THE STABILITY OF BINOCULAR FIXATION DURING READING IN ADULTS AND CHILDREN

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Two recent studies have shown that children's binocular vision can affect reading (Cornelissen *et al.* 1991, 1992). A binocular task, the Dunlop Test (DT), was used to define two groups of children who had been referred to an orthoptic clinic suspected of having reading difficulties. The groups were labelled 'DT pass' and 'DT fail', and the children were matched for age, reading age and IQ. Only children in the 'DT fail' group read differently if print size was reduced, or if they were asked to read with both eyes as opposed to one. The difference observed was an increase in the proportion of their reading errors which were non-words: misreading, for example, 'guest' as 'gustetit'. In both experiments, the only factor which differentiated the groups was their performance on the binocular task, and the only factor which was manipulated during the experiments was the visual appearance of text. Thus the change in the proportion of non-word errors made by the 'DT fail' group was probably the result of visual confusion when print size was reduced or when children read with both eyes instead of one.

During the Dunlop test, children view two almost identical macular-size fusion scenes through a synoptophore. The slide seen by the right eye has a house with an arrowheaded post to the left of the front door, while the left eye sees a house with a post with a circle on top, to the right of the front door. The angle of the synoptophore tubes is adjusted until children fuse the two scenes. Then the synoptophore tubes are abducted at 1·5°/s, and the children attempt to diverge their eyes to maintain fusion. When children understand clearly what they have to do, most gain a clear impression that one of the posts moves towards the door during this procedure. Beyond about 5° divergence, diplopia intervenes. The test is repeated 10 times, the slides being changed over frequently to try to prevent children guessing. In the two studies described above, children were put into the 'DT pass' group if they saw the post move on the same side in eight or more trials out of 10, because their test responses were stable; otherwise children were put into the 'DT fail' group, because of unstable responses.

Clearly the DT makes both 'motor' demands on the vergence system and 'sensory' demands on the fusion process, but it does not reveal which of the two may be at fault in children who fail the test. In the reading experiments described above, therefore, visual confusion of words might have been caused by a failure of vergence control in the 'DT fail' group: disparate retinal images might not have been brought into close enough register

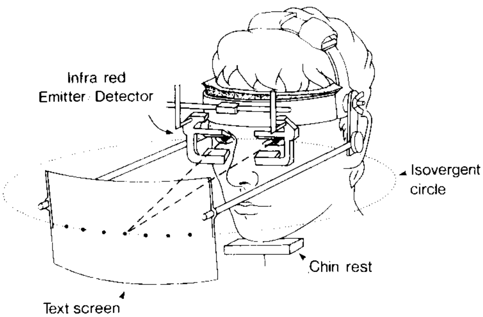

Fig. 1. Set-up of recording apparatus.

to allow fusion to occur. Alternatively, children in the 'DT fail' group might have had some kind of sensory abnormality where, despite adequate vergence control, visual confusion of words could have been caused by a factor such as a failure of stereo-correspondence.

In this paper we address the first of these possibilities: do children who fail the DT make unusually large fixation vergence errors when they read? In the first experiment we obtained control data about the stability of vergence during reading fixations in normal children and adults. This was necessary because very little is known about changes in binocular vergence during reading. For example, Stromberg (1938) used a photographic technique developed by Tinker (1931) to identify marked changes in divergence during reading fixation. Unfortunately, his data are not reported in terms of angular movement of the two eyes. More recently, Kowler *et al.* (1992) used magnetic search coils to record the movements of both eyes as well as the head while their experienced adult subjects read printed text. Although binocular variations in vergence were not described, fixational drift velocities of up 1°/s were frequently observed monocularly. In the second experiment, we compared the binocular reading eye-movements of normal schoolchildren with those of poor readers who had been referred to an orthoptic clinic and who passed or failed the DT.

Method

Apparatus

In order to minimise recording errors due to head movement, subjects wore a helmet on which both a text screen and an infra-red eye-movement recorder (Skalar IRIS EM6500) were mounted (Fig. 1).

The IRIS system has a horizontal recording range of ±30° with a linearity of 3 per cent within ±12°. It can resolve movements of a model eye as small as 1·5′ of arc.

The text comprised eight lines of single words mounted on a screen which subtended 30° of visual angle; therefore, the horizontal eye-movements which we recorded were well within the limits of the system. Words were printed in 12-point Courier font with single-line spacing. Each letter subtended about 0·25° at the retina. Words were displayed on a white screen which was curved around an isovergent circle with a 15·7cm radius in the horizontal plane (assuming an average interpupillary distance of 58mm). This geometry ensured that the distance from the centre of the pupil to the middle of the screen was as close as possible to 30cm. The curvature of the screen ensured that the vergence demands of the reading task were held constant for all eccentricities, so that vergence drift during fixation at all eccentricities could be compared. Analogue signals from the IRIS amplifier were sampled at 250Hz and saved to disk for off-line analysis.

Procedure

Each child was given the British Ability Scales (BAS) reading test to establish reading age, and the list of single words to be read during eye-movement recording was selected from one of five difficulty levels on this basis of reading age (see Cornelissen *et al.* 1991 for details); therefore children read material appropriate for their reading ability. Adults were asked to read from a list of low-frequency words (less than about 50/million) (Thorndike and Lorge 1944).

Subjects sat with their heads supported by a chin rest. At the beginning of each experimental run, they were asked to look at calibration points straight ahead and at 5°, 10°, and 15° to the left and right. Following separate pre-calibration of the left and right eyes, subjects read two lines of words to themselves. As soon as they had finished reading, post-calibration of the left and right eyes was carried out.

This sequence was carried out four times, so that subjects read 90 words in all.

Analysis

READING EYE-MOVEMENTS

To analyse the reading data, a computer algorithm identified binocular saccade/fixation/saccade sequences according to a velocity threshold. For each eye, the algorithm placed a start mark at the beginning of fixation. This was defined as the point when eye velocity first fell below 10°/s. A 'finish mark' was then placed at the end of fixation, which was defined as the point when eye velocity first exceeded 10°/s.

The abducting eye usually tended to overshoot at the end of a saccade, whereas the adducting eye tended to reach minimum velocity asymptotically. Dynamic overshoot of the abducted eye, especially for small amplitude saccades, is well documented (Carpenter 1988, Collewijn 1988*a*), and has been attributed to assymetry in the performance of the ocular motor plant. This asymmetrical behaviour meant that, at the beginning of fixation, the right eye's 'start mark' was often placed before the left eye's. We defined binocular fixation as the period between the latest 'start mark' and the earliest 'finish mark'.

Three measures were extracted from each period of binocular fixation: (1) the size of the saccade prior to fixation, (2) the duration of fixation, and (3) the standard deviation (SD) of the mean vergence angle (left eye position minus right eye position) which was calculated for each fixation to estimate fixation vergence error (*cf.* Collewijn *et al.* 1988*a*).

CALIBRATION

Straight lines were fitted to the pre- and post-calibration data for left and right eyes separately. Error curves were then constructed from the pre- and post-calibration data to provide estimates of any drift in the system. Such drift was necessary because the slopes and intercepts of the pre- and post-calibration graphs were seldom identical. DC drift occurs because of minute shifts in the positions of the infra-red detectors relative to the eyes as well as altered reflectivity of the scleral–corneal

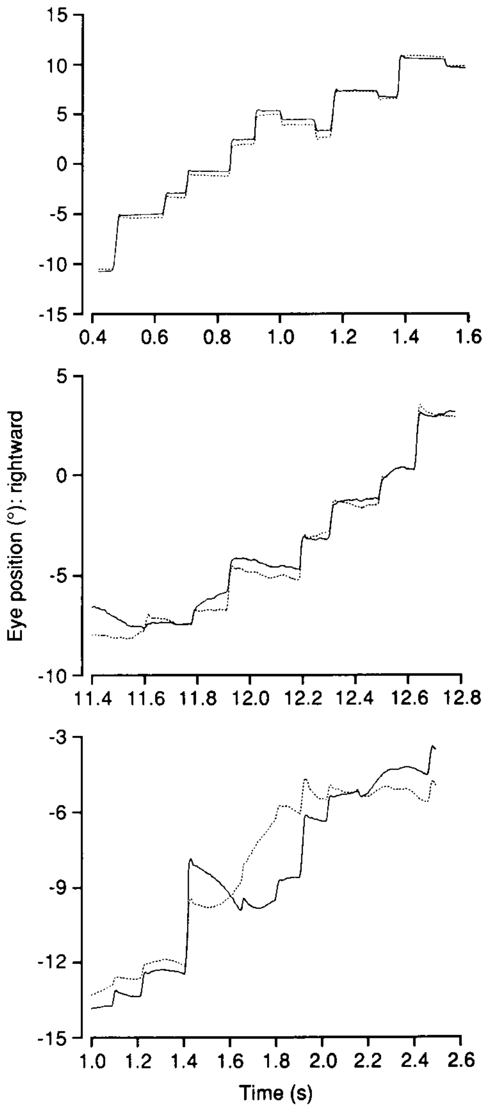

Fig. 2. Raw eye-movement data showing good, intermediate and poor stability. Y axis shows eye position in degrees (0° = straight ahead, -ve° = leftward and + ve° = rightward); X axis shows time. Right eye is represented by solid line *and left eye by* dotted line.

boundary due to drying of the eye's surface. So we needed to be sure that our results were not confounded by this unavoidable problem of infra-red reflectometry. To do this we used the absolute values of the slopes of the error curves for left and right eyes to estimate the amount of error in our measurements which could be attributed to such drifts.

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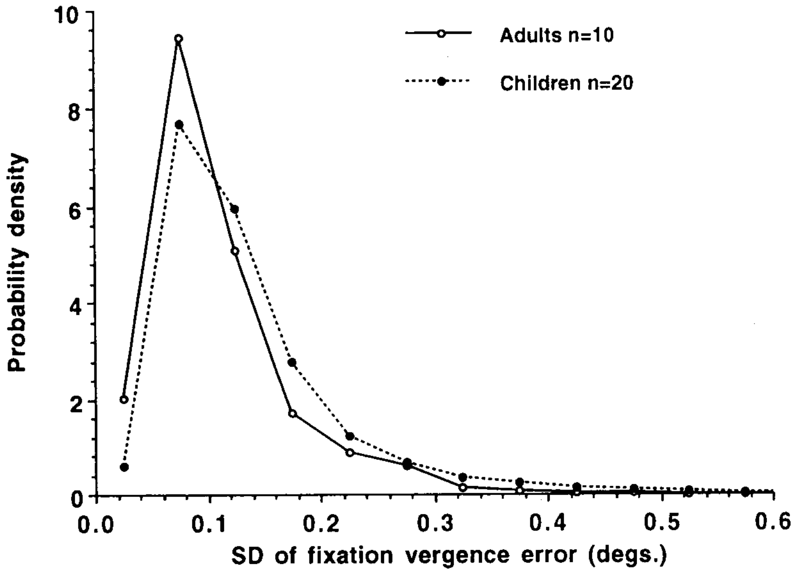

Fig. 3. Probability density functions for SD of fixation vergence error. Total area under each curve is unity.

TABLE Ia
Fixation vergence

Group	*Fixation vergence error (°)*		
	Mean (SD)	*Range*	*Skew*
Control adults (N = 10)	0·083 (0·063)	0·011–0·46	1·89
Control children (N = 20)	0·116 (0·115)	0·013–2·30	6·39
Passed DT (N = 10)	0·111 (0·107)	0·015–1·01	3·85
Failed DT (N = 10)	0·129 (0·128)	0·017–1·78	3·68

TABLE Ib
Fixation duration and saccade size

Group	*Fixation duration (ms)*		*Saccade size (°)*	
	Mean (SD)	*Range*	*Mean (SD)*	*Range*
Control adults (N = 10)	172·1 (86·4)	28–672	2·85 (1·67)	0·54–8·90
Control children (N = 20)	220·6 (147·6)	20–1680	2·69 (1·57)	0·29–8·87
Passed DT (N = 10)	241·5 (147·9)	16–1088	2·67 (1·46)	0·35–8·81
Failed DT (N = 10)	248·9 (169·2)	16–1504	2·57 (1·48)	0·36–8·10

Experiment 1

Objectives

We aimed to measure the fixation vergence errors in normal adults and children while they were reading and to see whether there was any difference between the two groups.

Subjects

With local ethical permission and informed consent from teachers, parents and subjects, we randomly selected 20 children between the ages of nine years three months and 11 years eight months from two senior classes at a local primary

TABLE II
Mean error attributable to calibration for eyes of adults and control children

Group	*Left eye (°) Mean (SD)*	*Right eye (°) Mean (SD)*
Control adults (N = 10)	±0·0024 (0·0013)	±0·0031 (0·0016)
Control children (N = 20)	±0·0067 (0·0046)	±0·0068 (0·0031)

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school. Children who wore glasses were excluded from the study. We deliberately avoided differentiating between good and poor readers because we wanted to gain some impression of the range of fixation stability during reading in schoolchildren of this age. We compared these children with 10 adult subjects who were all university graduates and whose ages ranged from 24 to 36 years.

Results

READING EYE-MOVEMENT DATA

Figure 2 shows typical examples of the raw data selected from the 3297 fixations we analysed in Experiment 1. The examples are deliberately chosen to reveal the variability in vergence fixation error between normal individuals.

Figure 3 shows the probability density functions for SDs of fixation vergence for all 10 adults and 20 primary schoolchildren together. It demonstrates that adults were less likely to make larger vergence errors while reading, though the difference was small.

For every subject, we calculated individual means for the SD of their fixation vergence, as well as mean fixation duration and mean saccade size. Table Ia shows that there was wide inter- and intra-subject variability. The mean SD of fixation vergence ranged from 0·011° to 0·46° (group mean 0·083°) in the adults and from 0·013° to 2·3° (group mean 0·115°) in the children. Table Ib shows that although there was little difference in mean saccade size between adults and children, fixation durations were shorter in adults. However, Pearson correlation analysis showed that neither saccade size nor fixation duration accounted for more than 3 per cent of the variance of fixation vergence.

We wanted to test whether the fixation vergence error differed significantly between adults and children. To avoid statistical problems caused by repeated measures (each subject made about 100 fixations), we used the individual means of fixation vergence SD in a t test comparison between adults and children. We did not include fixation duration and saccade size in an ANOVA because they accounted for so little variance. We found that the difference in the SD of fixation vergence between children and adults was small, but it reached significance ($p = 0·03$, $t_{28} = 2·02$).

RELIABILITY OF DATA

Table II shows the mean error attributable to calibration for the left and right eyes of adults and normal schoolchildren. The calibration error of adults was smaller than that of the children. Analysis of variance showed this effect to be significant for both eyes ($F_{28,1} = 8·02$, $p < 0·01$ and $F_{28,1} = 12·62$, $p < 0·01$). Nevertheless, the magnitude of this error was too small to account for the differences between adults and children. For example, we found the mean SD of the left eye position to be 0·121° for children and 0·069° for adults. The probability that this difference could be accounted for by calibration error alone was less than 1 per cent.

Discussion

These results show that when reading single words, the vergence angle of both adults and children can vary by 0·5° to 1° over the course of each 200 to 250ms fixation. On average, children made significantly larger errors than adults, though the difference was small.

How do these results compare with other published data on the stability of binocular fixation? As far as adults are

TABLE III
Characteristics of children with reading difficulties and control children

Group	*Age (yrs:mths) Mean (SD)*	*Reading age (yrs:mths) Mean (SD)*
Control children (N = 20)	10:6 (0:8)	11:5 (1:10)
Passed DT (N = 10)	10:8 (0:11)	9:9 (2:2)
Failed DT (N = 10)	10:9 (0:11)	8:10 (1:8)

concerned, the most accurate measurements have been obtained using scleral magnetic search coils. Steinman *et al.* (1982) recorded eye movements in five subjects whose heads were fixed by means of a bite bar. They found that the precision of vergence (expressed as SD of fixation vergence) during binocular viewing of simple targets was only 0·05°; when viewing a fixation target with the head rotating at 0·2Hz over a 10° range, however, Steinman and Collewijn (1980) found that the angle of a subject's vergence changed by as much as 1°, generating speeds of image drift on the retina as high as 1°/s. Ferman *et al.* (1987) subsequently confirmed Steinman and Collewijn's results for subjects whose heads could move freely.

Recordings obtained with a bite bar are comparable to the head-mount plus chin rest that we used, because in both situations the head is prevented from moving freely. We found that the mean SD of fixation vergence of our 10 adult subjects was 0·083°, which is larger than the figure of 0·05° published by Steinman *et al.* (1982). However, mean SD of fixation vergence was 0·05° or less for four of our adult subjects, all of whom had experience of visual and eye-movement recording experiments. This suggests that experienced subjects may develop smaller vergence errors, possibly because they may adopt a more deliberate and careful strategy when reading under experimental conditions.

Experiment 2

Objectives

It has been claimed that children who fail the DT make reading errors due to visual confusion. Unfortunately, it is not clear from DT responses whether those who fail have an ocular motor problem or some form of sensory abnormality, or both. In Experiment 2 we compared the reading fixations of our normal subjects with those of age-matched, clinically referred poor readers who passed or failed the DT. This allowed us to test two proposals. First, if no differences in the SD of fixation vergence could be found when poor readers who passed or failed the DT were compared, then the change in the pattern of non-word errors made by the 'DT fail' group in Cornelissen and colleagues' studies (1991, 1992) cannot be attributed to abnormal ocular motor control. Second, children referred to an orthoptic clinic represent a biased population, therefore we wanted to know whether fixation vergence errors made by clinic children differed from those made by unselected schoolchildren of the same age.

Subjects

We selected 20 subjects from a large population of children who had been referred to the orthoptic department of the Royal Berkshire Hospital in Reading because of reading difficulties. Half of them failed the DT and the other half passed. Both groups of children were matched as closely as possible for chronological age. The characteristics of these children, as well as the normal sample from Experiment 1, are summarised in Table III. As might be expected, the mean reading age of the clinically referred children was lower than that of our sample of primary schoolchildren of the same chronological age-level.

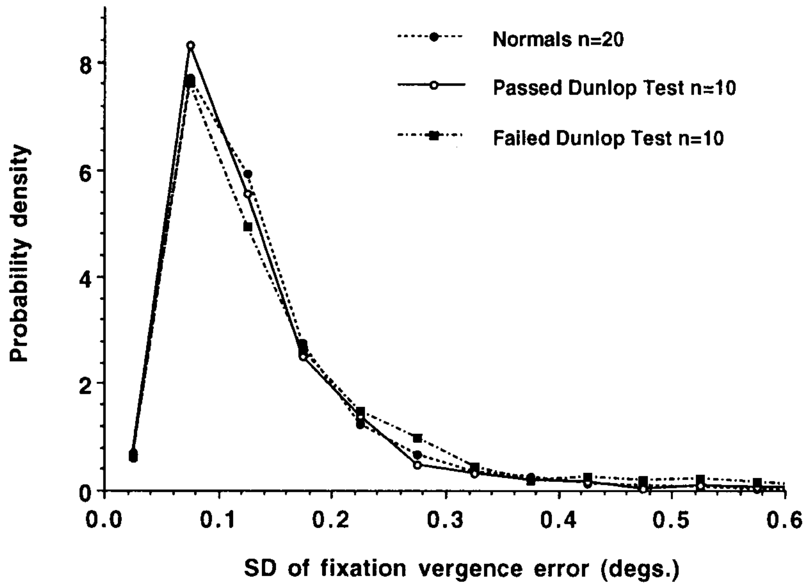

Fig. 4. Probability density functions for SD of fixation vergence error. Total area under each curve is unity.

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TABLE IV
Characteristics of subsample

Group	*Age (yrs:mths) Mean (SD)*	*Reading age (yrs:mths) Mean (SD)*
Control children (N = 8)	10:4 (0:8)	9:8 (0:11)
Passed DT (N = 8)	10:9 (1:1)	9:1 (1:0)
Failed DT (N = 8)	10:10 (1:10)	9:4 (1:7)

Orthoptic assessment, apparatus and procedure

Before performing the DT, every child was examined to exclude orthoptic and gross ocular motor as well as ophthalmological pathology (Stein and Fowler 1982). The apparatus and procedure for recording eye movements were identical to those used in Experiment 1.

Results

READING EYE-MOVEMENT DATA

Figure 4 shows the probability density functions of SD of fixational vergence from the 10 children who passed the DT, the 10 children who failed it and the normal children. It is quite clear from these curves that there was negligible overall difference between the three groups of children.

Table Ia contains the univariate statistics derived from individual means for the three groups of children. As in Experiment 1, we found wide inter- and intra-subject variability. Individual mean SD of fixation vergence error ranged from 0·013° to 2·3° (group mean 0·115°) in the normal children, 0·015° to 1·01° (group mean 0·111°) in the children who passed the DT, and 0·017° to 1·78° (group mean 0·129°) in the children who failed it. Analysis of variance confirmed that there was no significant effect of group (*i.e.* normal children, poor readers who passed the DT and poor readers who failed it) on SD of fixation vergence error ($F_{37,2} = 0·45$, $p = 0·6$).

So far the results reported come from three groups of children who were matched for chronological age: but the

TABLE V
Mean error attributable to calibration for children

Group	*Left eye (°)* *Mean (SD)*	*Right eye (°)* *Mean (SD)*
Control children (N = 20)	±0·0067 (0·0046)	±0·0068 (0·0031)
Passed DT (N = 10)	±0·011 (0·010)	±0·010 (0·010)
Failed DT (N = 10)	±0·0061 (0·0044)	±0·016 (0·022)

children from the clinic were poorer readers than the primary-school sample of children (Table III). Therefore, we wanted to ensure that the 'null' results reported still held when children were matched for reading age instead of chronological age. Table IV describes the characteristics of a subsample of three smaller groups of eight children each, matched for reading age.

Analysis of variance confirmed that again there was no effect of group (*i.e.* normal children and children who passed and failed the DT) on the SD of fixation vergence error in this subsample of children who were matched for reading age ($F_{21,2} = 0 \cdot 92$, $p = 0 \cdot 4$).

RELIABILITY OF DATA

Table V shows the mean error attributable to calibration for the three groups of children. Analysis of variance failed to show any significant effect of group on the means of the calibration error data ($F_{37,2} = 1 \cdot 77$, $p > 0 \cdot 1$ and $F_{37,2} = 2 \cdot 11$, $p > 0 \cdot 1$).

Discussion

Irrespective of whether the three groups of subjects were matched for chronological or reading age, we failed to find any differences between the fixation vergence errors of primary schoolchildren and poor readers who passed or failed the DT. Moreover, the data from the three groups are equally reliable because we failed to find systematic differences in the error attributable to calibration. Therefore, as a group, poor readers who fail the DT do not make abnormally large fixation vergence errors when they read. Furthermore, that the fixation vergence errors of our clinic children were representative of those found in unselected primary schoolchildren of the same age.

General discussion

In our sample of normal subjects we found that adults and children unused to vision or eye-movement recording experiments frequently made fixation vergence errors during reading which were larger than published (non-reading) data. We found that only the four adults who had experience in eye-movement recording experiments produced fixation vergence errors as small as those reported in previous publications. We also found that children aged nine to 12 years made larger fixation vergence errors than adults, though this difference was small. Finally, we failed to find any differences in fixation vergence error when we compared normal children and poor readers who passed or failed the DT.

The kind of vergence instability we measured in our subjects causes dynamic variations in absolute disparity. At this point in the discussion, therefore, it is important to distinguish between absolute disparity, which is used for the control of vergence and binocular fusion, and relative disparity which is used for depth judgements (stereopsis).

In Figure 5, the eyes are converged on the point of binocular fixation (P). The vergence angle (γ_O) is equal to the angle between the visual axes marked X and Y. The objects at A and B have binocular parallaxes γ_A and γ_B, which are the angles subtended by the nodal points of the two eyes at A and B.

The absolute disparities δ_A and δ_B of A and B are defined as:

$$\delta_A = \gamma_A - \gamma_O \text{ and } \delta_B = \gamma_B - \gamma_O$$

In contrast, points A and B have a relative disparity with respect to each other which is defined as:

$$\delta_{AB} = \delta_A - \delta_B = \gamma_A - \gamma_B$$

The important difference is that in the second expression neither ocular vergence nor conjugate eye-position is involved; therefore it is absolute disparity and fusion, rather than relative disparity and stereopsis, which depend on the accuracy of eye-movement control (Collewijn *et al.* 1991).

In order to obtain a binocularly fused image of an object, the two eyes must be directed so that the left and right images of the object are aligned with the left and right foveae respectively; then correspondences between the left and right images can be identified and integrated into a single image. Thus fusion depends on the ability of the vergence system to minimise absolute disparity.

Normally, fusion is remarkably tolerant of the kinds of dynamic variation in absolute disparity that we measured in our subjects. For example, Fender and Julesz (1967) used stabilized retinal images to allow absolute disparity to be manipulated directly. They found that the absolute disparity of line-pair stereograms could be increased to about 1° before fusion broke. These stimuli subtended 1° vertically and 0·2° horizontally at the retina, *i.e.* about twice the size of printed letters viewed from the standard reading distance of 30cm. When they used random dot stereograms subtending 3·4°×3·4°, fusion did not break until absolute disparity was stretched to 2°. These results were confirmed by Piantanida (1986) and Erkelens (1988).

If the fusion process is normally so tolerant of variations in absolute disparity, why do children who fail the DT suffer visual confusion of print which causes them to make non-word reading errors? We suggest that the sensory fusion system of children who fail the DT cannot compensate adeqúately for dynamic variation in absolute disparity, leading to visual confusion of strings of letters. This might happen in at least two different ways. First, when they read, these

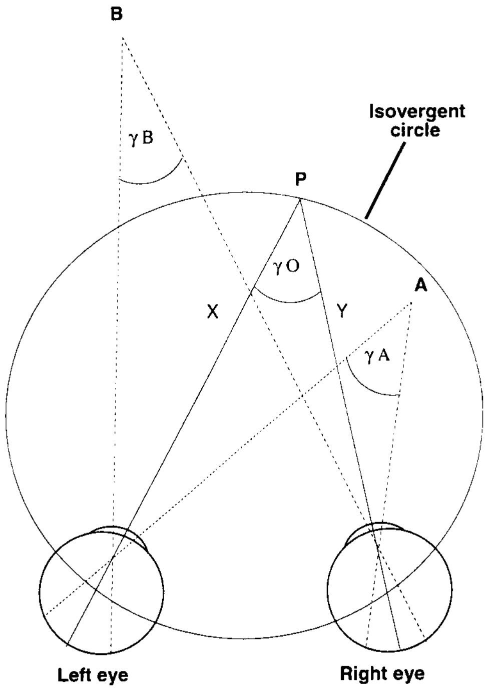

Fig. 5. Schematic view from above of left and right eyes viewing target P (see text).

children may sometimes fail to obtain the correct correspondences between the two retinal images, leading to diplopia. The second possibility does not mean that children who fail the DT are necessarily unable to fuse binocular images. Instead, visual confusion of letter strings could occur if children who fail the DT make unstable judgements about the direction of binocularly fused, disparate images (Stein and Fowler 1982, Ono 1991, Simpson and Barbeito 1992). These two possibilities are currently under investigation.

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SUMMARY
The authors recorded the binocular eye-movements of children and adults while they read single words appropriate for their reading ability. Normal data were obtained from nine- to 11-year-old

primary-school children and adults, because very little is known about changes in binocular vergence during reading. These normal data were compared with those from poor readers of the same age who had passed or failed the Dunlop Test. On average, normal children made larger vergence errors while they fixated words than did adults. There were no differences between the groups of children, therefore the authors conclude that poor vergence control during reading fixations is not the immediate cause of the non-word error effect found among children who fail the Dunlop Test.

RÉSUMÉ

La stabilité de la fixation binoculaire au cours de la lecture chez l'adulte et l'enfant

Les auteurs ont enregistré les mouvements binoculaires des yeux chez des enfants et des adultes, lisant des mots isolés correspondant à leur capacité de lecture. Des références normales ont été obtenues chez des enfants du primaire âgés de neuf à douze ans et des adultes, car il y a fort peu de données sur les modifications de la vergence binoculaire au cours de la lecture. Ces références ont été comparées aux performances de mauvais lecteurs de même âge ayant passé le test de Dunlop ou y ayant échoué. En moyenne, les enfants normaux faisaient des erreurs de vergence plus marquées que chez les adultes, lorsqu'ils fixaient les mots. Il n'y avait pas de différence entre les groupes d'enfants. Aussi les auteurs concluent qu'un mauvais contrôle de la vergence durant la fixation de lecture n'est pas la cause immédiate de l'effet d'erreur sur les non-mots chez les enfants ayant échoué au test de Dunlop.

ZUSAMMENFASSUNG

Binokulare Fixation beim Lesen bei Erwachsenen und Kindern

Die Autoren haben binokulare Augenbewegungen bei Kindern und Erwachsenen abgeleitet, während diese einzelne, ihren Lesefähigkeiten angepaßte Wörter lasen. Von neun- bis 12-jährigen Grundschulkindern und von Erwachsenen wurden Normaldaten erstellt, wil sehr wenig über Veränderungen in der binokularen Blickrichtungsänderung beim Lesen bekannt ist. Diese Normaldaten wurden mit denen von schlechten Lesern desselben Alters verglichen, die den Dunlop Test bestanden oder nicht bestanden hatten. Im allgemeinen machten normale Kinder größere Fehler bei der Blickrichtungsänderung beim Fixieren von Wörtern als Erwachsene. Es fanden sich keine Unterschiede zwischen den Gruppen der Kinder, daher kommen die Autoren zu dem Schluß, daß eine schlechte Kontrolle der Blickrichtungsänderung beim Lessen nicht der grund für den non-word error effect ist, der bei Kindern gefunden wird, die den Dunlop Test nicht bestehen.

RESUMEN

Estabilidad de la fijación binocular en la lectura en adultos y niños

Los autores registraron los movimientos binoculares de niños y adultos al leer palabras simples apropiadas a su habilidad de lecrura. Se obtuvieron datos normales en niños de escuela primaria de nueve a 12 años y en adultos, puesto que se conoce muy poco sobre la convergencia binocular durante la lectura. Estos datos normales se compararon con los de lectores con dificultad de la misma edad que habían pasado o no el test Dunlop. Como promedio, los niños normales hacían mayores errores de convergencia al fijar palabras que los adultos. No había diferencias entre los grupos de niños, por lo que los autores concluyen que el pobre control de convergencia durante las fijaciones de la lectura no es la causa inmediata del efecto de error hallado en niños que no pasaron el test de Dunlop.

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