Accommodation–Convergence Relationships and Age

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Purpose. The objective of this study was to determine if there are differences in accommodative–convergence/accommodation (AC/A) and convergence-accommodation/convergence (CA/C) ratios in subjects with increasing age. The authors aimed to relate the findings to the present theories of the development of presbyopia.

Methods. Using a Canon AutoRef R-1 to measure accommodation and an IRIS eye movement monitor to measure eye movements, the authors determined objective AC/A and CA/C ratios for 23 subjects between 17 and 42 years of age with normal binocular vision. Changes in accommodation and convergence responses were stimulated by lenses (−1.00 DS and −2.00 DS) and prisms (4 and 8 prism diopters), respectively. Measures were made at two visits on consecutive days.

Results. A moderate linear relationship was found between AC/A ratio and age (P < .002), and a strong linear relationship was found between CA/C ratio and age (P < .0001). The decrease in CA/C ratio with age was due to a decreased accommodative response to prisms (P = .0001). Measurements were reliable, with 95% confidence intervals at ±1.28 Δ/D and ±0.02 D/Δ for AC/A and CA/C ratios, respectively. A reciprocal relationship existed between the AC/A and CA/C ratios.

Conclusion. The AC/A ratio increases, and the CA/C ratio decreases, in persons between 20 and 40 years of age. This may be because increasing ciliary muscle contraction is required to produce a given change in accommodation with increasing age or because of changes in the adaptability of the tonic accommodation and vergence systems with age. Invest Ophthalmol Vis Sci. 1995;36:406-413.

Because the amplitude of accommodation decreases steadily with increasing age, it is likely that convergence, which is intricately interwoven with the accommodative mechanism, should also change with age. The interactions between accommodation and convergence result in a combined operation of the two systems that is different from their isolated operation. Accommodative convergence (AC) is the convergence resulting from the accommodative effort, and convergence accommodation (CA) is the amount of accommodation (A) elicited through convergence (C). These phenomena are measured by the AC/A and CA/C ratios, respectively. Several models of the accommodation–convergence interactions have been proposed in the past; however, relatively little has been written about the effect that age might have on these interactions.

Previous studies of the effect of age on accommodation–convergence interactions have produced different results depending on whether they used the stimulus method or the response method. To determine stimulus AC/A, the denominator refers to the value of the stimulus, whereas to determine response AC/A, the actual accommodation elicited is the denominator. Determination of response AC/A shows an increase in AC/A mainly after 40 years of age, whereas assessment of the stimulus AC/A does not show change in AC/A with increasing age. Whether there is a significant increase in the response AC/A before age 40 is unclear. Research on convergence accommodation (CA) shows a decrease in CA/C, whether measured by response or stimulus methods, with increasing age.

Of the previous studies investigating accommodation vergence interactions and age, in only one were
both AC/A and CA/C measured and with the same subjects. Only six subjects were used. A comparison of the changes in these ratios, in relation to the repeatability of the measurements, does not appear to have been previously made. The purpose of our study was to determine response AC/A and response CA/C ratios on the same large sample of subjects with presbyopia. All subjects had normal binocular vision, and the repeatability of each technique was ascertained by repeating measurements on a different day.

We anticipated that an experiment with these characteristics would give us a better understanding of the complex interactions between the accommodation and vergence mechanisms and also would carry implications for theories of presbyopia. The Hess-Gullstrand theory of presbyopia suggests that a similar level of ciliary muscle contraction is needed to produce a given change in accommodation at all ages. According to this theory, accommodation-vergence relationships would remain unchanged in persons between 20 and 40 years of age, when a considerable decrease in amplitude of accommodation occurs and if other factors remain constant.

METHODS

The research followed the tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology’s Biomedical Ethics Committee. Informed consent was obtained from subjects after the nature of the study was explained.

Subjects

Thirty-four subjects between 17 to 42 years of age were assessed. Subjects included in the study had normal ocular health, amplitude of accommodation (push-up method) normal for their ages, visual acuity equal in both eyes and corrected to at least 6/6, and astigmatic corrections of no more than 0.75 D. Subjects who required optical correction had to be comfortable contact lens wearers because the nature of the apparatus (Fig. 1) did not allow for spectacle correction. Three subjects were excluded from the study because of discomfort with contact lenses, and one was excluded because of uncorrected myopia.

Subjects were also required to have normal binocular vision. Binocular vision was assessed with routine clinical tests, including stereopsis of 60 seconds or less (Titmus fly) and near point of convergence of less than 12 cm. Horizontal phorias with Prentice card at 5 m and 35 cm were also measured. Five subjects were excluded owing to binocular vision anomalies that resulted in either suppression or diplopia. One subject was not able to appreciate physiological diplopia, and another was unable to attend all the required sessions.

Twenty-three subjects successfully met the required criteria and completed the experiments. Their ages, visual acuities, amplitudes of accommodation, and binocular vision characteristics are shown in Table 1. The data illustrate the normal pattern of declining accommodation amplitude as a function of age. None of the subjects reported either suppression or diplopia at any time during measurements.

Equipment and Experimental Setup

The accommodative response of the right eye of each subject was measured with a Canon (Tokyo, Japan) AutoRef R-1 autorefractor. This instrument allows free space viewing while measurements are made. The stimulus to accommodation and vergence was a Mattese cross-target placed at a distance of 2 m from the subject. The convergence response was measured with an IRIS infrared eye movement recorder (Scalar Medical, Delft, Netherlands), which uses a binocular infrared limbal sensing system to monitor convergence. Both the Canon AutoRef R-1 and the IRIS systems were linked to a computer to facilitate data collection.

Lenses, prisms, and occluders were placed on holders on the AutoRef where they could be interchanged without interfering with the IRIS. To avoid artefacts in eye movement monitoring, each subject’s head was restrained onto a system comprising a chinrest and headgear. A suppression monitor comprising a vertical stick target was placed at the midline, just below the line of sight, at the far end of the AutoRef to ensure that subjects were not suppressing one eye. The stick appeared in physiological diplopia as the subject viewed the target at two meters. The suppression monitor played an important role in maintaining binocularity.

Accurate alignment of the IRIS sensors with the eyes was crucial for linearity and symmetry of response. Initially, the eyes were aligned by the pinhole or white lines
with both eyes and for adequate signal strength from the apparatus before consistent results could be obtained. As a test of reliability, experiments were conducted on two consecutive days.

The accommodation loop was opened by placing 0.5-mm pinholes in front of both eyes. The pinholes produced a large depth of focus that ensured that there was no blur feedback to guide the accommodation response. The periphery of the pinhole was opaque to visible light but transparent to infrared light for the measurement of accommodation (Wratten [Eastman Kodak, Rochester, NY] filter 89B). The pinholes were mounted between two plastic rings in a trial lens holder to ensure that the filters remained flat and did not warp. The lens holders were then attached in front of the IRIS limbal sensors. The pinholes were slightly tilted at 5° to 10° from the vertical to avoid reflections affecting the AutoRef. The vergence loop was opened by occluding the left eye. Before measuring the effect of each set of lenses and prisms on the vergence system, the IRIS was calibrated using known horizontal shifts in fixation.

Protocol

The AC/A ratio, which is the induced change in convergence divided by the change in accommodation, was measured by changing the accommodative task and measuring the consequent changes in accommodation and convergence. Subjects were instructed to focus on the target and to keep it clear at all times. The convergence loop was opened. Three baseline measures of accommodation status and eye position were initially taken, using the Canon R-1 and IRIS eye tracker. Lenses of -1.00 D and -2.00 D power were placed in front of the right eye to stimulate different levels of accommodation. Accommodation and vergence responses were assessed in two separate experiments, for the different lens conditions. Three sets of recordings of change in accommodation (in units of diopters) and convergence (in units of prism diopters) were then made for each lens.

The CA/C ratio, which is the induced change in accommodation divided by the change in convergence, was measured by changing the vergence task and measuring the resultant changes in accommodation and convergence. Subjects were instructed to keep the target appearing single at all times. The accommodation loop was opened. Three baseline measures of eye position and accommodation status were initially determined. Prisms of -1.00 D and -2.00 D power were placed in front of the right eye to stimulate different levels of accommodation. Accommodation and vergence responses were measured by changing the vergence task and measuring the consequent changes in accommodation and convergence. Subjects were instructed to keep the target appearing single at all times. The accommodation loop was opened. Three baseline measures of eye position and accommodation status were initially determined. Prisms of 4 and 8 prism diopters (Δ) base out were placed in front of the left eye to alter convergence. Three sets of recordings of accommodation and convergence were made for each prism, in two separate experiments.

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<th>.35 m phoria (Δ)*</th>
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VA = visual acuity of right eye in logMAR units; Amp of Acc = amplitude of accommodation of right eye; NPC = near point of coverage.

* Phoria negative = esophoria; phoria positive = exophoria.
TABLE 2. AC/A and CA/C Ratios on Days 1 and 2

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<tr>
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<th>Day 1</th>
<th>Day 2</th>
<th>df</th>
<th>t-value</th>
<th>Significance</th>
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<td>CA/C 4A  (D/A)</td>
<td>0.074 ± 0.030</td>
<td>0.075 ± 0.026</td>
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<td>NS</td>
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<td>CA/C 8A  (D/A)</td>
<td>0.076 ± 0.026</td>
<td>0.076 ± 0.024</td>
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<td>0.18</td>
<td>NS</td>
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<td>AC/A -1.00 (Δ/D)</td>
<td>4.42 ± 1.55</td>
<td>4.47 ± 1.37</td>
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<td>AC/A -2.00 (Δ/D)</td>
<td>4.32 ± 1.50</td>
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<td>± 1.37</td>
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Day 1 and day 2 values are mean ± standard deviation. NS = not significant.

Analysis

For each subject and condition, AC/A and CA/C ratios were calculated. An analysis of variance was performed for statistical significance of regression, with age as an independent variable. Repeatability of results was assessed from the difference in the AC/A and CA/C ratios, respectively, on the two days of measurement.

RESULTS

Concordance of measures obtained on two different days and with two different lenses (or prisms) was examined to assess repeatability, as well as the feasibility of averaging measurements in other analyses. Neither AC/A nor CA/C measurements were significantly different across days or lenses (paired t-test, df = 22, P > 0.05). Indeed, the ratios were highly repeatable measurements (Table 2). The high degree of concordance between ratios determined with the different prism or lens powers indicated the ratios to be linear across the range of powers tested.

Confidence limits for repeatability were calculated from the variability of the differences between measures on the two days. The mean (± standard deviation) difference in AC/A measures on the two days was 0.01 (±0.064) Δ/D for the 23 subjects. The corresponding figure for CA/C was 0.00 (±0.01) D/Δ. Ninety-five percent confidence intervals were thus ±1.28 and ±0.02 for AC/A and CA/C, respectively.

Figures 2(a) and (b) show a high reliability of results for both measurements.

The AC/A ratio, averaged for the two days and two lenses, showed a substantial increase with age from approximately 3.5 Δ/D at age 20 to 6.0 Δ/D at age 40. The average increase in the response AC/A per year was 0.126 Δ/D per year. A significant linear correlation was present between AC/A ratio and age, as illustrated in Fig 3a (r² = 0.37, p = 0.002), although some variability about the regression line was present.

The individual components of the AC/A ratio, the accommodative–convergence and accommodation response to the lenses, were also analyzed for the effect of age. Some increase in accommodative–convergence appeared to occur with age, although the correlation was not statistically significant (r² = 0.14, P = 0.07, Fig. 4a). Surprisingly, there was little change in accommodative response to lenses with age (r² = 0.03, P = 0.4, Fig. 4b). The lack of a significant correlation may be due to the variability in accommodative response to the lenses, with variation from 0.50 D to 1.10 D. The significant effect of age on the AC/
A ratio, when the individual components do not show such an effect, is most likely due to the ratio reducing overall variability by accounting for possible covariation between the two parameters. The mean CA/C ratio showed a substantial decrease with age, from approximately 0.1 D/Δ at age 20 to 0.03 D/Δ at age 40. The response CA/C decreased an average of 0.003 D/Δ per year. A highly significant correlation was present between CA/C ratio and age (r² = 0.75, P = 0.0001), with comparatively little variability about the regression line (Fig. 3b).

The individual components of the CA/C ratio, the convergence–accommodation and convergence response to the prisms, were also analyzed for the effect of age. A substantial decrease in convergence–accommodation occurred with age (r² = 0.54, P = 0.0001), with convergence–accommodation nearing zero at age 40 (Fig. 5a). There was little change in the convergence response with age (r² = 0.15, P = 0.07, Fig. 5b). Some of the variability in the observed convergence response may be due to experimental error, perhaps due to slight head movements relative to the direction of gaze or to variations in the palpebral aperture.

A reciprocal relationship between AC/A and CA/C ratios was present for individual subjects (Fig. 6). The linear regression was statistically significant (F₁,₂₁ = 7.31, P = 0.01), although substantial variability was present. For a CA/C ratio of 0.03 D/Δ the AC/A ratio was approximately 5.5 Δ/D, whereas a CA/C ratio of 0.11 D/Δ was associated with a lower AC/A of approximately 3.5 Δ/D.

DISCUSSION

Measures of AC/A and CA/C obtained on two different days and with two sets of lenses and prisms showed remarkable repeatability, yielding comparable results. Ninety-five percent confidence intervals were ±1.28 Δ/D and ±0.02 D/Δ for AC/A and CA/C ratios, respectively. This appears to be the first time that such reliability measurements have been reported.

The results for the 23 subjects showed the response AC/A ratio to increase with age (Fig. 2a) and the response CA/C ratio to decrease with age (Fig. 3b). Previous studies had shown little change in response AC/A before age 40 and an exponential increase after that age. The difference in results may be due to the fully objective techniques used in this study. An increase in the AC/A ratio between 20 and 40 years of age is consistent with the finding that a considerable decrease in the response amplitude of

FIGURE 3. Change with age in the (A) Accommodative-convergence/accommodation (AC/A) ratio and (B) convergence-accommodation/convergence (CA/C) ratio.

FIGURE 4. Change with age in the (A) accommodative convergence and (B) accommodation components of the AC/A ratio.
accommodation occurs during this period. This finding is also consistent with the claim that "presbyopia is a function of age, not aging." 

The increase in the response AC/A suggests that either greater effort is necessary to produce a unit diopter of lens accommodation, or a given amount of effort would produce a decreased response with age. We evaluated each of the components of the AC/A ratio against age and found the former to be more likely. The increase of the AC/A ratio with age is not well understood but could be related to Schor's work on the effect of fatigue on the AC/A ratio, which showed an increase in AC/A with fatigue and further substantiated the plasticity of the accommodative convergence mechanism.

As mentioned earlier, the decrease in CA/C ratios found with age is consistent with previous research. Looking at the convergence–accommodation mechanism with age, that is, per unit prism diopter change in convergence, we noted a considerable decrease in the response. This decrease continued until convergence–accommodation reached almost zero by age 40.

Our findings suggest that a reciprocal relationship exists between the AC/A and CA/C ratios for individual subjects. This indicates that with increasing age, accommodative–convergence increases as convergence–accommodation decreases. This finding adds further impetus to Schor’s model of accommodation and convergence, because our results are based on subjects with normal binocular vision and a wider age range. In an earlier study of AC/A and CA/C ratios, Schor and Narayan did not find evidence of a reciprocal relationship between the two ratios; however, only six subjects were assessed.

The increase in AC/A and the decrease in CA/C with age may have some ramifications on the mechanisms underlying presbyopia. The mechanism of presbyopia is still not well understood, and, although different theories attempt to explain it, not one is entirely consistent with existing evidence. Current theories of presbyopia are as follows:

1. The Hess–Gullstrand theory attributes presbyopia to age-related changes in the lens, with the amount of ciliary muscle contraction required for a particular change in accommodation remaining the same as age increases, provided that this level is within the amplitude limit.

2. The Fincham theory is similar to the Hess–Gullstrand theory in claiming that presbyopia is due to the lens being less easily deformed with increasing age, but the maximum ciliary muscle contraction is required for maximum accommodation at all ages.

3. The geometric theory posits that presbyopia is attributed to changes in the size and shape of the lens that make the zonules apply tension more parallel to the surface of the lens. Changes in zonule tension will thus have smaller effects on lens shape.

4. Extralenticular theories claim that presbyopia is caused by weakening of the ciliary muscle or by loss of elasticity of zonules or ciliary body and choroid components.

The Hess–Gullstrand theory is distinct from other
theories in one important respect. According to this theory, with increasing age there is an increasing excess of ciliary muscle contraction beyond the ability of the lens and the capsule to respond to it. For all other theories, the maximum possible amount of ciliary muscle contraction is necessary to produce maximum accommodative amplitude beyond the age at which this amplitude begins to decline.

Support for the Hess–Gullstrand theory is provided by evidence that the ciliary muscle continues to contract at stimulus levels greater than the maximum amplitude of accommodation. Ciliary muscle activity has been assessed from electrical impedance in the equatorial region of the lens, the electrical impedance possibly reflecting changes in blood flow. Impedance changes continue to occur after the maximum accommodation has been reached. However, this evidence is equivocal; Bito and Miranda suggested that blood flow might be altered by neural activity concomitant with an accommodation effort, irrespective of ciliary muscle activity.

The Hess–Gullstrand theory predicts that accommodation–convergence relationships remain unchanged throughout life (within the accommodation limit). If the same effort of ciliary muscle contraction is needed to produce a given change in accommodation at all ages, this can be expected to stimulate a similar level of convergence change. Similarly, if a given level of convergence simulates the ciliary muscle to a given degree of contraction at all ages, this produces the same change in accommodation. As found in this and in previous studies, the AC/A ratio increases with age and the CA/C ratio decreases with age. This is evidence against the Hess–Gullstrand theory; all the other theories of presbyopia predict the direction of changes found in the studies.

The prediction regarding the age constancy of AC/A and CA/C ratios according to the Hess–Gullstrand theory presumes that accommodative convergence and convergence accommodation remained linked in a constant fashion to ciliary muscle contraction throughout life. However, other factors may influence the accommodation–convergence interactions. Schor and Tsubakik have demonstrated that robust vergence adaptation and poor accommodative adaptation result in a raised AC/A ratio. The converse situation results in a raised CA/C ratio. Thus, changes in the accommodation–convergence interactions with age may be due to changes in adaptability of tonic accommodation and vergence or to an alteration in the relationship between ciliary muscle contraction and accommodative response. If changes in the adaptability of tonic accommodation and vergence do occur with age, the observed changes in the accommodative–vergence cross-links would be explained and the Hess–Gullstrand model of presbyopia may still hold.

In this way, the possibility remains that the relationship between ciliary muscle contraction and accommodative response is unchanged with age.

In summary, we have confirmed an increase in the AC/A ratio and a decrease in the CA/C ratio with age. Measurements were made on a moderate sample size of subjects who had normal binocular vision. Changes in the accommodative–vergence interactions were significant in relation to the repeatability of the two techniques. Experiments of this nature may be unable to differentiate between the various models of presbyopia unless other factors that could concurrently influence the accommodative–vergence interactions, such as the adaptability of tonic vergence and accommodation, are taken into account.

**Key Words**

accommodation, convergence, AC/A ratio, CA/C ratio, presbyopia

**Acknowledgments**

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