaction time task like this provided a difficult test of our hypothesis because there was so little room for manoeuvre in terms of generating differences between groups; we could only expect to see small effects. The fact that we found comparable false positive and false negative rates when 'good' and 'poor' motion detectors were compared, suggests that the data from both groups of subjects was equally reliable. The fact that we found differential group effects in Experiment 2 supports our attempt to explain the results of Experiment 1 in terms of early letter position encoding.

Peressotti and Grainger [30] interpreted their findings from the 'multiple alphabetic decision task' in the context of McClelland and Rummelhart's [31] model of letter-in-word perception. According to this interactive-activation competition (IAC) model, letters within a string are processed in parallel by a set of specialized position-specific letter detectors (PSLDs). Each letter in a stimulus string is allocated to a channel in which information is analyzed for the presence of specific letter features. The outputs of the feature detectors for a given channel serve as input to a bank of letter detectors for that channel. Thus, position information is automatically coded by the system, and a letter is always identified in its specific position within the string.

According to the IAC model, SP trials produce the fastest reaction times because the prime letters facilitate the same position specific letter units that are activated by the target letters. In comparison, AP trials produce markedly slower reaction times because none of the position specific letter units activated by the prime letters coincide with those of the target. The fact that we only found position specific priming in 'good' motion detectors is consistent with the notion that 'poor' motion detectors encode position less efficiently. In these individuals, either the allocation of each channel's position could be uncertain, or, within a given channel, there could be uncertainty about where features are with respect to each other, leading in turn to activation of inappropriate letter units. Either of these mechanisms would account for 'poor' motion detectors being unable to generate position specific priming.

In their original experiment, Peressotti and Grainger [30] recognized that it was not possible to explain the faster reaction times for DP and CP trials, compared to AP trials, in the rigid terms required by the IAC model with PSLDs. The interactive-activation model postulates independent processing channels for each letter position with no cross-activation possible between channels. Yet they observed significant priming when position information was only partially shared between prime and target. They proposed two ways in which the PSLD version of the IAC model could be modified to account for this 'position independent priming'. One involved adding a set of higher-level, position-independent alphabetic units (PILDs) that receive input from the PSLDs. The other involved relaxing the independent-channels aspect of the model by introducing some form of cross-talk between neighboring letter positions. In their Experiment 4, Peressotti and Grainger [30] showed that position independent priming developed after position specific priming, consistent with their PILD modification to the PSLD hypothesis. In the present study, 'good' motion detectors reacted about equally to AP, CP and 'distant' DP trials. This suggests that even though letter identity was shared between prime and target in the CP and 'distant' DP trials, position information was nevertheless too widely distributed to allow position independent priming to develop. However, these same subjects' did respond more quickly in 'adjacent' DP trials than AP trials, consistent with the appearance of position independent priming in this situation. This result suggests that the cross-talk required to modify the PSLD model adequately may only need to extend across adjacent letter positions. The fact that the reaction times of 'poor' motion detectors were indistinguishable across all conditions is consistent with failure to encode letter position accurately, even in a modified PSLD model.

5. General discussion

In this study of young adults, we have found an association between coherent motion detection and performance in two tasks in which optimal responses

explicitly depend on accurate information about letter position. Since the only major difference between 'good' and 'poor' motion detectors was their visual function, it is reasonable to suggest that this link may in fact be causal. However, there are two ways in which this link could have occurred. The first 'bottom up' process is one we have previously suggested [18]: variability in our motion detection task directly reflects abnormal magnocellular system function. Any process which requires input derived from the magnocellular system-like position encoding and motion detection-would therefore be impaired. Alternatively, a 'top down' mechanism might affect performance in both our motion detection task as well as the letter position tasks. A likely candidate for such a mechanism is attentional processing in which the magnocellular pathway has also been implicated [32].

The relationship between objects, their locations and attention has been one of the central questions in the attention literature. In a series of experiments, Triesman and Schmidt [33] showed that before attention was allocated, the location of information about the features associated with display elements was poorly coded. Indeed the coding of position was so poor that illusory conjunctions could occur, where for example the colour of one item became associated with the form of another item. Although there has been some doubt about the status of these errors [34], the poor coding of location, along with the possible lack of binding between stimulus elements, would result in a poor spatial code for relatively complex stimuli such as letters.

Within features integration theory [35], attention acts to bind the various features of an item together and to a specific location. Attention within this kind of framework is often conceptualized as a spotlight moving spatially [36]. However a growing body of evidence suggests that attentional processing itself is modulated by display structure [37]. As a result, a number of researchers have suggested that attention is object-based and directed to objects independent of their spatial extent or location [37,38]. This in turn suggests that attention acts after the formation of complex embedded structures such as words. There are then two clear possibilities for the role of attention in the relationship between letter position coding and motion detection. If the 'poor' motion detectors in the current study have a deficit in the processes that occur before the action of attention, such a deficit is best conceptualized as pre-attentive. Alternatively the pre-processing of the stimuli may be unaffected, but the attentional process itself may be defective. This would be a primary deficit of attention. Although it is conceptually simple to see pre-attentive and attentive processes as two separate modules, the distinction may not be so clear cut, indeed attentional modulation of processes may occur throughout the system [39]. Further research is

therefore 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 starting point for this research is the observation that reading disabled individuals perform poorly on visual tasks like motion detection. Previously, we have shown that in an unselected sample of primary school children, 'poor' motion detectors are at greater risk of making orthographically inconsistent nonsense, or 'letter' errors when they read-an effect which can be explained in terms of inaccurate letter position encoding. The findings of this study make an explicit link between motion detection and letter position encoding. Therefore, we suggest that impaired visual sensitivity of the kind frequently seen in reading disabled people may directly affect how they read.

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