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ORIGINAL ARTICLE

Age Changes in the Interactions between the Accommodation and Vergence Systems

GORDON HERON, PhD, FAAO, W. NEIL CHARMAN, DSc, and CLIFTON M. SCHOR, OD, PhD, FAAO

Vision Sciences, Glasgow Caledonian University, Glasgow, United Kingdom (GH), Department of Optometry and Neuroscience, UMIST, Manchester, United Kingdom (WNC), School of Optometry, University of California, Berkeley, California (CMS)

ABSTRACT: Experiments are described in which static and dynamic accommodation (Ar), accommodative convergence (AC), vergence (C) and convergence accommodation (CA) responses to small stimuli were measured dynamically in 13 subjects with ages in the range 16 to 48 years. Analysis showed that the amplitudes of both blur and disparity-driven accommodation declined significantly with age, whereas the two types of vergence response did not. As a result, the AC/Ar ratio rose significantly with age, whereas the CA/C ratio fell. No significant change with age was found in response latencies and durations. (Optom Vis Sci 2001;78:754–762)

Key Words: accommodation, vergence, AC/A ratio, CA/C ratio

For fully functional binocular vision, the retinal images of the object of regard at any distance must not only be sharply focused in both eyes but must also lie on their foveas. This can only be achieved over a range of object distances if the ocular accommodation and convergence systems are intimately linked. The last century has seen steady advances in our understanding of this linkage, with experimental results being summarized by increasingly sophisticated models in which cross-links between the two systems allow vergence changes (C) to drive convergence accommodation (CA) and accommodation (A) to elicit accommodative convergence (AC).[1–7] Clinically, the strength of such links is usually described in terms of the AC/A and CA/C ratios (e.g., Schor and Ciuffreda[8]). If A is described in terms of the accommodation stimulus, As, the stimulus ratio AC/As is obtained, and if in terms of the response, Ar, the response ratio AC/Ar is given: stimulus and response CA/C ratios can be defined similarly.

Despite these advances, many aspects of the accommodation-vergence system remain imperfectly understood. In particular, debate continues over the extent to which the AC/A and CA/C ratios may be subject to change under a variety of conditions.[9, 10] One important possibility is that they may be affected by age. The existence of an age-dependent decline in the amplitude of accommodation has been clearly recognized since the time of Donders,[11] whereas the nearpoint of convergence and, hence, the amplitude of the overall vergence response remains relatively constant.[12–14] This inevitably raises the question of whether the synkinetic relationship between the two oculomotor functions changes with age, with alterations in the accommodation-vergence cross-links. A further question is whether the speed of the two types of response is a function of age, particularly because the elastic constants of the lens and its capsule are known to be age-dependent,[15–19] as is the form of the ciliary body[20–22] and a variety of other factors of importance to accommodation (see, e.g., Atchison,[23] Gilmartin,[24] Ciuffreda,[25] Glasser and Kaufmann[26] for reviews). It is clear that fuller information on these issues is likely to throw further light on the still imperfectly understood factors underlying the development of presbyopia.

Early work suggested strongly that stimulus AC/As shows little change with age up to and beyond the onset of presbyopia.[25–33] Recent work by Rosenfield et al.[34] supports this finding. In contrast, response AC/Ar is found to increase with age: some investigators[32, 35–37] found a nonlinear change with the rate of increase accelerating fairly abruptly around the age of 40, whereas others suggest an approximately linear change through adulthood up to the age of about 50 years.[38–40] There is more general agreement that the response CA/C ratio declines almost linearly over an age range of about 15 to 55 years,[34, 38, 39, 41, 42] although Kent[43] and others have argued that the decline may be more closely related to the amplitude of accommodation rather than age.

Much less is known about the way in which the speed of the accommodation and convergence systems and their cross-links change with age. Several studies have found that the dynamics of the monocular accommodation response deteriorate with age,[44–48] but more recent work[49–51] suggests that any loss in speed is small when modest stimuli lying within the amplitude of accommodation are used. There is little information available on the changes in the dynamics of vergence alone with age or on any possible changes through life in the speed of accommodation convergence and convergence accommodation.

The aim of the present study was, then, to simultaneously record and explore under appropriate open-loop conditions the static accommodation and vergence responses to modest stimuli and their ratios as a function of age to confirm earlier work on this topic and to determine the dynamics of the various responses. All the measurements were carried out on the same group of normal subjects, and a particular goal was to determine whether the response AC/Ar and CA/C ratios varied independently with age in the same population of subjects.

METHODS

An SRI Dual Purkinje three-dimensional eyetracker[52, 53] was used to record vergence and accommodation simultaneously. The stimulus for accommodation and vergence was a high-contrast Maltese cross with a luminance of 50 cd/m^2. The target subtended 5° and was surrounded by a black, 20 min arc subtense border. The subjects were instructed to keep this target clear and single at all times. To minimize noise and other artifacts in the records, the subjects were kept in position relative to the eyetracker with a bitebar and head restraint. Pupils were dilated using 2 drops of 2.5% phenylephrine to maintain a good instrumental signal-to-noise ratio. It is known that phenylephrine may slightly reduce the static amplitude of accommodation[54–56] as well as having minor effects on response dynamics,[57] but in view of the small magnitude of the changes reported, it was felt that overall these effects would have only minor influence on the results obtained. The accommodation and vergence responses were sampled at 40 Hz.

Thirteen subjects were used, with ages ranging from 16 to 48 years (mean, 32.0 ± 11.1 years). All had normal and equal acuity in both eyes, no ocular pathology, and normal binocular vision. Subjects were either emmetropic or were made so by introducing appropriate spherocylindrical correction into the optometer's optical system. Their amplitudes of accommodation, as measured with a standard push-up method,[58, 59] lay within normal limits for their ages.[60] Informed consent was given after the purpose of the experiment had been explained.

Two experimental conditions were used, chosen to involve only modest demands on accommodation and vergence so that responses could be obtained from subjects over the full age range used. In the first (condition 1), the left eye was occluded while the optical vergence was changed by 2 D (between 0.25 and 2.25 D). These dioptric changes were provided by the eyetracker motorized Badal stimulus system.[53, 61] Dioptric changes followed a 0.1-Hz square wave, so that each 40-s trial contained four near-to-far and four far-to-near vergence steps. Under binocular conditions with a 6-cm pupillary distance, a 2 D change in accommodation demand would be associated with a 12 prism diopter change in convergence demand. This first condition provided measures of accommodation convergence and accommodation, which were used to derive the AC/Ar ratio.

In the second condition (condition 2), 0.5-mm pinholes were centered on the entrance pupil of the vision stimulator and used with binocular viewing. Additional external lighting was provided to maintain the retinal illuminance of the target images with the reduced pupil diameters at approximately the same level as in condition 1. The pinholes were used to increase ocular depth-of-focus[62] so that changes in accommodation did not blur the retinal image. Thus, accommodation operated under open-loop conditions. Six prism diopter step changes in stimulus vergence were provided at a frequency of 0.1 Hz using the mirror galvanometers of the SRI vision stimulator. The optical distance of the target was kept constant at 0.25 D. Hence, in each 40-s recording under condition 2, convergence accommodation and vergence were measured to provide data for the response CA/C ratio.

Before recording, the eyetracker was carefully aligned to prevent cross-talk with the optometer. Calibration for eye movements was made by requiring each subject to make horizontal versional eye movements in 2° steps over a 14° range.

RESULTS

Typical Recordings

Fig. 1 shows typical recordings for a single subject. In the example shown (SS, 35 years), accommodation (Fig. 1A) and accommodative convergence (Fig. 1B) responses were vigorous, as was the vergence response (Fig. 1D): convergence accommodation was less consistent, however (Fig. 1C). Because the accommodation changes were quite small, the noise caused by fluctuations in accommodation was relatively prominent. Some asymmetry in the

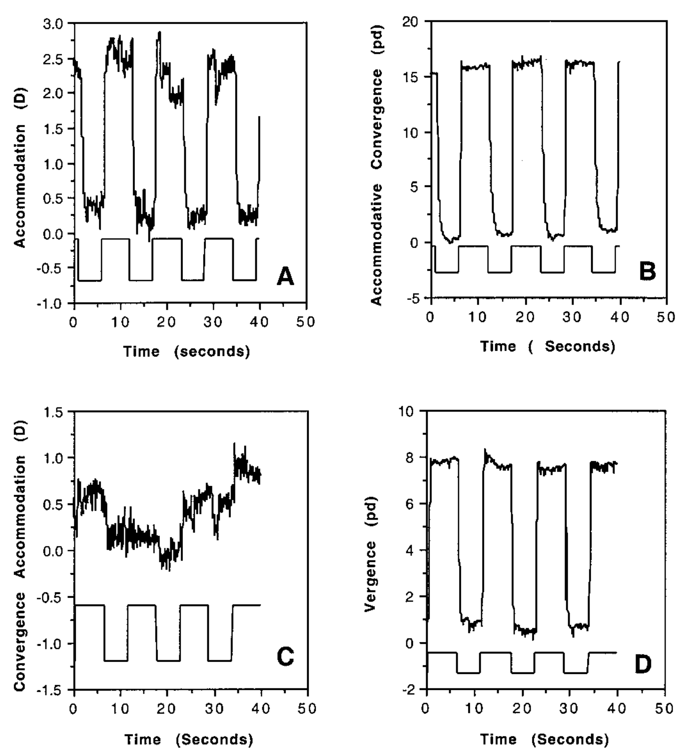

FIGURE 1.

Examples of responses as a function of time for an individual subject (SS, age 35 years) subjective amplitude of accommodation 5.00 D. A: Accommodation response (Ar) in diopters; B: accommodative convergence (AC) in prism diopters; C: convergence accommodation (CA) in diopters; D: vergence (C) in prism diopters. Traces (A) and (B) were obtained simultaneously under condition 1, and (C) and (D) were obtained under condition 2. To avoid overlap with the response traces in the illustrations, the stimulus changes are only shown schematically: the times of stimulus change are correct but the levels are not (see text for true values).

near-to-far and far-to-near accommodative vergence responses was apparent, with the near-to-far response taking longer to stabilize to its new level.

Records of this type for each subject were examined in terms of the mean amplitudes, time constants, and velocities of the responses (see below for definitions). The age dependence of the various parameters was then explored.

Response Amplitudes

The amplitudes of response for accommodation (Ar), accommodative convergence (AC), convergence accommodation (CA), and vergence (C) were read off from the recordings, and mean values were compared as a function of age. The plotted data are shown in Fig. 2. For simplicity, regression lines (full lines) have been fitted to the data for all subjects. Table 1 gives the equations of the regression lines, together with the associated square of the product moment correlation coefficient (r^2) and probability (p) values.

Both measures of accommodation (Ar, CA) showed a significant ($p < 0.05$) decline with age. Although linear fits to the data have been used, inspection of Fig. 2A suggests that in fact, Ar remains roughly constant to the age of 40 years, when the 2.25 D stimulus level approaches the upper limits of the amplitude of accommodation, and then declines abruptly; this effect is not obvious in the case of CA. The dashed line in Fig. 2A ($y = 0.99 + 0.017x$; $r^2 = 0.275$; $p = 0.15$) represents a linear fit to the data for subjects under the age of 40 years, confirming that Ar is essentially constant in earlier life. In contrast, the two measures of vergence (AC and C) show only a small, statistically insignificant increase in amplitude over the full age range.

TABLE 1.
Table of regression equations, r^2 values, and significance levels for the variation with age of the amplitudes of the listed parameter.

Response Type	Regression Equation[a]	r^2	p Value
Ar[b]	$y = 2.2 - 0.034x$	0.391	0.022
AC	$y = 3.11 + 0.098x$	0.076	0.36
CA	$y = 0.72 - 0.012x$	0.411	0.016
VERG	$y = 2.85 + 0.088x$	0.167	0.17

[a] In each equation, x is the age in years.
[b] Ar, accommodative response; AC, accommodative convergence; CA, convergence accommodation; VERG, vergence.

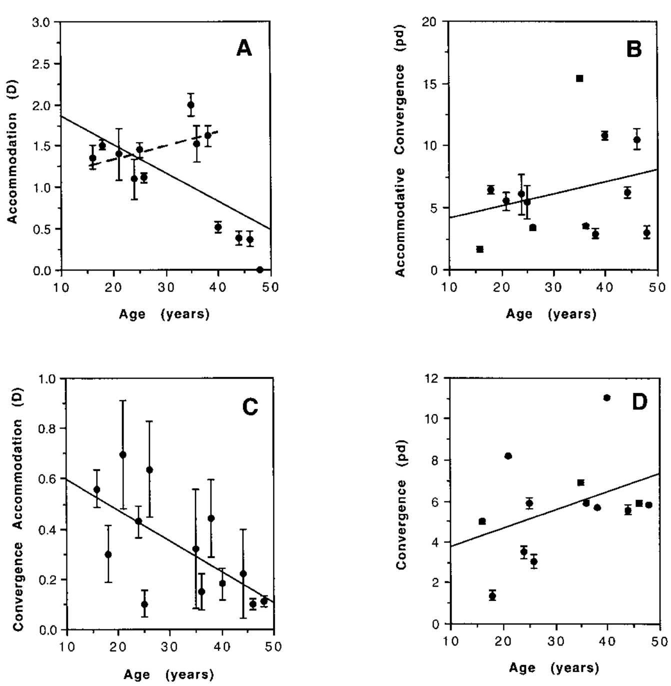

FIGURE 2.
Mean response amplitudes as a function of age. A: Accommodation response (Ar) in diopters; B: accommodative convergence (AC) in prism diopters; C: convergence accommodation (CA) in diopters; D: vergence (C) in prism diopters. Error bars indicate SD. Regression equations for each complete data set are given in Table 1. The dashed line in (A) is a linear regression fit to the data for subjects aged less than 40 years: it suggests that Ar is almost independent of age for such subjects.

AC/As, AC/Ar, and CA/C Ratios

The data for the AC/As, AC/Ar, and CA/C ratios are plotted as a function of age in Fig. 3, and the parameters for the corresponding regression line fits over the full age range are given in Table 2.

It is evident that with As = 2.00 D, the regression line for the AC/As ratio relates directly to that for AC in Table 1, which shows that the ratio does not change significantly with age. The slope of the regression for AC/Ar vs. age is significant ($p < 0.01$); however, Fig. 3A suggests that rather than showing a linear change, the ratio may again be better described as being approximately constant up to the age of 40 years and rising abruptly thereafter. This is supported by the regression line fit (dashed) to data for subjects aged

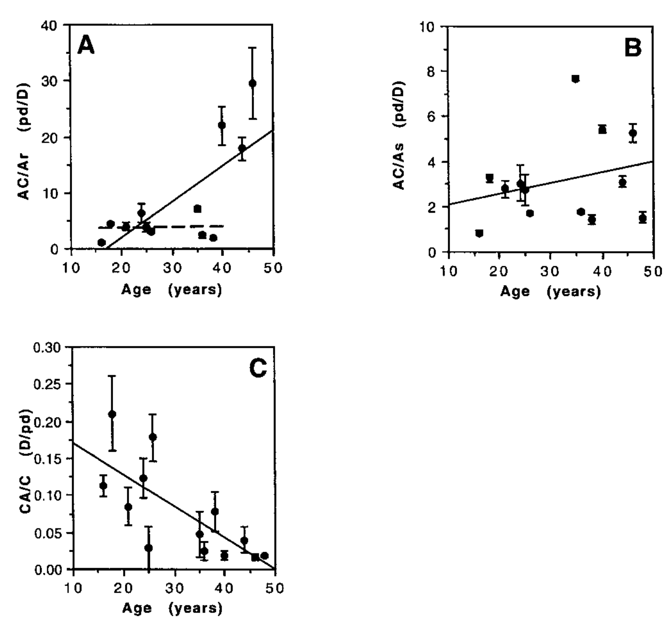

FIGURE 3.
Variation with age in (A) the response AC/Ar ratio in prism diopters/diopter; (B) the stimulus AC/As ratio in prism diopters/diopter; and (C) the CA/C ratio in diopters/prism diopter. Vertical bars indicate SD. Regression equations as shown by the full lines are given in Table 2: the dashed line in (A) is a regression fit to the data for subjects aged less than 40 years.

less than 40 years ($y = 3.4 + 0.0016x$; $r^2 = 0.004$; $p = 0.87$). CA/C shows a significant ($p < 0.01$) decline with age.

Dynamic Time Constants and Velocities

The dynamics of the various far-to-near and near-to-far step responses (Ar, AC, CA, and C) were characterized in terms of the following time constants: latency (the time interval between the stimulus change and the initiation of a response), response time (the time interval between the initiation and completion of a response), mean velocity (the amplitude divided by the response time), and maximal velocity (as derived by differentiating the response). Table 3 summarizes the regression fits for the changes of these parameters with age for each of the responses. Note that most parameters show no significant changes with age. The exceptions are the mean and maximal near-to-far Ar velocities and the maximal far-to-near CA velocity, all of which reduce with age, and the mean far-to-near C velocity, which increases with age.

TABLE 2.
Equations, r^2 and, p values for regression line fits for the variation of AC/As, AC/Ar, and CA/C ratios as a function of age × years.[a]

Ratio	Regression Equation	r^2	p Value
AC/As	$y = 1.56 + 0.049x$	0.076	0.36
AC/Ar	$y = -11.2 + 0.65x$	0.518	0.008
CA/C	$y = 0.21 - 0.0043x$	0.634	0.005

[a] AC, accommodative convergence; As, accommodation stimulus; Ar, accommodative response; CA, convergence accommodation; C, vergence changes.

DISCUSSION

Response Amplitudes and Their Ratios

The most striking feature about the present results is that over an age range (16 to 48 years) when the subjective amplitude of accommodation declines fairly steadily from about 12 to 2 D, many aspects of the accommodation and vergence responses and the interactions between them remain remarkably robust with the passing years, at least for stimuli lying within the modest ranges used in the present study (Fig. 2 and Table 1). There is, however, a significant fall with age in Ar and CA, whereas there is no significant change in either AC or C amplitudes.

Considering first the accommodative response, Ar, it appears that rather than the changes being linear with age, it is only when the age of 40 years is passed and the 0.25 to 2.25 D accommodation stimulus levels used start to approach the limits of the objective amplitude of accommodation that Ar starts to diminish. This broadly agrees with studies of the age-dependence of the slope of the monocular accommodation response/stimulus curve.[63, 64] These show that the slope of the linear portion of the curve, and, hence, response magnitudes for modest stimuli, reduces only slowly with age up to about 40 years and then declines rapidly as complete presbyopia is approached.

TABLE 3.
Regression data for the changes with age, x, in the dynamic characteristics of Ar, AC, CA, and C.

Response Type	Regression with Age[a]	r^2	p Value
Ar			
Latency (ms)	FN: $y = 403 - 2.7x$	0.047	0.30
	NF: $y = 186 + 3.7x$	0.109	0.29
Response time (ms)	FN: $y = 944 - 2.5x$	0.004	0.93
	NF: $y = 603 + 8.4x$	0.029	0.69
Mean velocity (D/s)	FN: $y = 2.3 - 0.013x$	0.021	0.67
	NF: $y = 2.5 - 0.029x$	0.448	0.019
Maximum velocity (D/s)	FN: $y = 4.1 + 0.0023x$	0.000	0.99
	NF: $y = 5.9 - 0.070x$	0.424	0.023
AC			
Latency (ms)	FN: $y = 20.5 + 4.0x$	0.213	0.11
	NF: $y = 158 + 0.9x$	0.013	0.72
Response time (ms)	FN: $y = 1230 + 15x$	0.024	0.62
	NF: $y = 1248 + 13x$	0.057	0.43
Mean velocity (pd/s)	FN: $y = -2.56 + 0.74x$	0.042	0.47
	NF: $y = 2.0 + 0.084x$	0.047	0.48
Maximum velocity (pd/s)	FN: $y = 6.9 + 0.25x$	0.045	0.49
	NF: $y = 3.8 + 0.38x$	0.032	0.56
CA			
Latency (ms)	FN: $y = 276 + 2.6x$	0.021	0.63
	NF: $y = 216 + 2.7x$	0.036	0.51
Response time (ms)	FN: $y = 731 - 6.0x$	0.063	0.52
	NF: $y = 891 - 13.5x$	0.227	0.16
Mean velocity (D/s)	FN: $y = 2.6 - 0.032x$	0.238	0.18
	NF: $y = 2.7 - 0.014x$	0.009	0.80
Maximum velocity (D/s)	FN: $y = 5.58 - 0.086x$	0.718	0.004
	NF: $y = 4.86 - 0.048x$	0.107	0.36
C			
Latency (ms)	FN: $y = 75 + 1.8x$	0.068	0.39
	NF: $y = 72 + 1.4x$	0.146	0.20
Response time (ms)	FN: $y = 249 - 44x$	0.041	0.12
	NF: $y = 855 + 15x$	0.087	0.33
Mean velocity (pd/s)	FN: $y = 1.66 + 0.20x$	0.382	0.025
	NF: $y = 3.5 + 0.051x$	0.039	0.52
Maximum velocity (pd/s)	FN: $y = 24.1 - 0.025x$	0.000	0.95
	NF: $y = 11.6 + 0.17x$	0.030	0.57

[a] Ar, accommodative response; AC, accommodative convergence; CA, convergence accommodation; VERG, vergence; FN, far-to-near responses; NF, near-to-far responses.

As noted earlier, the accommodative convergence (AC) shows no significant changes with age. It is, however, evident from Fig. 2B that the variability in AC between subjects becomes larger as their age approaches 40 years. This probably reflects the fact that some subjects were having difficulty in accommodating sufficiently to clear the target (Fig. 2A), so the accommodative feedback loop was essentially open. Because AC remains approximately constant with age, whereas Ar shows a significant decline, it is not surprising to find in Fig. 3A that the AC/Ar ratio increases with age over the complete age range studied (16 to 48 years) However, Fig. 2A suggests strongly that as would be expected from the previous paragraph, the real increase only occurs after an age of about 40 years, when Ar starts to decline: this is supported by the finding that a linear fit to the data for younger subjects (Fig. 3A) shows no evidence for any systematic change in AC/Ar. Note that our 48-year-old subject had Ar = 0, although his AC was non-zero: thus his AC/Ar would nominally be infinite. Similar nonlinear behavior of AC/Ar with age was well illustrated in the longitudinal studies of Fry[37] and Eskridge.[39] Transverse studies also show an increase in AC/Ar with age.[34, 38, 40, 41]

It is obvious that if the accommodation convergence, AC, is unaffected by age, the ratio AC/As is also going to show no significant change, in agreement with numerous earlier studies.[27–33, 35, 40]

It is of interest that although as in previous studies there is considerable scatter in the results shown in Fig. 2, convergence accommodation (CA) may decline more steadily with age than does accommodation (Ar), in the sense that there is a strong suggestion that the closed-loop accommodation response remains robust up to the age of about 40 years before declining rapidly, whereas the open-loop convergence accommodation decreases gradually throughout adulthood.[34, 41–43, 65–67]

Considering vergence (C), some of our subjects produced very inaccurate responses to the step stimuli (Fig. 2D). We attribute this to the unfamiliarity and difficulty of the task, rather than to calibration problems or any intrinsic defect in the near response systems of the subjects. We have previously noted cases in which normal subjects experience difficulty in responding accurately during near-vision experiments of the present type.[49] In general, vergence (C) does not appear to vary significantly with age. The implication may be that with constant innervation from the vergence system, the resultant convergence accommodation reduces with the fall in the general responsiveness of the accommodation system after age-dependent changes in lenticular and capsular elasticity, lens geometry, etc., i.e., it relates to the objective amplitude of accommodation and only indirectly to age. This argument was advanced by Kent,[43] who was able to show that CA/C varied almost linearly with the amplitude of accommodation over the range 2 to 10 D.[68, 69] Wick and Currie[65] found a much weaker relationship, although many of their subjects had amplitudes outside the 2 to 10 D range over which Kent[43] found that linearity applied. Fig. 4 shows our CA/C data plotted against the subjective amplitude of accommodation for our subjects: the r^2 value is similar to that found when age is used as the abscissa ($y = -0.01 + 0.013x$; $r^2 = 0.66$).

If we simply consider the regression of CA/C (pd/D) on age (years), the present results agree quite well with those obtained by earlier authors:

Bruce et al.[41]: $y = 0.17 - 0.003x$
Rosenfield et al.[34]: $y = 0.31 - 0.006x$
Present study: $y = 0.21 - 0.0043x$

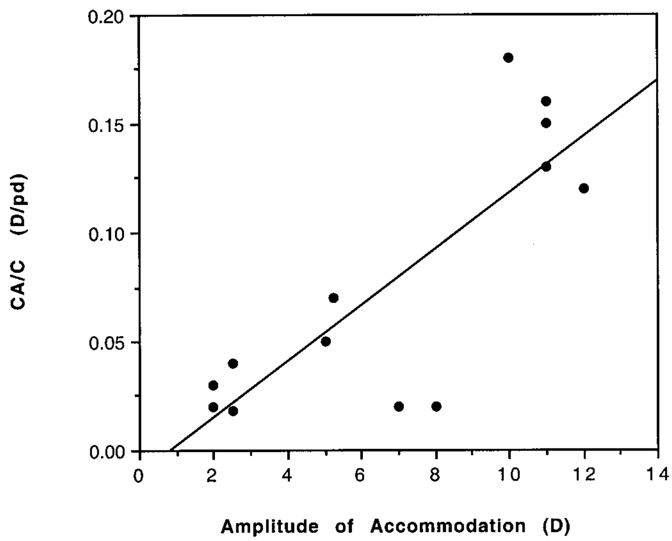

FIGURE 4.
CA/C ratio plotted as a function of subjective amplitude of accommodation, rather than age.

Fincham and Walton[42] suggested that the actions of accommodation and convergence are reciprocally related. Rosenfield et al.[34] tested this as a function of age using [(CA/C) − 1/(AC/Ar)] as the measure of reciprocity. The latter quantity would equal zero if reciprocity was exact. The results of Rosenfield et al.[34] are replotted in Fig. 5, together with results from the present study. In both cases, the reciprocal of the AC/Ar ratio exceeds the CA/C, implying that exact reciprocity does not hold. It is not possible to identify pairs of AC/Ar and AC/A values for individual subjects from the data provided by Bruce et al.,[41] but if the regression line fits are used for the individual ratios, [(CA/C) − 1/(AC/Ar)] varies from −0.06 at the age of 20 years to +0.18 at the age of 50 years, again suggesting imperfect reciprocity.

Dynamic Effects

It is striking that very few significant changes with age can be detected among the large number (32) of parameters studied (Table 3). None of the latencies or response times showed a significant

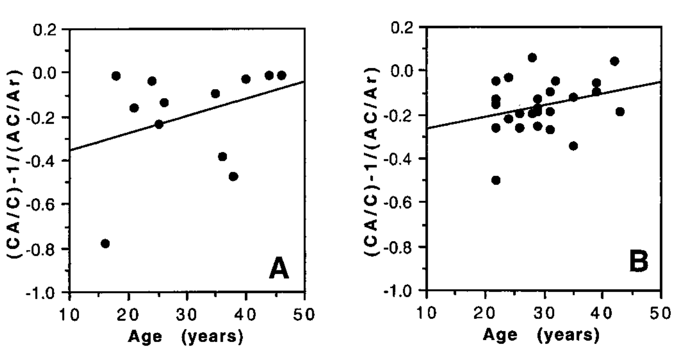

FIGURE 5.
Plots of the quantity [(CA/C) − 1/(AC/Ar)] as a function of age for (A) the present study and (B) the study by Rosenfield et al.[34] If the AC/Ar and CA/C ratios were reciprocally related, the ordinate would always be zero. The regression equations are (A) $y = -0.43 + 0.0077x$; $r^2 = 0.110$ and (B) $y = -0.32 + 0.0055x$; $r^2 = 0.081$.

change, suggesting that up to the age of complete presbyopia, the overall response duration of both the accommodation and vergence systems shows little extension with age when dealing with modest stimuli. This supports recent work on monocular accommodation dynamics with small stimuli.[49–51] Table 4 gives the means of the various far-to-near and near-to-far latencies and response times for all the subjects used in the study.

Evidently, because there is a tendency for Ar and CA to decline with age (Fig. 2) and the response times are unchanged (Table 3), a tendency for the mean response velocities to decline might be expected in the corresponding cases. In practice, this effect was only observed in two cases (Table 3).

The latencies of about 120 ms reported for vergence and maximal velocities of about 10 deg/s are similar to those classically described.[70] Latencies for accommodation, Ar, were generally longer, at around 300 ms, again in agreement with standard values in the literature.[45, 71–74] The vergence response was initiated more quickly than that of accommodation,[72] although the overall response times were similar.

Accommodative convergence was generally found to be slower than disparity vergence, having a longer latency (although this was not significant) and significantly slower maximal velocity.[75] Finally, convergence was found to be faster than divergence, which is consistent with earlier work.[76–78]

One way of evaluating the relative importance of changes with age in the dynamics of the accommodation and convergence system is to determine how the ratios of the maximal velocities of the different responses change as a function of age. Three such comparisons are made in Fig. 6, with the regression data being given in Table 5.

Fig. 6 A and B shows the ratio, under condition 1, of the maximal velocity for accommodation convergence, AC, to that for accommodation, Ar, for far-to-near and near-to-far as a function of age. It can be seen that accommodative convergence appears to become relatively faster in comparison to accommodation as age increases. Fig. 6 C and D shows similar plots for the ratio of maximal speed of vergence, C, to that for convergence accommodation, CA, under condition 2. Again, it appears that the relative speed of vergence becomes greater with age (although not, of course, its absolute speed). Finally Fig. 6 E and F compares the maximal speeds of accommodative convergence, AC, with convergence accommodation, CA. Here, although there is a slight upward trend with age for the far-to-near case, the effects are not significant. Because all stimulus changes were relatively small, we do not do not believe that these conclusions are affected by the differences in the vergence demands associated with condition 1 (12 prism diopters) and condition 2 (6 prism diopters).

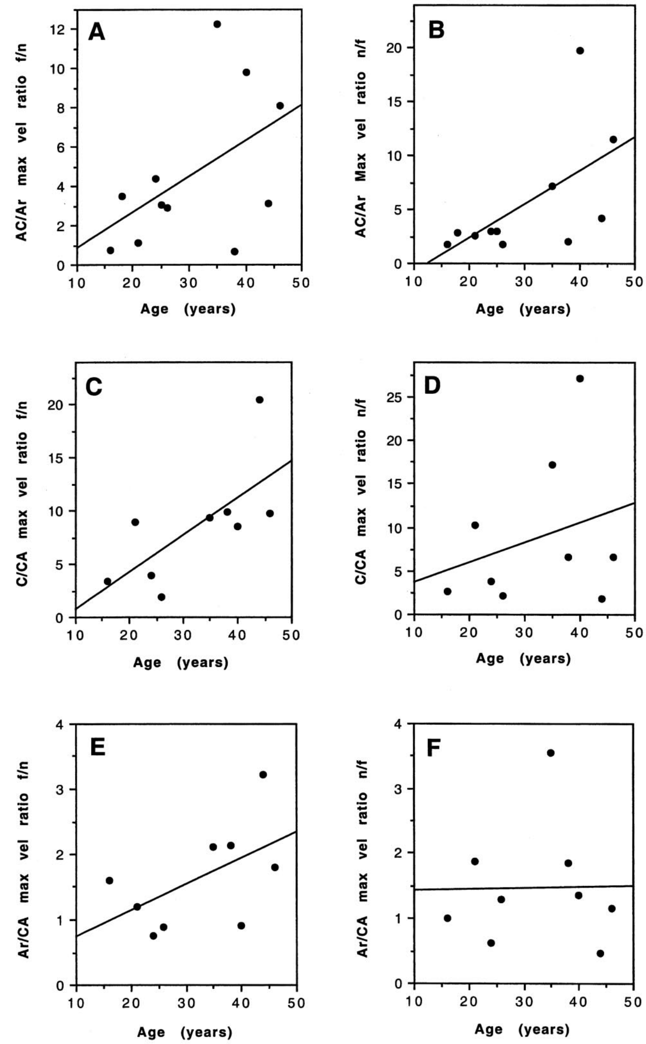

FIGURE 6.
Variation with age in the ratio of the maximal velocities for (A) far-to-near (AC/Ar); (B) near-to-far (AC/Ar); (C) far-to-near (C/CA); (D) near-to-far (C/CA); (E) far-to-near (Ar/CA); and (F) near-to-far (Ar/CA). The regression equations are given in Table 5. AC, accommodative vergence; Ar, accomodation response; C, vergence; CA, convergence accommodation.

TABLE 4.
Mean latencies and response times for all the subjects used in the study.

	Latency (ms)	Response Time (ms)
Accommodation, Ar	FN: 317 ± 142[a]	FN: 865 ± 445
	NF: 302 ± 126	NF: 870 ± 557
Accommodative convergence, AC	FN: 148 ± 95	FN: 1869 ± 680
	NF: 168 ± 92	NF: 1670 ± 603
Convergence accommodation, CA	FN: 362 ± 197	FN: 539 ± 256
	NF: 272 ± 176	NF: 435 ± 320
Convergence, C	FN: 132 ± 74	FN: 752 ± 219
	NF: 116 ± 39	NF: 1343 ± 565

[a] FN, far-to-near responses; NF, near-to-far responses.

TABLE 5.
Regression data for Fig. 6, giving relative maximal speeds of response for the various parameters as a function of age, x years.

Ratio of Maximal Velocities	Regression Equation	r^2	p Value
AC/Ar[a]	FN: $y = -1.0 + 0.18x$	0.256	0.112
	NF: $y = -4.0 + 0.31x$	0.354	0.054
C/CA	FN: $y = -2.9 + 0.31x$	0.481	0.038
	NF: $y = 1.5 + 0.22x$	0.081	0.46
Ar/CA	FN: $y = 0.35 + 0.04x$	0.285	0.14
	NF: $y = 1.4 + 0.002x$	0.001	0.95

[a] AC, accommodative convergence; Ar, accommodative response; C, vergence changes; CA, convergence accommodation.

Implications for Models of Presbyopia

The present data (Fig. 2A) showing that C does not vary with age agree with a substantial body of earlier work in suggesting that the vergence system maintains its efficiency almost throughout adult life.[12–14] However, open-loop convergence accommodation (Fig. 2C) was found to reduce steadily with age (see also Kent,[43] Wick and Currie,[65] and Rosenfield et al.[34]). This must imply that the presumably constant innervation to convergence accommodation provided by the vergence system cannot compensate for a gradual fall in efficiency of the accommodation plant, so CA falls steadily with the diminishing amplitude of accommodation as presbyopia is approached.

In contrast to the steady decline in CA, Ar (Fig. 2A) for any given modest As is relatively robust against increasing age up to about the age of 40 years, with a rapid decline thereafter as complete presbyopia is approached (see also Mordi and Ciuffreda[63] and Kalsi et al.[64]). To explain these apparent conflicts in accommodative behavior, we suggest that a slow adaptive change[79, 80] must be taking place in the blur-driven, closed-loop, accommodative system, with increased innervation being applied to achieve the same accommodative change, Ar, as the accommodation plant becomes less efficient. Maintenance of Ar is obviously necessary if marked blur of the retinal image is to be avoided in the older pre-presbyopic eye. The finding that despite this increased innervation, accommodation convergence, AC, does not show a significant change (Fig. 2B) could be interpreted as suggesting that this cross-link must also show adaptation to maintain AC/Ar at an almost constant level up to the age of 40 years. However, Schor and Kotulak[6] found that AC/Ar was reduced as the slow adaptive tonic component increased its contribution to the total accommodation response. This, together with other observations, suggested that adaptable accommodation had weak or no cross-links with convergence, in contrast to the faster, phasic component of accommodation. Thus, when the pre-presbyope uses more tonic accommodation, less accommodative convergence is stimulated than when more phasic accommodation is used. In consequence, the cross-link is not necessarily adapted, only the input to the cross-link is reduced by the shift in control from phasic to tonic accommodation.

We note the possibility of an alternative explanation for some aspects of the results that does not involve an adaptive process. The maintenance of the accommodation response to an approximately constant level up to the age of 40 years despite lenticular and other age-related changes may simply be explained by the closed-loop feedback nature of the accommodative system. In contrast, as noted earlier, the convergent accommodation response is open-loop. It does not benefit from feedback and, hence, shows a steady age-related decline. It is not clear, however, how open-loop accommodative convergence can be maintained constant with age on this basis.

It is interesting to compare these results with those predicted by classical models of presbyopia, particularly the Hess-Gullstrand and Duane-Fincham models. As usually interpreted,[25, 81–83] the Hess-Gullstrand model[84, 85] states that the ciliary muscle maintains its strength throughout life and that a constant amount of ciliary muscle force is required for each diopter of accommodative change. The amplitude of the possible response change is, however, limited by age-dependent changes in the lens and capsule, leaving latent muscle contraction after maximal accommodation has been achieved. This model predicts, then, that the accommodation response, Ar, to small stimuli remains accurate as age increases and demands constant innervation, but that amplitude gradually diminishes. On the other hand, the Duane-Fincham model[86–88] assumes that due to lens hardening, more ciliary muscle force is required for each diopter of accommodation as age increases. Maximal accommodation at any age therefore requires maximal ciliary muscle contraction. Although Duane believed that the ciliary muscle might weaken with age, Fincham believed that it maintained its strength, a belief that was subsequently justified by the work of Fisher[15–18] (see also Strenk et al.[20]). Although the Fincham-Duane model is often pictured as predicting a fall in the slope of the accommodation response/stimulus curve,[25, 81–83] this does not appear to be a valid interpretation of the model.[64] Fincham merely suggests that for any level of stimulus, more accommodative effort is required to achieve a satisfactory response: he does not state that the response is any smaller (provided that the stimulus lies within the amplitude of accommodation). Thus the Duane-Fincham model predicts lags of accommodation that are similar to those suggested by the Hess-Gullstrand.

It is evident that based on our interpretation, the present data better support the basic ideas behind the Duane-Fincham model because it appears necessary to assume an increase of innervation to accommodation, Ar, with increasing age. A great deal of additional relevant information has, of course, become available since the Hess-Gullstrand and Duane-Fincham models were proposed, allowing the development of more sophisticated models of the genesis of presbyopia.[48, 89, 90] The present data appear to be compatible with all these models.

CONCLUSIONS

While the amplitude of accommodation falls by a factor of about five over the age range 16 to 40 years, the accommodation response to small accommodation stimuli lying within the amplitude of accommodation remains little changed, as also does accommodative convergence and the AC/Ar ratio.[50] It is only after the age of about 40 years that Ar starts to fall and AC/Ar to rise. Convergence is found to be almost constant over the age range 16 to 48 years, although convergence accommodation and the CA/C ratio fall steadily with age over this age range. The latencies and response times for the small accommodation and convergence stimuli used are remarkably robust against the effects of age. Thus, the overall picture that emerges is that of an accommodation-convergence system that apart from its loss of accommodative amplitude, continues to function with remarkable efficiency and to satisfy normal everyday visual needs until the age of about 40 years is reached.

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W. N. Charman
Department of Optometry and Neuroscience
UMIST
Manchester M60 1QD
United Kingdom
e-mail: MJCWNC@fs1.op.umist.ac.uk