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INTER-INDIVIDUAL VARIABILITY IN THE DYNAMICS OF NATURAL ACCOMMODATION IN HUMANS: RELATION TO AGE AND REFRACTIVE ERRORS

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SUMMARY

1. To study the relationship between accommodation under natural viewing conditions, age and refractive errors, we have measured time courses of accommodation in thirty-nine human subjects aged 5–49 years using a newly developed technique. The technique is based on infrared photoretinoscopy and involves fully automated on-line image processing of digitized video images of the eyes with a sampling rate of 5·3 Hz.

2. The distance between the subject and the video camera was about 1·3 m. Head movements of the subject required little restriction because the eyes were automatically tracked in the video image by the computer program. All subjects were tested under binocular viewing conditions.

3. Both refraction of the right eye and pupil diameter were measured with a precision of 0·2–0·4 dioptres (D) and 0·1 mm, respectively, and were plotted on-line. The data were subsequently automatically analysed.

4. Automated infrared photoretinoscopy proved to be very convenient and easy to handle in both children and adults.

5. The maximal speed of accommodation for a target at a distance of 5 D declined in the subjects with age (from up to 21·7 D s^{-1} for accommodation and 32·7 D s^{-1} for subsequent accommodation to a distant target ('near to far accommodation') in children down to 2–18 D s^{-1} in adults). There was a striking inter-individual variability in the maximum possible speed of accommodation and near to far accommodation.

6. Speed of accommodation and of near to far accommodation was correlated for each subject. However, in most of the subjects, the process of near to far accommodation was faster than accommodation ($P < 0{\cdot}005$, if averaged over all subjects). This correlation was independent of age.

7. The accommodation-induced pupillary constriction (pupillary near response) was absent in children for a 4 D target; even at 10 D, there was no reliable pupillary response. The pupillary near response increased to about 1·6 mm D^{-1} of accommodation at the age of 47. Since a pupillary near response could still be elicited

in presbyopic subjects unable to accommodate, the ratio of pupillary constriction per dioptre of accommodation approached infinity.

8. The magnitude of the pupillary near response was highly variable even among subjects of the same age but was typical for each subject. There was a correlation ($P < 0.01$) to refractive error: corrected myopes had weaker pupillary near responses than emmetropes or hyperopes.

9. Both speed and time course of accommodation were significantly different among individuals such that they could be distinguished based on their accommodation behaviour. However, we did not detect any features in the dynamics of closed-loop accommodation that could be related to the refractive errors (range -4.5 to $+2$ D) of the subjects.

INTRODUCTION

Recent studies on the dynamics of human accommodation (e.g. Leibowitz & Owens, 1978; Maddock, Millodot, Leat & Johnson, 1981; Gilmartin, 1986; Gilmartin & Bullimore, 1987; McBrien & Millodot, 1987; Ebenholtz, 1991) and its relationship to refractive errors (McBrien & Millodot, 1987; McBrien & Millodot, 1988; Owens, 1991) have in common that the plasticity of the resting level of accommodation in the absence of visual stimulation has been examined but not accommodation behaviour under natural viewing conditions, and that the effects of age were not analysed.

In an attempt to isolate features of closed-loop accommodation possibly important for refractive development, and to separate them from age-related influences, we have studied the dynamics of accommodation in human subjects of different ages. There is a lack of information regarding (1) the development of the dynamics of natural accommodation from childhood to adulthood, (2) the relationship of the dynamics of accommodation and accommodation during distance focusing after a period of focusing on a close target (here termed as near to far accommodation) during ageing, (3) the changes of the pupillary near response with age (which could be an indicator of the softness of the crystalline lens or the response properties of the ciliary muscle or changes in the innervation) and (4) the relationship of these parameters to refractive errors.

To measure all these features simultaneously and non-invasively, it was necessary to develop a new technique that could sample accommodation under binocular viewing conditions with sufficiently high temporal frequency.

METHODS

Equipment

The refraction procedure requires a real-time video board to grab and store single video frames (in this study Oculus 200, Coreco, Canada). The board occupies one slot in a 386 personal computer (in this study Papcomp 86386, 33 MHz). An infrared-sensitive video camera (Canon CI-20 PR) equipped with a Zeiss f/1·4, 85 mm lens and a Sony TV monitor PVM-122 CE were used to display the video frames. The infrared photoretinoscope (shown schematically in Fig. 1*A*) used eighteen infrared LEDs (light-emitting diodes; emission peak at 890 nm; LTE-239, Metro Technical Sales Corporation, Jericho, NY, USA) positioned at four eccentricities (E1, 5 mm; E2, 8 mm, E3, 12 mm; E4, 17 mm). The LEDs were run at their maximal possible current (as determined by the

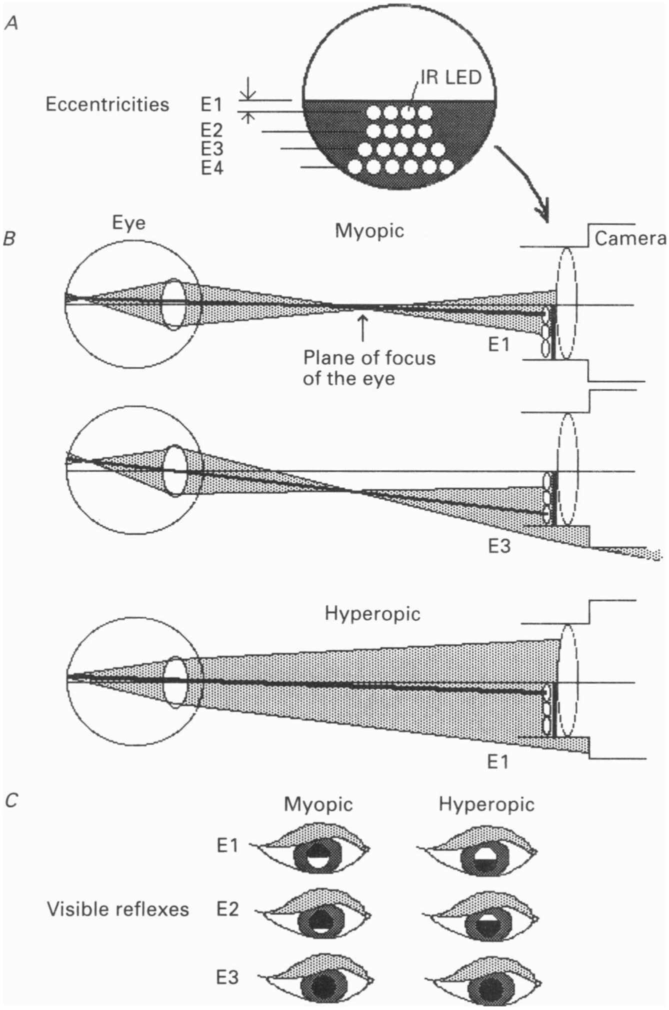

Fig. 1. Optics and design of infrared photoretinoscopy. *A*, the infrared photoretinoscope consists of rows of infrared light-emitting diodes (IR LED) positioned at different distances ('eccentricities', E1–E4) from the edge of a shield that covers about half of the camera lens aperture. *B*, the infrared light emitted from the retinoscope enters the pupil and a small proportion returns to the camera upon reflection from the fundus. The vergence of rays returning from the eye provides information on the refractive state of the eye: in a myopic eye the rays are brought into focus in front of the camera (plane of focus of the eye). Because the lower half of the camera lens aperture is occluded, only the rays coming from the lower part of the pupil are detected by the camera (see paths of the rays). Accordingly, the lower part of the pupil appears illuminated (*C*, eccentricity E1). If LEDs from higher eccentricities are radiating, the light crescent seen in the lower part of the pupil is smaller for a given amount of defocus, and disappears for even higher eccentricities (see, for example, eccentricity E3). For a hyperopic eye, only rays emerging from the upper proportion of the pupil are detected. *C*, schematic illustration of the appearance of the fundus reflexes seen in the pupil for three eccentricities, E1–E3, for a myopic and a hyperopic eye.

maximal light output) but none of them burned out during a period of 1 year. Their maximal power at a distance of 1·3 m was 14·8 mW m^{-2}. For a 7 mm pupil, $7{\cdot}25 \times 10^{-7}$ J entered the eye per second. An LED with a diameter of 3 mm creates an image of the retina with an area of $1{\cdot}134 \times 10^{-5}$ cm^2. Accordingly, the energy on the retina was 0·0639 J s^{-1} cm^{-2} which resulted in a safe time of 45·7 s (Calkins, Hochheimer & D'Anna, 1980). These calculations assume perfect sustained fixation of the LED and 100% transmission of the ocular media which is not really realistic.

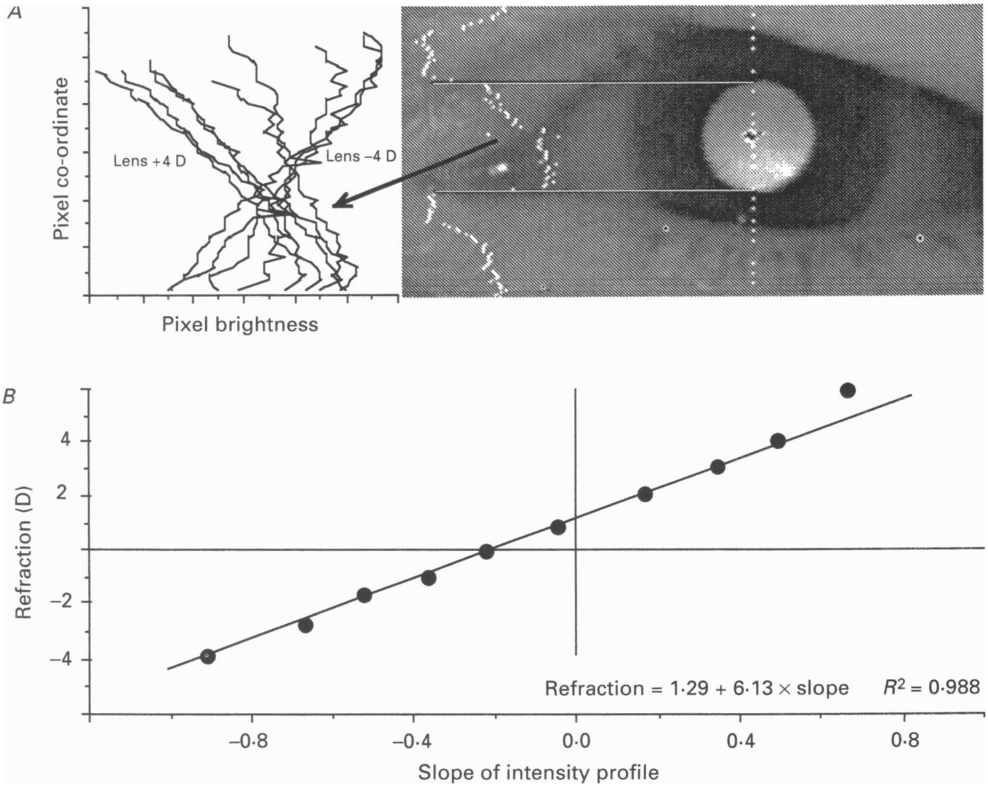

Fig. 2. Infrared photoretinoscopy with LEDs from different eccentricities radiating simultaneously. *A*, the reflex crescents in the pupil created from differently eccentric light sources (compare to Fig. 1) superimpose and create an intensity profile in the pupil which is almost linear. On the left side, the pixel brightness values across the vertical pupil meridian are plotted against the pixel co-ordinate for different ophthalmic lenses held in front of the eye. Note that the slope is changing with different lenses in front of the eye and can be used to measure the refraction of the eye. *B*, the power of the lens held in front of the eye is plotted against the slope of the intensity profile through the pupil. Note that there is a linear relationship from at least −5 D to +5 D of lens power, and that the refraction can be determined if the slope of the intensity profile is known.

Subjects

The subjects were co-workers from the laboratory ($n = 9$) and patients from the hospital with no ocular pathology ($n = 30$). Their refractive errors ranged from −4·5 to +2 D, but the major proportion ($n = 24$) was near emmetropic (range, +0·7 to −0·7 D). They were not trained. Ages ranged from 5 to 49 years. The measurements were performed with the understanding and consent of the subjects.

Procedure

The subjects sat down in front of the video camera at a distance of 1·3 m; they were tested under binocular viewing conditions and wore their normal refractive corrections. They could observe their own faces on the video monitor which was positioned next to the camera at a distance of 1·5 m. While the program was running and data were collected on the refractive state of the right eyes of the subjects (as refracted approximately along the optical axis), they were asked to observe their own images on the video monitor. After about 15 s, they then had to read a text presented

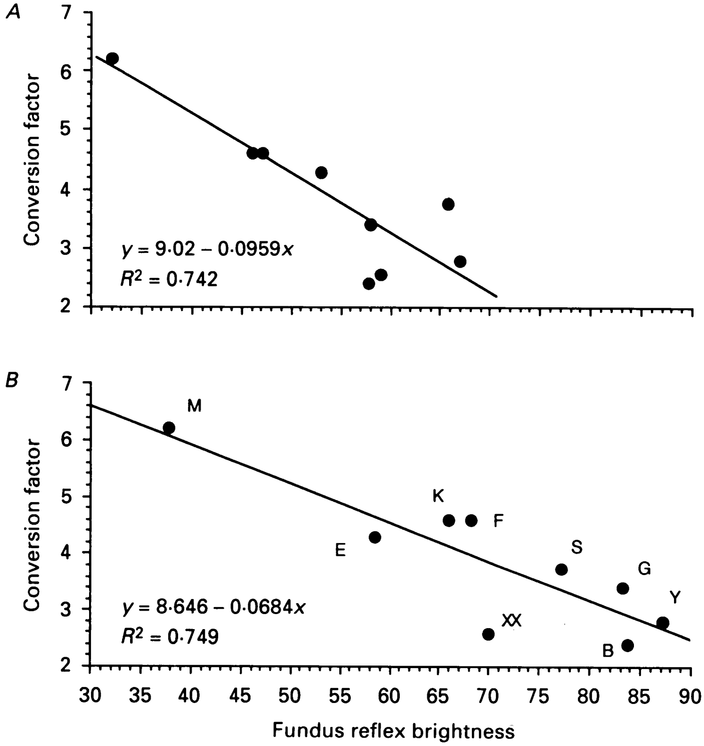

Fig. 3. Experimental calibration of technique. The most important parameter for the refraction procedure is the conversion factor from slope of the profile to refraction. Average fundus reflex brightness (in average grey level of pixels) is plotted against conversion factor. It was found that the conversion factor is very variable among individuals, ranging from 2·3 to 6·3. However, if plotted against the brightness of the fundus reflex with the refraction corrected, there is a linear relationship with a correlation coefficient of $R^2 = 0.742$ (*A*). Because the technique should also measure accommodation if the spectacle correction is not known, it was tested whether the conversion factor remained related to fundus reflex brightness even if refractive errors were uncorrected (*B*). The correlation remained similar. Therefore, the program can be used to measure refraction without previous calibration of the conversion factor with lenses (letters indicate different subjects; for details see text).

close to the line of sight at various distances for another 15 s, and, subsequently, they were asked to focus back onto the monitor. The procedure was repeated five times. The total period of data collection lasted about 50 s and provided 250–300 data points. Possible measurement errors due to off-axis measurements as they result from eye movements during reading the text were also examined. In agreement with previous findings (Millodot, 1981), refractive state did not vary more than a quarter of a dioptre 10 deg away from the optical axis (data not shown). The room illuminance was dimmed down to 30 lux to assure that pupils were sufficiently large for measurement.

Optics of infrared photoretinoscopy and its limitations for on-line measurements

The original infrared photoretinoscope (Schaeffel, Farkas & Howland, 1987; US patent no. 4.834.528) consisted of six horizontal rows of infrared LEDs positioned at different distances ('eccentricities, E') from the edge of a shield which occluded about half of the aperture of the video camera lens (Fig. 1*A*). If light from the LEDs is projected into the eye, a small proportion is also reflected from the fundus and returns to the camera. If the eye is focused onto the camera, the returning light is refocused back on the LEDs. As a result, for a properly focused eye, the pupil appears almost dark. If the eye is defocused with respect to the camera (see Fig. 1*B*, for a myopic eye), the returning light is refocused in a plane between the eye and the camera, and subsequently spread out in a cone the angle of which depends on the amount of defocus. The relative position of the reflex in the pupil tells the sign of the refractive error. For an eye myopic relative to the camera, only rays coming from the lower part of the pupil (see Fig. 1*B*) can be detected by the camera due to the shield which covers the lower part of the aperture. For a hyperopic eye (Fig. 1*B*), only the upper part of the pupil appears illuminated. For a retinoscope arranged as shown in Fig. 1*A*, the amount of defocus of the eye in the vertical meridian can be calculated from the relative height of the light crescent in the pupil (Howland, 1985). If light is projected into the eye from different eccentricities, the height of the light crescents seen in the pupil varies (Fig. 1*C*). By this procedure the event that the entire pupil is flooded with light for large amounts of defocus can be prevented. Therefore, multiple eccentricities extend the range of measurement and also improve its precision (Schaeffel *et al.* 1987). If the LEDs are flashed in sequence, the fundus reflex appears to move in the pupil. Although this procedure proved to be very useful for refracting freely behaving animals (Mathis, Schaeffel & Howland, 1988; Schaeffel & Mathis, 1991; Wagner & Schaeffel, 1991), it is not very useful for a dynamic photorefraction because (1) the resolution of the technique is optimal only for a certain eccentricity and LEDs at that particular eccentricity are only flashed one-fifth of the time, and (2) the edge of the light crescent cannot easily be detected by image-processing computer programs because of scattered light in the eye (Hodgkinson, Chong & Molteno, 1991; Schaeffel & Howland, 1991). A program of this kind detects an edge of a light crescent in the pupil even if it is not present because there is always a brightness gradient in the pupil due to the scattered light. To avoid incorrect detections of light crescents, a threshold has to be set. Due to the threshold, measurement can start only if crescent brightness surpasses a certain level which, in turn, does not allow continuous measurement over the whole range of refractions. Accordingly, there appears a step in the measured time course of accommodation (Schaeffel & Howland, 1991).

Photorefraction with multiple eccentricities

The problems described above can be bypassed if LEDs at all eccentricities operate continuously. In this case, the light crescents in the pupil created by the differently eccentric light sources add up to an almost linear intensity gradient of the reflex in the vertical pupil meridian (Fig. 2*A*). The slope of the intensity profile can be determined by an image-processing program and, because the slope changes continuously with refraction, it also permits continuous measurement of refractive state in that meridian. Certainly, the steepness of the intensity profile in the pupil has to be converted to refractive error by an experimental calibration (see below), or theoretically (H. C. Howland, in preparation).

Calibration of the photoretinoscope with multiple eccentricities in nine subjects

The photoretinoscope was calibrated by placing ophthalmic lenses of different powers in front of the eyes. To ensure that no accommodation was induced by the lenses, the eyes remained covered with a filter OG 695 (Schott). The filter transmitted infrared light for the measurement without attenuation but did not permit the subjects to see. For calibration, the contralateral eye was occluded and could not provide stimuli for accommodation.

Intensity profiles through the vertical pupil meridian as measured with different lenses in front of the eye are shown in Fig. 2*A*. It can be seen that the pixel brightness values change across the vertical pupil meridian in an almost linear fashion. The profiles were fitted by linear regressions with correlation coefficients better than 0·95. The slopes of the profiles changed with different lenses in front of the eye (Fig. 2*A*). In a plot of the power of the lenses *vs.* the slopes of the intensity profiles, it can be seen that the relationship is linear again (Fig. 2*B*) and can also be fitted by linear regression with a high correlation (R^2 range, 0·92–0·98 for nine subjects). Therefore, the steepness of the intensity profile provides reliable information on the refractive state in the vertical meridian, and changes of only a quarter of a dioptre were detectable (Fig. 2*B*). However, there was a striking variability among subjects: in some, the lenses held in front of the eye resulted in a larger change in the steepness of the intensity profile than in others. Accordingly, the slope of the regression in Fig. 2*B* (subsequently referred to as 'conversion factor') was very variable, ranging from 2·3 to 6·6 (Fig. 3). To determine the unknown parameter responsible for this variability, the following cross-correlations were determined: (1) pupil diameter (x) *vs.* conversion factor (y): $y = 11{\cdot}866–0{\cdot}1766x$, $R^2 = 0{\cdot}683$, and (2) fundus reflex brightness (as determined by the average pixel brightness value in the vertical pupil meridian, with the refraction optically corrected, x) *vs.* conversion factor (y): $y = 9{\cdot}018–0{\cdot}0959x$, $R^2 = 0{\cdot}742$ (see Fig. 3*A*).

The negative correlation shows that the conversion factor changes with brightness of the fundus reflex. The variability of the reflex brightness could either result from variable pupil sizes in the different subjects and/or from variability of the reflectivity of the fundus for infrared light. The two possibilities were tested by calculating the 'effective' reflectivity of the fundus. For point sources, the brightness of the reflex in the pupil varies proportionally to the square of the pupil radius. Therefore, the brightness of all reflexes was corrected for pupil size. Subsequently, it was tested whether the conversion factors were still correlated with the brightness of the fundus reflex. However, the correlation disappeared ($R^2 = 0{\cdot}021$, n.s.). The result shows that the major reason for the variability in the conversion factors is pupil size and not reflectivity of the fundus. However, because the correlation between pupil size and slope was not perfect, some influence of unknown factors (which could include fundus reflectivity) cannot be ruled out.

From the data above, the conversion factors for different subjects could basically be predicted. However, first it was necessary to determine the brightness of the fundus reflex with the refraction corrected, a procedure which is inconvenient if the refraction procedure is supposed to be fully automated. Therefore, it was tested whether the correlation of fundus reflex brightness and conversion factor also persisted if the eyes were *not* corrected during the calibration procedure (Fig. 3*B*). The correlation (fundus reflex brightness, x, *vs.* conversion factor, y: $y = 8{\cdot}646–0{\cdot}0684x$, $R^2 = 0{\cdot}749$) remained high. The measured slope of the intensity profile in the pupil could, therefore, be directly converted into refractive error of an eye if the average fundus reflex brightness was known. The required conversion factor could be obtained for every subject from Fig. 3*B* because the fundus reflex brightness was automatically measured by the program. It was also clear that an automated program would have to determine the brightness of the fundus reflex repeatedly for every single measurement of refraction because the reflex brightness varies with changing pupil size during accommodation. It was tested whether the procedure worked reliably. Eight subjects (aged 25–30) were asked to focus at targets at different distances (7·1, 5·0, 4·0, 3·3, 2·5 and 1·0 D). In Fig. 4*A*, refractions are shown as measured with conversion factors determined automatically from fundus reflex brightness. In contrast, to plot Fig. 4*B*, the individual conversion factors were used as previously calibrated by lenses. There is only a minor improvement in precision of measurement of accommodation. The result indicates that (1) the procedure to determine the conversion factor from the regression line in Fig. 3*B* is valid and (2) despite the change in pupil size with accommodation, the measured refractions remain correct. The procedure was, therefore, applied to the other thirty-one subjects in the automated version.

Automated infrared photoretinoscopy by an image-processing computer program

The above operations were performed automatically by a computer program written in lattice-C for the video board by one of us (F.S.). It started by searching for the corneal Purkinje reflex which appeared quite bright and sharp because the infrared photoretinoscope acted as a point source at a distance of 1·3 m. If no Purkinje reflex was found, the program restarted searching. This procedure was advantageous because the program could run continuously (without collecting data) even if no subject was present. However, a subject's eye moving into the field of view of the video camera caused immediate start of recording. It was found that eyes could be reliably located by

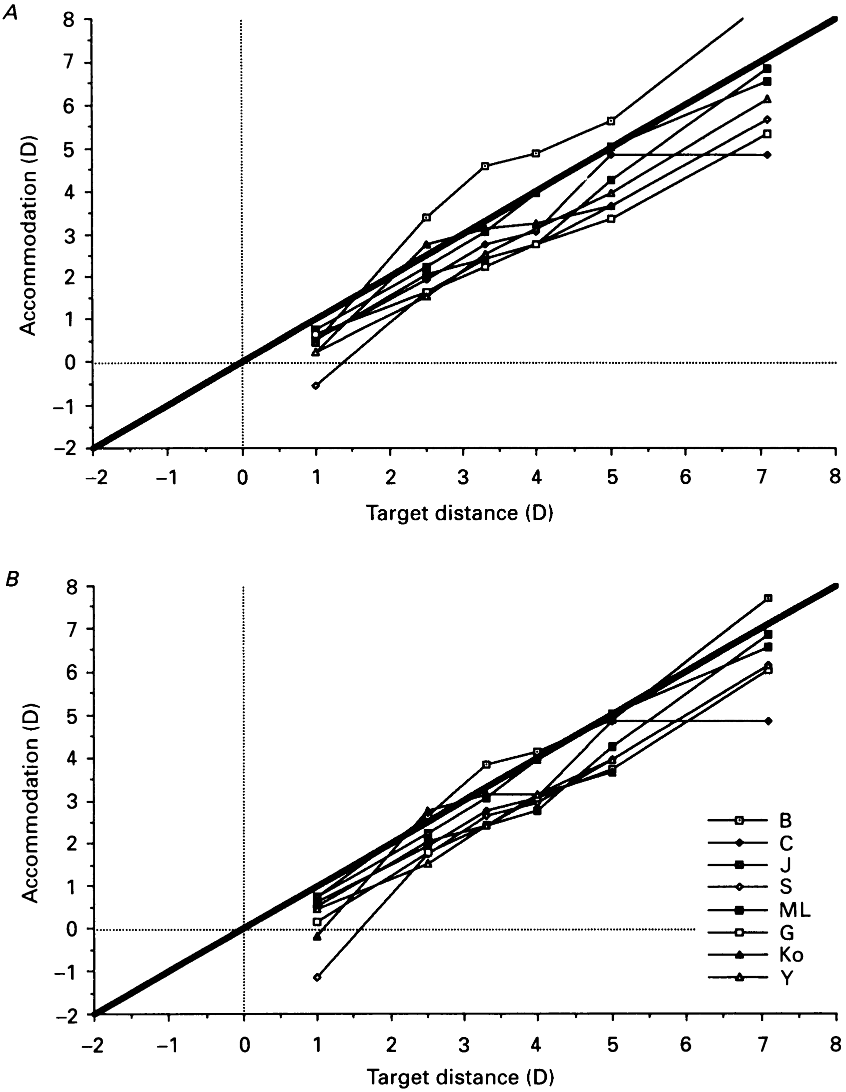

Fig. 4. Test of the validity of calibration of the refraction procedure. Eight subjects aged 25–30 years were asked to focus on targets at 1, 2·5, 3·3, 4, 5 and 7·1 D distance. Accommodation was measured continuously and compared to data provided by McBrien & Millodot (1986*b*). *A*, the procedure was used in its fully automated version in which the conversion factor was determined by the program from Fig. 3*B*. Except for subject B in which over-accommodation was measured (too large a conversion factor), the data are comparable to the ones from the literature. *B*, before measurements took place, the conversion factors were determined individually for each subject by lenses. There is only a slight improvement of precision of measurement.

their Purkinje reflexes, although the eyes of subjects wearing glasses were more difficult to measure because additional reflexes were caused by the spectacle frame; in these cases, the program occasionally was trapped and tried to measure at the wrong position. After the Purkinje reflex was found, the pixels to the left and the right were recorded and the edges of the pupil were detected by a threshold criterion of pixel contrast. From the distance between the pupil margins to the Purkinje reflex, the direction of gaze was calculated from the Hirschberg ratio (Brodie, 1987). The program then proceeded to determine the vertical pupil diameter. Subsequently, horizontal and vertical pupil diameters were averaged. If the vertical and the horizontal pupil diameter differed by more than 0·2 mm, the measurement was rejected and the program restarted searching for the Purkinje reflex. However, such events were rare. The average brightness of the fundus reflex was also measured (as described above) to determine the conversion factor from slope to refraction. Finally, refractive state in the vertical meridian was calculated from the steepness of the vertical intensity profile. All data were plotted on-line (see Fig. 5, with sample records from four subjects) and were also stored in files in the computer. One recording session (as shown in Fig. 5*A–D*) took about 40 s and provided 200–300 measurements with a sampling rate of about 5·3 Hz with an 80386 computer run on 33 MHz.

RESULTS

Illustration of the measured parameters of accommodation in individuals of different ages

Features in human accommodation behaviour that were analysed are shown in Fig. 5*A–D*. The graphs were plotted by a computer program written in Turbo-C which automatically analysed the collected data. In *A*, accommodation behaviour is shown of a child aged 7 years. Refraction *vs.* time is plotted in the upper left-hand corner, pupil size *vs.* time in the lower left-hand corner, refractive state *vs.* pupil size in the upper right-hand corner, and a summary of parameters which characterize accommodation of the subject is provided in the lower right-hand corner. Both accommodation and near to far accommodation are fast (here, maximal speed 11·1 D s^{-1}). Strikingly, the pupil does not change its size during accommodation. Accordingly, the value of pupillary constriction per dioptre (see summary of data in the lower right-hand corner) is almost zero. The pupillary near reaction is also weak in the subject aged 26 shown in Fig. 5*B*, although the correlation between pupil size and accommodation is significant ($R^2 = 0{\cdot}167$, d.f. = 271, $P < 0{\cdot}001$). There is little change in speed of accommodation as compared to Fig. 5*A*. In Fig. 5*C*, data from a 38-year-old subject are shown. The pupillary near response is now highly correlated with accommodation ($R^2 = 0{\cdot}778$; constriction per dioptre of accommodation, $-0{\cdot}42$). The maximal speed of accommodation is reduced to 2·7 D s^{-1}. Finally, in a 47-year-old subject (Fig. 5*D*), the amplitude of accommodation has declined to about 1 D and the speed is reduced to 0·9 D s^{-1} but the pupillary near response is very pronounced (pupillary constriction in millimetres per dioptre of accommodation, 1·74).

Inter-individual variability in the time courses of accommodation and near to far accommodation

It was expected that the dynamics of accommodation were strongly dependent on age. Strikingly, there were also large differences in the speed and time courses of accommodation in people of similar age. In Fig. 6*A*, the time courses of accommodation are shown of a 26-year-old emmetropic subject who was asked to focus at various distances (1, 2, 3·3, 4, 5 and 7·1 D, respectively). The traces in Fig.

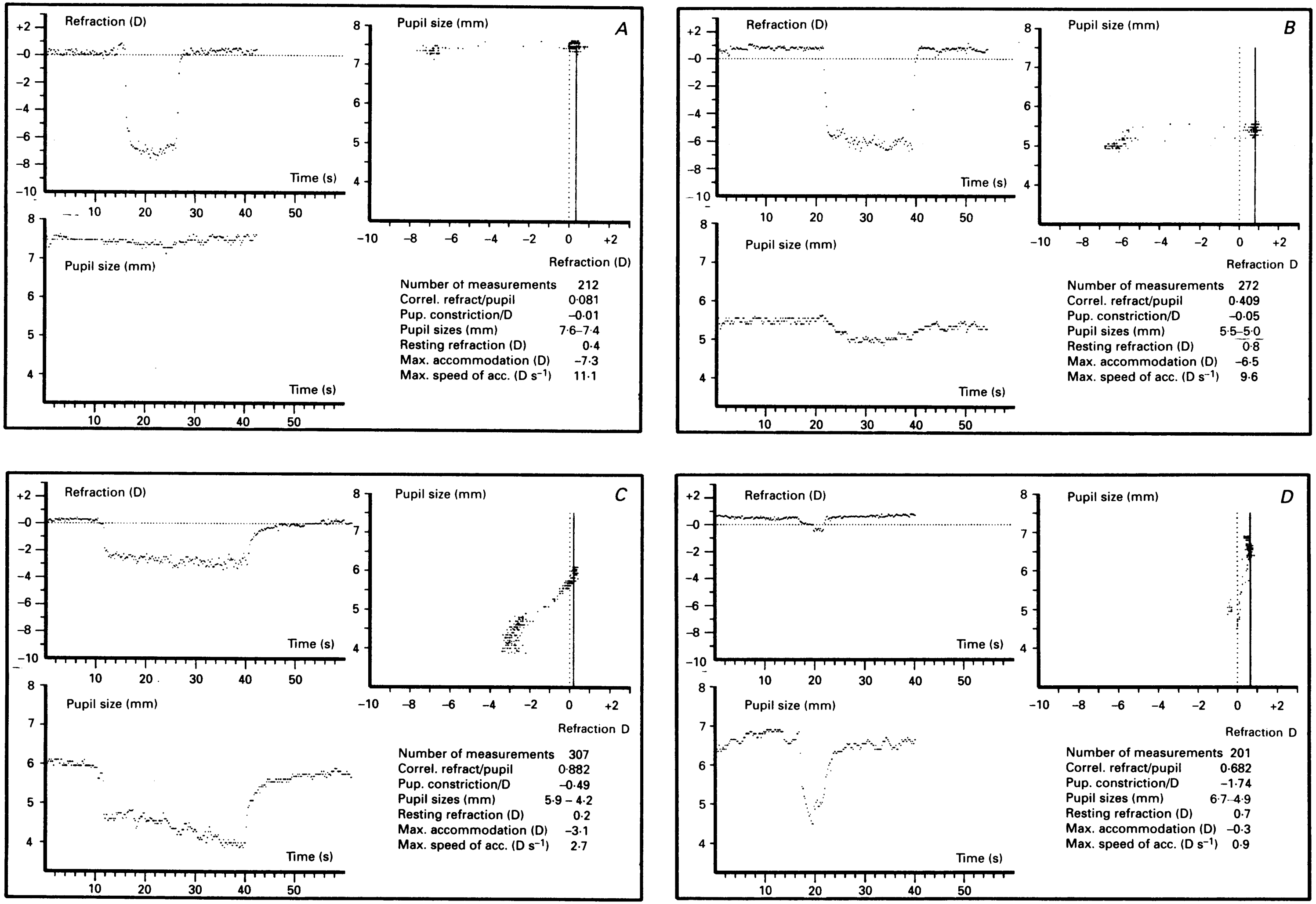

Fig. 5. For legend see facing page.

6*B* show how five subjects accommodated for the target at a distance of 5 D. Note that the time scale is stretched as compared to Fig. 6*A*. Each trace represents averages from five repetitions with standard deviations shown for each subject. Four subjects had a similar age (26–27 years) and one subject (F, ○) was 38 years old. It can be seen that, even in similarly aged subjects, the speed and amplitude of accommodation differed significantly (subject J accommodated less than B and M ($P < 0{\cdot}001$), and also with a lower speed ($P < 0{\cdot}01$)). Subjects B, G and F were myopic ($-4{\cdot}5$, $-2{\cdot}5$ and $-3{\cdot}5$ D, respectively) while the two others were near-emmetropic. There is no obvious effect of refractive errors on the time course of accommodation. Figure 6*C* shows the time courses of near to far accommodation. Again, there are significant differences in the speed of near to far accommodation. The near to far accommodation of subject J was significantly faster than the others. Subject F required more than 10 s to reach his initial resting refraction.

Changes in speed of accommodation and near to far accommodation with age

Thirty-nine subjects were asked to focus at a target at 4 D and then to focus back at a distance (Fig. 7). The procedure was repeated five times. The maximal speed of accommodation and near to far accommodation was determined for each trial and subsequently averaged. Although the speed of accommodation (●) and near to far accommodation (○) was variable as can be seen from the large standard deviations in Fig. 7, children under 10 years of age reached higher speeds of accommodation and near to far accommodation (up to 32·7 D s^{-1}) than adults. Subjects older than 40 years had trouble accommodating at 4 D. Their speed of accommodation finally declined to zero due to the fact that no accommodation took place at all (see ○ to right of abscissa). It is striking that, particularly in the age group 20 to 40 years, there are highly significant differences in the speed of accommodation and near to far accommodation among the subjects. The speed of accommodation and next to far accommodation was correlated, however (Fig. 7*B*), suggesting that some mechanical features of the lens, the ciliary body or choroid affect both accommodation and near to far accommodation in a similar fashion. A regression line (thick line in Fig. 7*B*) has an offset with regard to the line describing equally rapid near to far accommodation and accommodation. Apparently, on average, near to far accommodation is faster than accommodation as can also be seen in Fig. 8*A*. The difference in speed of accommodation and near to far accommodation was calculated for all of the thirty-

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Fig. 5. Original plots of the time courses of accommodation and pupillary responses as provided automatically by the refraction program. The results of measurements in four subjects are shown (*A*–*D*). In the upper left corner of each of *A*–*D* refraction is plotted *vs.* time, in the lower left corner the corresponding pupil size *vs.* time, in the upper right corner refraction *vs.* pupil size, and in lower right corner a summary is given of relevant parameters of the accommodation of the studied subject. *A*, emmetropic, 7-year-old child. Note the lack of a pupillary near response. *B*, myopic, 26-year-old subject (refraction, −4·5 D), wearing his correction. Note the weak pupillary near response. *C*, Myopic, 38-year-old subject (refraction, −3·5 D), wearing his correction. Note the prominent pupillary response and the age-related drop in speed of accommodation. *D*, emmetropic, 47-year-old subject. Note the pronounced pupillary near response despite a low amplitude of accommodation.

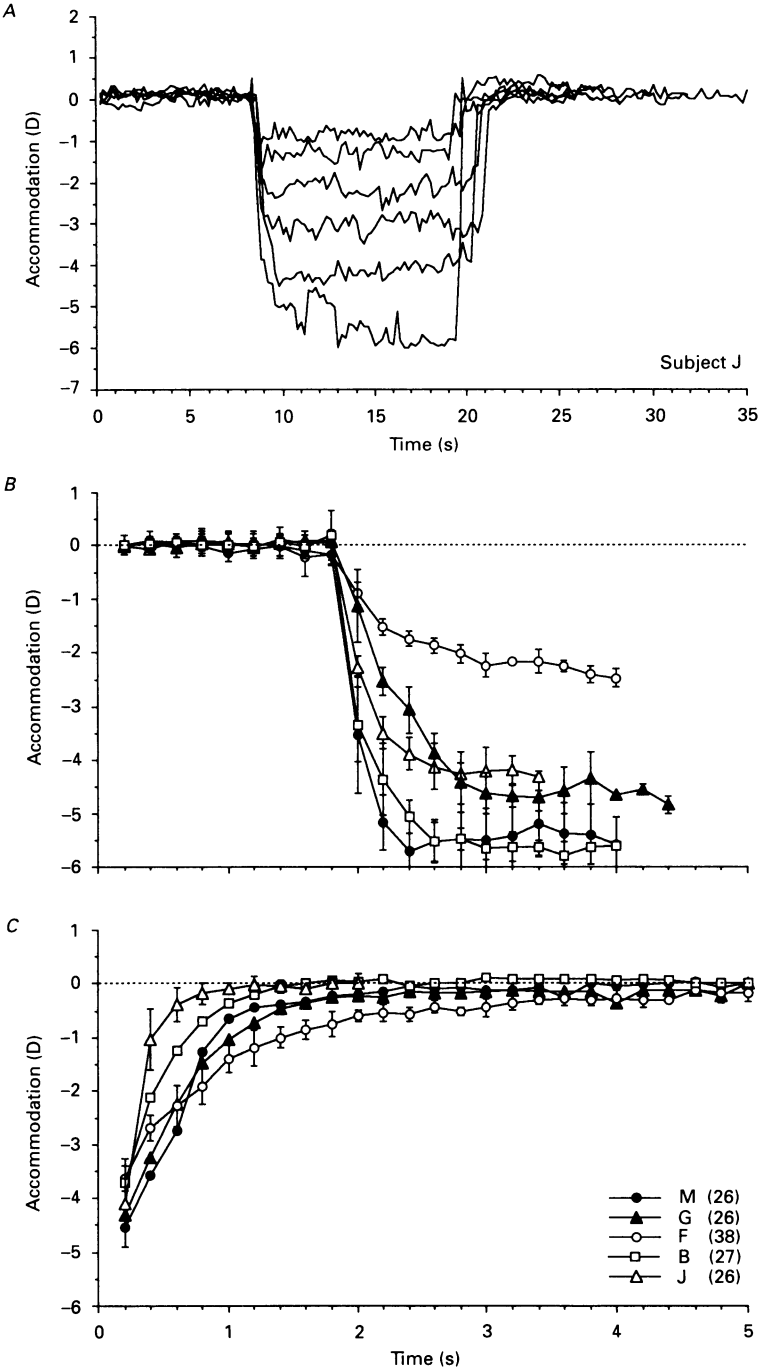

Fig. 6. Inter-individual variability in the time courses of accommodation. *A*, experimental protocol: the subject was asked to focus at a distance for 10 s and then focus at a target at different distances (1, 2·5, 3·3, 4, 5 and 7·1 D) for another 10 s. Subsequently, the subject had to focus back at the distance. The procedure was repeated five times. The time courses of accommodation and near to far accommodation were averaged and provided the standard deviation for *B* and *C*. *B*, time courses of accommodation in five subjects

nine subjects, and the results were ranked. In twenty-nine subjects, near to far accommodation was faster than accommodation. The standard deviations (Fig. 8*A*) for differences were calculated from the square root of the sum of the squares of the original standard deviations. Although the difference in speed of accommodation and near to far accommodation was statistically significant for a few subjects only, near to far accommodation was significantly faster than accommodation when averaged over the whole sample (d.f. = 38, $t = 2{\cdot}99$, $P < 0{\cdot}005$). We tested whether the equilibrium between the elasticity of the chorioid and ciliary body (presumably mediating near to far accommodation) and the strength of the ciliary muscle and/or the elasticity of the lens (responsible for accommodation) was a function of age. There was no age-related change detectable, however (Fig. 8*B*).

Inter-individual variability and age-related changes in the pupillary near response

In young children, it was difficult to elicit a near pupillary response at all. For a target at a distance of 4 D (Fig. 9), the pupil response was not significant in any of the subjects. Even for 10 D of accommodation there was no reliable response of the pupil. In the age range of 20–40 years there was, again, a high variability in the pupillary near response (Fig. 9). It was very pronounced in one subject aged 20 years (about 0·6 mm D^{-1}, Fig. 9) but did not show up in another one aged 33 years. After 35 years, the near response was always very clear and reached 1 mm D^{-1}. With age-related decline of the range of accommodation, it rapidly increased to 1·6 D mm^{-1} (in a 49-year-old subject). In three subjects aged 47, 52 and 54 years, there was a prominent pupillary constriction when an attempt was made to focus at the target but the refraction did not change. The near pupillary response could, therefore not be expressed in terms of diopters of accommodation and was arbitrarily set to about 2 mm D^{-1} (with an arrow in Fig. 9 to indicate that it is, in fact, infinitely large). This procedure permitted the inclusion of these measurements in Fig. 9.

Relationship between speed of accommodation, near to far accommodation and near pupillary response to refractive error

To minimize the effects of age on the subsequent analysis, we considered only subjects between 25 and 33 years of age ($n = 19$). The refractive errors of the subjects were low and fitted into the category of 'late-onset myopia' (McBrien & Millodot, 1987). We found that the refractive errors had no effect on either the speed of accommodation or near to far accommodation (Fig. 10*A*).

It was expected that axial elongation of the eye and the thinning of the layers of the globe might have lowered the tension of the ciliary body and the chorioid and, therefore, reduced the speed of near to far accommodation. However, even a subject with 4·5 D of myopia could accommodate very fast (14·3 D s^{-1} on average; age, 26 years). In contrast to accommodation, the pupillary near response was affected by

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focusing at a 5 D target (same symbols denote same subjects as in *C*, with standard deviations from five repeated measurements). To make time courses more comparable, curves were shifted up or down to start out at zero refraction (range of original resting refractions, +0·6 to −0·3 D). Note significant differences among subjects of the same age. *C*, time courses of near to far accommodation. Note significant differences among subjects.

refractive errors ($P < 0{\cdot}01$, d.f. = 18, Fig. 10*B*): myopic subjects had a weaker response than near-emmetropes or the two hyperopes that were in the sample. These effects were present despite the fact that refractive corrections were worn during testing. The correlation was also not the result of sampling bias because the four

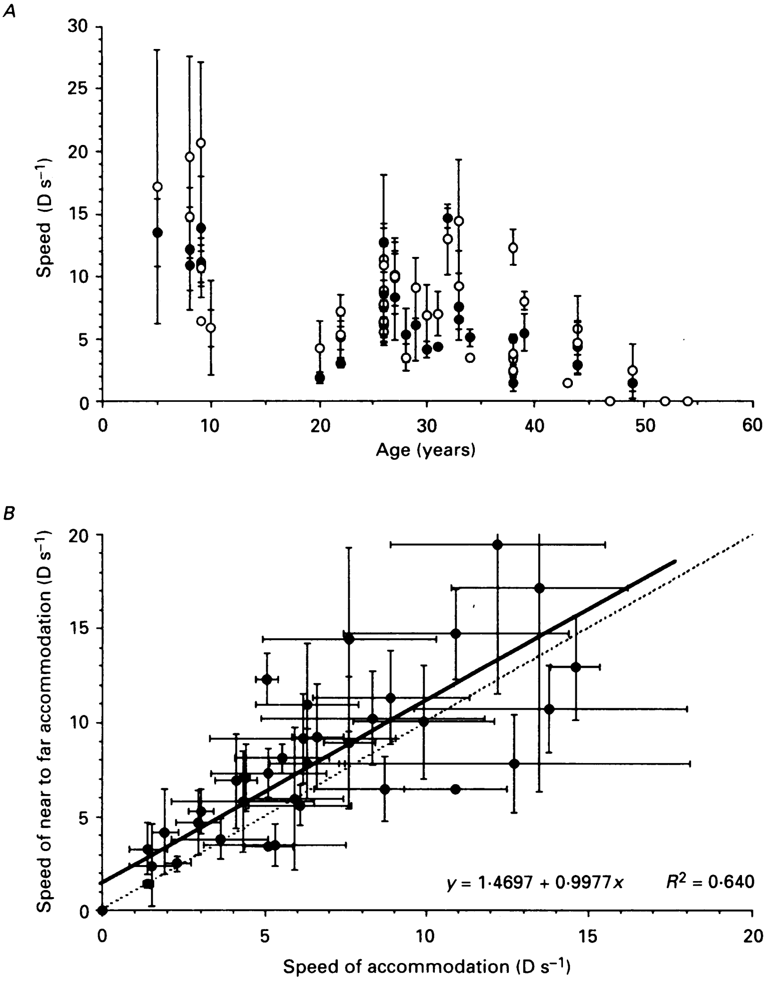

Fig. 7. Speed of accommodation and near to far accommodation in thirty-nine subjects when focusing at a target at a distance of 4 D. *A*, speed of accommodation (●) and near to far accommodation (○) with standard deviations from five repetitions are plotted against age. Note that there are significant inter-individual differences in speed of accommodation in subjects of similar age and that speed declines continuously with age. The subjects older than 40 years were no longer able to accommodate 4 D. *B*, speeds of accommodation and near to far accommodation were correlated for all the subjects ($P < 0{\cdot}001$), indicating that some internal parameters in the mechanics of the eye were responsible for the speed of both accommodation and near to far accommodation.

myopes were of similar age to the two hyperopes; effects of age cannot, therefore, be responsible.

DISCUSSION

In an attempt to further isolate properties of human accommodation that are related to refractive errors, we have studied how age, inter-individual variability, and refractive errors affect the dynamics of natural accommodation. It is necessary to establish a framework of how much of the variability is due to age and unspecific inter-individual variation before effects of refractive errors can be detected. In

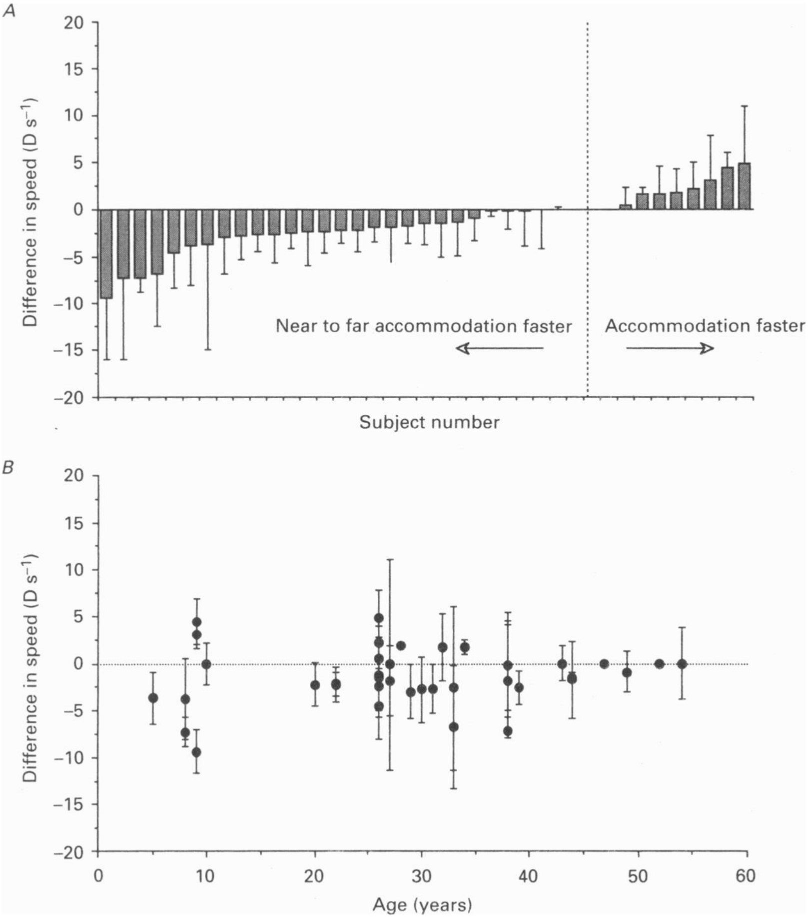

Fig. 8. Relationship between the speed of accommodation and near to far accommodation in the thirty-nine subjects. *A*, the difference between accommodation and near to far accommodation was calculated for each subject along with the standard deviations. The data were sorted. In twenty-nine subjects, near to far accommodation was faster than accommodation. On average, near to far accommodation was 1·46 D s^{-1} faster than accommodation (S.D. = 3·04, $n = 39$, $t = 2{\cdot}99$, $P < 0{\cdot}005$, paired t test). *B*, the difference in the speed of accommodation and near to far accommodation was not affected by age, despite its large inter-individual variability.

agreement with previous studies (see Owens, 1991, for a review), our results show that there is generally a high variability in the parameters of accommodation behaviour even among subjects of the same refractive state and age. The variability has to be taken into account if effects of refractive errors are to be isolated.

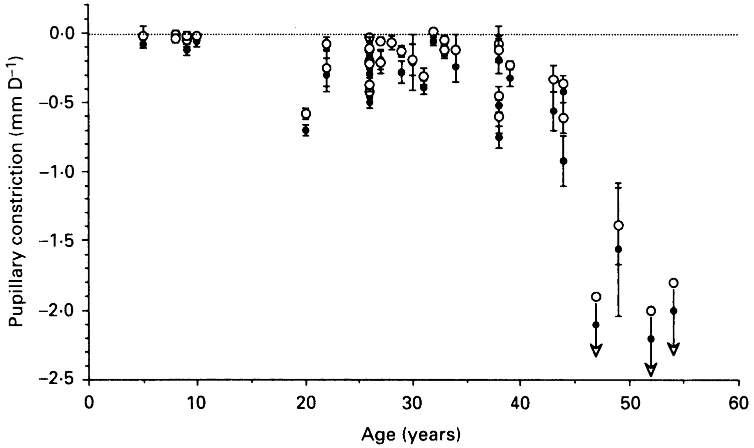

Fig. 9. The pupillary near response (as measured in mm D^{-1} of accommodation for a target at 4 D) is plotted against age (years). The near pupillary response was almost lacking in children below 10 years and increased non-linearly with age. There was a high inter-individual variability even in subjects of similar age. Shortly before onset of presbyopia, the pupillary near response was extremely augmented (arrows indicate that the ratio of pupillary constriction to dioptre of accommodation approached infinity). ●, accommodation; ○, near to far accommodation.

Due to a new technique developed by one of us (F.S.), it became possible to study a new aspect of accommodation: its dynamics under closed-loop conditions and its relation to the pupillary near response. Under normal binocular viewing conditions, the pupillary near response developed slowly with age and was not present in children under 10 years of age. The speed of accommodation for a target at a distance of 4 D declined with age even if the required amount of accommodation could be elicited. The speed of accommodation and near to far accommodation was correlated but, in the majority of the subjects, near to far accommodation was faster than accommodation. Unexpectedly, there was no correlation detected between the speed of accommodation or near to far accommodation and refractive errors. Only the pupillary near response was reduced in corrected myopes as compared to emmetropes and hyperopes.

Dynamics of accommodation and refractive errors

It has been shown previously that, similar to the parameters of closed-loop accommodation, the level of tonic accommodation in the absence of visual stimulation is also very variable among individuals (Leibowitz & Owens, 1978; Maddock *et al.* 1981; McBrien & Millodot, 1987). The variability has been attributed to different innervation patterns of the ciliary muscles, with a weaker sympathetic innervation relative to parasympathetic innervation in the myopes and vice versa in hyperopes (McBrien & Millodot, 1988). The difference in accommodation behaviour would then be determined by a genetical factor, and not by experience. Based on their hypotheses, we had expected that myopes have a slower near to far accommodation than emmetropes or hyperopes, but this result was not found. Apparently, the level of tonic accommodation is affected by refractive errors while speed of accommodation is not affected. It is desirable, however, to confirm the previously described relationship between tonic accommodation and refractive

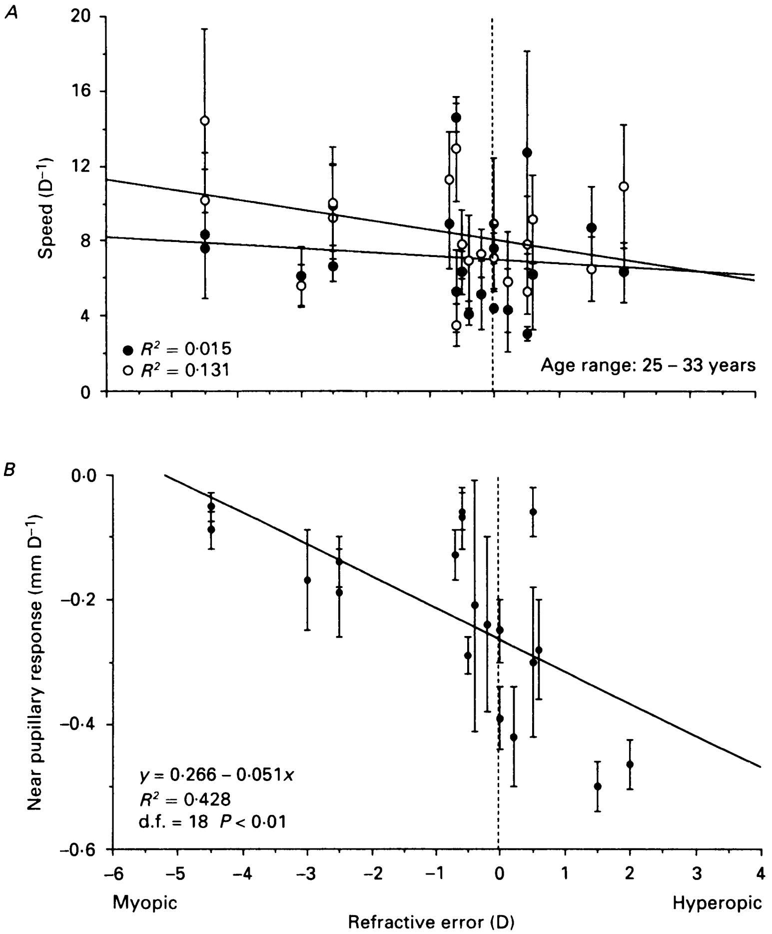

Fig. 10. Relation of the speed of accommodation and the pupillary near response to refractive errors. *A*, surprisingly, in myopes both accommodation and near to far accommodation were equally as fast as emmetropes or hyperopes; ●, accommodation; ○, near to far accommodation. *B*, the near pupillary response was affected by refractive errors ($n = 19$, $R^2 = 0{\cdot}428$, $P < 0{\cdot}01$): in myopes it was reduced as compared to emmetropes and hyperopes, despite the fact that refractive corrections were worn and the subjects were young enough to easily accommodate the required amount of 4 D.

errors (McBrien & Millodot, 1988) for our subjects with the new refraction technique, particularly since all their findings resulted from measurements with the Canon autorefractor R-1.

Pupillary near response: its relationship to age and refractive error

Strikingly, children under 10 years of age accommodated without any pupillary near response, whereas the pupil response became increasingly pronounced with age. One possible hypothesis is that, due to parallel innervation, the magnitude of the near pupillary response is correlated to the strength of the motor signal to accommodate. For a more rigid lens, the motor output of the Edinger–Westphal nucleus has to increase to produce the same amount of accommodation. The near pupillary response could, therefore, provide information on the softness of the crystalline lens and/or the resistance of the ciliary body and the choroid. It remains to be explained why myopes have a weaker near pupillary response than hyperopes. One speculation is that, due to thinning of the ocular coats in axial myopia, the resistance of the choroid becomes weaker in myopes than in emmetropes or hyperopes. The forces that must be brought about by the ciliary muscle are then lower and the motor signal to accommodate is weaker. Accordingly, the pupillary near response is reduced. Such a speculation is consistent with the observation that the range of accommodation is larger in myopes than in emmetropes or hyperopes (McBrien & Millodot, 1986*a*). McBrien & Millodot (1986*b*) have also found that myopes generally tend to under-accommodate for a target. Less accommodation would also result in a weaker pupillary near response. However, the observed amount of under-accommodation was too small (less than 0·5 D for a target at a distance of 5 D) to explain our observation.

It is, however, also possible that the observed age-dependent changes in the pupillary near response are not related to accommodation at all but represent independent age-related changes in the pupillary mechanics. It is well established that the average pupil size declines with age, probably due to a decrease in inhibition of the Edinger–Westphal nucleus and concomitant reduction of sympathetic tonus (Loewenfeld, 1973). Decline of the sympathetic influence could also explain the observed increase in the near response. An augmentation in the pupillary near response with age was also observed in young chickens (Schaeffel, Howland & Farkas, 1986) in which the softness of the crystalline lens probably did not change during the early period of development.

Speed of accommodation and age

There are only a few studies which provide data on the speed of human accommodation. Campbell & Westheimer (1960) measured a maximum speed of about 10 D s^{-1} in subjects aged 20–40 years for a target distance of only 2 D. Their value is comparable to ours. Hung & Cuiffreda (1988) found up to 10 D s^{-1}, also for a target distance of 2 D. Howland, Dobson & Sayles (1987) have measured a lower value for speed of accommodation in infants aged 2–10 months (4·6 D s^{-1}) but the sampling frequency of only 2 Hz made detection of peak velocities difficult. Accommodation speed is roughly linearly correlated with accommodation amplitude (Hung & Cuiffreda, 1988) and it is clear that higher peak velocities are obtained during accommodation for more distant targets. We have also found that speed increases linearly with target distance (data not shown) and that it declines roughly linearly with age (Fig. 7*A*). Children can reach velocities of accommodation up to $21{\cdot}7\,\mathrm{D\,s^{-1}}$ which is impressive if one considers that the ciliary musculature is smooth. The contrast with birds which have striated ciliary muscles and which are considered to possess extremely fast accommodation (Murphy & Howland, 1983) then becomes less spectacular.

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