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Influence of Gravity on Ocular Lens Position

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PURPOSE. We determined whether human ocular lens position is influenced by gravity.

METHODS. Anterior chamber depth (ACD) and lens thickness (LT) were determined with a Haag-Streit Lenstar LS900 for right eyes of participants in two age groups, with a young group of 13 participants aged 18 to 21 years (mean, 21 years; SD, 1 year) and an older group of 10 participants aged 50 to 63 years (mean, 58 years; SD, 4 years). There were two sessions for each participant separated by at least 48 hours, with one session for the usual upright head position and one session for a downwards head position. In a session, testing was done for minimum accommodation followed by testing at maximum accommodation. A drop of 2% pilocarpine nitrate was instilled, and testing was repeated after 30 minutes under minimum and maximum accommodation conditions.

RESULTS. Gravity, manipulated through head posture, affected ACD for young adult and older adult groups but mean effects were only small, ranging from 0.04 to 0.12 mm, and for the older group required the instillation of an accommodation-stimulating drug. Gravity had a weakly significant effect on LT for the young group without accommodation or a drug, but the effect was small at 0.04 ± 0.06 mm (mean $\pm$ SD, $P = 0.04$).

CONCLUSIONS. There is a small but real effect of gravity on crystalline lens position, manifested as reduction in ACD at high levels of accommodative effort with the head in a downwards position. This provides evidence of the ability of zonules to slacken during strong accommodation.

Keywords: accommodation, anterior chamber depth, gravity, lens

According to the theory of accommodation propounded by Helmholtz in the 1850s,[1] and as modified by Fincham,[2] accommodation is achieved by the crystalline lens altering its shape. In the unaccommodated form, corresponding to the eye's focus being at its far point, the lens is flattened by the tension of the zonules connecting the lens to the ciliary body. When the eye accommodates the lens changes shape, with increase in surface curvatures, increase in center thickness and decrease in equatorial diameter. This occurs because the ciliary body moves forwards and inwards upon contraction of its muscle, reducing the tension on the zonules, which in turn reduces the tension on the lens, allowing it to become more rounded under the influence of its elastic capsule. If the ciliary contraction is considerable, the tension on the zonules is reduced sufficiently so that they become slack.[3,4]

The Helmholtz theory has been challenged a number of times, including in the last two decades. Schachar[5] proposed that contraction of the ciliary muscle increases tension on the zonules and, hence, on the lens, so that the lens becomes more spindle shaped on accommodation (increased surface curvatures in center but not in the periphery, and increased diameter). Schachar et al.[6-15] has presented a number of papers and a book purporting to prove his theory. To do so, he had to assign different functions to different parts of the zonules[6] and to different parts of the ciliary muscle.[9] He claimed that the anterior and posterior zonules reduce tension upon accommodation, but have a stabilizing role at low levels

of accommodation rather than being responsible for accommodation. It is only the equatorial zonules, which Schachar claims are not observable during accommodation,[6] that are responsible for accommodation and these increase in tension upon accommodation.

Experimental evidence to distinguish between the two rival theories can be provided by investigating the influence of gravity on accommodation. The Helmholtz theory allows for the zonules to slacken at high levels of accommodation, provided that the mechanical limits of the lens and capsule are overcome. The lens then would be free to move according to gravity, although this may be reduced in the direction of the posterior pole because of vitreous support.[4,5] There are two associated theories here which are themselves rivals.[16] These are the Hess-Gullstrand theory, which is that the amount of ciliary muscle contraction required for a given change in accommodation remains constant throughout life, and the Duane-Fincham theory, which is that at any age the ciliary muscle is contracted maximally once the amplitude of accommodation has been achieved. The former predicts that this movement would be more pronounced with increasing age, while the latter predicts that the lens would move in the direction of gravity only in young eyes. Schachar's theory predicts that, as the lens always is under tension, it will never be free to move according to gravity.

There have been reports of the lens position being affected by gravity during maximum accommodation and with the head

in the downward position as compared to the head straight ahead or facing upwards; that is, the anterior chamber depth (ACD) is smaller for the downwards position for maximum accommodation. From observing shadows cast on the retina of his own eye by a small cataract, Hess[17-19] estimated a difference of approximately 0.3 mm between downwards and upwards positions, increasing to 0.5 mm with the application of the parasympathomimetic drug eserine (physostigmine). Using a biomicroscope, Fincham[2] determined a difference of approximately 0.2 mm in one eye between downwards and straight ahead positions. Using ultrasound and the parasympathomimetic drug pilocarpine (6%), Lewis (unpublished report, 1982) and Lewis and Oehrlein[20] found a difference of 1.0 mm in one participant. In addition to these studies, Storey and Rabie[21] cited Storey and Phillips[22] using ultrasonography to find the lens moving downwards when the head was facing upwards.

Indirect support that lens position is influenced by gravity in the accommodated state is provided by several studies of subjective accommodation amplitude. The amplitude increases when the eye turns down compared to when it turns up or is directed straight ahead, due mainly or completely to changes in the near point attributable to the forward movement of the lens in the former case increasing ocular power. Hess[17] found increases in amplitude of accommodation on looking downwards of 0.3 to 0.5 diopters (D) in four people in their 20s and early 30s, which his modeling indicated corresponded to lens movements of 0.15 to 0.21 mm. Larger effects were found with the instillation of the parasympathomimetic drug physostigmine. Fincham[2] claimed to have found a closer near-point in young participants for the head facing down equivalent to over 1 D accommodation. Ripple[23] found considerable change in amplitude of accommodation with change in direction of eye gaze, amounting to as much as 3 D between 20° upgaze and 40° downgaze. Gallagher[24] found difference in accommodation between head facing upwards and facing downwards of a mean 1.1 D in participants aged 8 to 42 years. Atchison et al.[25] obtained a mean amplitude of 9.8 D in an 18- to 25-year age group, averaged over a range of head and eye positions, with the maximum mean difference between conditions being 1.1 D. The mean difference between the head down and head up conditions was 0.3 D. The effect declined with increase in age, and the investigators concluded that the data supported the Duane-Gullstrand theory over the Hess-Gullstrand theory.

The one exception to the finding of variation in subjective amplitude of accommodation with direction of eye gaze or head position is the study of Schachar and Cudmore.[11] They measured amplitude of accommodation with participants strapped to a board and rotated to face upwards or downwards. Near points were measured relative to the board behind the head. Using their data of the 27 participants whose near points were measured with and without contact lenses, estimates of amplitude were made. These showed surprising little variation within a set of measurements or between the head positions, with the maximum difference for the latter being no more than 0.25 D, even for amplitudes up to 15 D. The authors wrote that their results were consistent with three other studies.[26-28] However, in one of these studies Koster[26] merely mentioned that he could not find changes in the near point between upwards and downwards gaze, as had been reported by his colleague Hess,[17] for his own eye. Another study had heads rotated by 30° upwards and downwards, but did not involve accommodative effort.[27] The third study involved microgravity and is not relevant as there was not a comparison with downwards and upwards head positions under the influence of gravity.[28]

Although there already is evidence that the lens moves under the influence of gravity in the accommodated state,[2,17,19-22,29] the studies involved had few participants, and, most had little detail of method or were not published prominently.[20-22] Studies in recent decades used ultrasonography and suffered from subject discomfort, lack of certainty about eye orientation because the target was presented to the nonmeasured eye, poor resolution of approximately 0.10 mm and possibly ocular compression. A more extensive investigation of the influence of gravity on lens position is described here to look for evidence to support or refute the rival theories of accommodation mechanisms. This will involve the use of a partial coherence interferometer, which has resolution of 0.01 mm, and there is no eye contact so that eye orientation can be controlled.

METHODS

The study was conducted in accordance with the tenets of the Declaration of Helsinki. Approval was obtained from the Queensland University of Technology Human Research Ethics Committee and all participants gave written consent.

We separated 23 participants with normal general and ocular health into two age groups, with a young group of 13 participants aged between 18 and 21 years (mean, 20.9 years; SD, 0.9 years) and an older group of 10 participants aged between 50 and 63 years (mean, 58.3 years; SD, 4.3 years). Criteria for inclusion were right eyes with corrected distance visual acuity of 6/6 or better, spherical equivalent refraction between −3.0 and +3.0 D, and cylinder less than or equal to 0.5 D.

Participants' left eyes were patched, and measurements of anterior chamber depth (ACD) and lens thickness (LT) were obtained on right eyes with a Lenstar LS900 (Haag-Streit, Koeniz, Switzerland). There were two sessions for each participant separated by at least 48 hours, with one session for the upright head position and one session for the prone head position. In a session, testing was done for minimum accommodation followed by testing at maximum accommodation. A drop of 2% pilocarpine nitrate was instilled, and after 30 minutes the testing was repeated under minimum and maximum accommodation conditions. For 9/13 young participants and 8/10 older participants, the upright head position session was conducted before the prone head position session.

A target consisted of a series of four fine circles, crossed by eight lines at 45° intervals, with the inner circle subtending an angle of 5°. During measurements, it was ensured that the instrument fixation axis was within the center circle. This was back illuminated by a white light emitting diode and viewed through a Badal system which intersected the path between the eye and the Lenstar at a thin 45° angled beam splitter (Fig. 1a). The system enabled correction of refractive errors and providing an accommodation stimulus without additional lenses. Preliminary experiments showed that the beam splitter did not affect readings. The Badal lens power used for most people was +13.3 D. For five of the young group, maximum subjective amplitude of accommodation was not attained at the highest possible stimulus level of −10.5 D and for these people a +16 D lens was used (range to −12 D).

For minimum accommodation, the target was placed at the +4 D position and moved in −0.5 D steps towards the Badal lens until the participant reported that it appeared clear. A set of at least five consistent readings was made and the average was determined. For maximum accommodation, the target was moved until the participant first reported the target to appear blurry (the previous position was noted as the subjective limit of clear vision). A series of measurements was taken. The target was moved to more negative settings to push the participant to the maximum accommodation as recognized by maximum LT (Fig. 2).
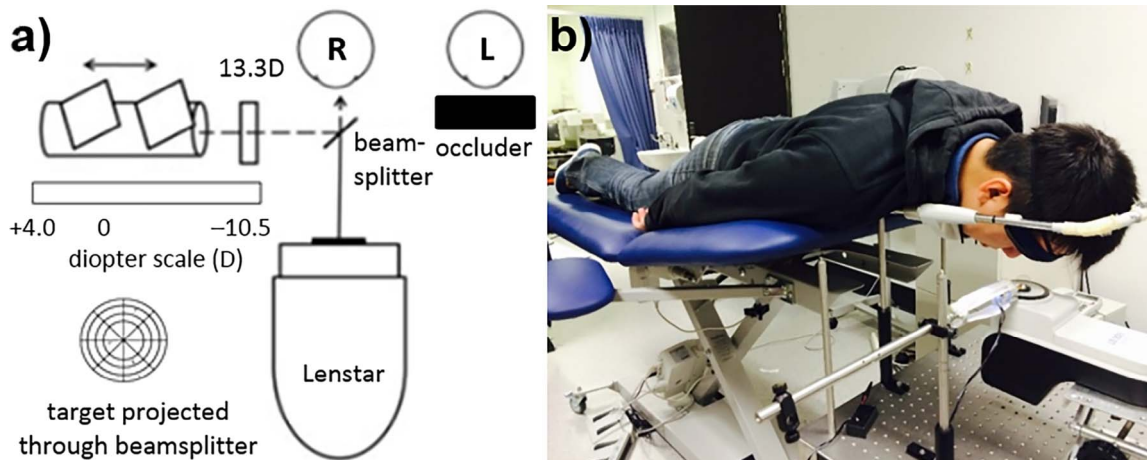
FIGURE 1. (**a**) Diagram of experimental system with the +13.3 D Badal lens. (**b**) Participant in prone position with the Lenstar "on its back."

For upright vision, the Badal system was attached to the instrument headrest. For the prone position the instrument was turned on its back and the participants lay on a bed with adjustable height and leaned forward into the headrest (Fig. 1b). There were no differences in measurements between upright and prone positions for the model eye supplied with the Lenstar.

The data were normally distributed and accordingly parametric statistics were applied. Repeated measures ANOVAs were conducted separately for each age group because of large differences in amplitudes of accommodation between the groups. Analyses were done for ACD and LT, with head position (upright or prone), drug state (no drug or drug), and accommodation state (minimum or maximum accommodation) as within-subject conditions. Paired t-tests were used to determine the significance of differences between accommodation states, head positions, and drug states. As there were 4 combinations for any one of these, for example comparison of head positions for no drug/minimum accommodation, no drug/accommodation, drug/minimum accommodation, and drug/accommodation combinations, a Bonferroni correction was applied to determine significance at $P = 0.0125$ as well as at $P = 0.05$.
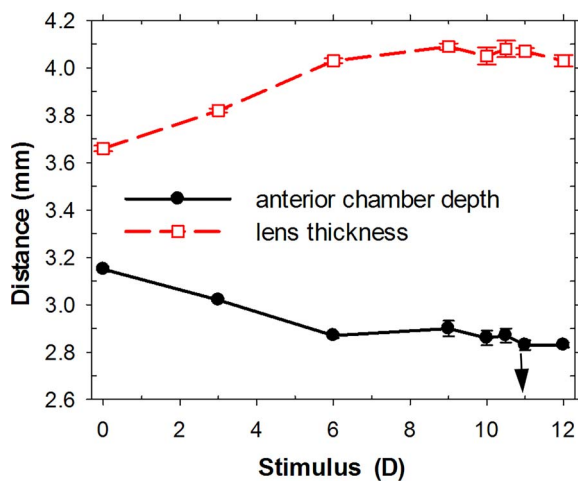

FIGURE 2. Anterior chamber depth and LT as a function of accommodation stimulus for one of the young participants. The *arrowhead* indicates the 11 D stimulus at which maximum LT and minimum ACD occurred. *Error bars*: Standard deviations.

RESULTS

Figures 3 and 4 show results for ACD and LT, respectively. Figures 3a and 4a show head upright results for various combinations of age, accommodation and drug state. Significant differences between accommodation and drug states are shown by asterisks. Figures 3b and 4b are similar to Figures 3a and 4a, but show head prone results. Figures 3c and 4c show differences between the head upright and prone positions for various combinations of age, accommodation, and drug states.

Anterior Chamber Depth

For the young group, all within-subject factors were significant (head position $F_{1,12} = 28.3$, $P < 0.001$; drug $F_{1,12} = 172$, $P < 0.001$; accommodation $F_{1,12} = 18.0$, $P = 0.001$) and there was significant interaction between head position and drug state ($P = 0.01$). For the older group, all factors were significant (head position $F_{1,9} = 19.3$, $P = 0.002$; drug $F_{1,9} = 16.8$, $P = 0.003$; accommodation $F_{1,9} = 9.9$, $P = 0.012$) and there was significant interaction between head position and accommodation ($P = 0.045$). Prone head position, drug instillation, and maximum accommodation decreased ACD compared to upright head position, no drug instillation, and minimum accommodation, respectively.

The main finding for the young group is that head position affected ACD for all drug state and accommodation combinations (Fig. 3c), but mean effects were small at 0.04 to 0.07 mm and much smaller than reported in the literature.[2,17–20] The main finding for the older group was that the head position affected ACD only when the drug pilocarpine was being used, with mean effects of only 0.10 to 0.12 mm (Fig. 3c).

Lens

For the young group, all within-subject factors were significant (head position $F_{1,12} = 7.2$, $P = 0.020$; drug $F_{1,12} = 227.3$, $P < 0.001$; accommodation $F_{1,12} = 15.5$, $P = 0.001$) and there were significant interactions between head position and drug state ($P = 0.037$) and between drug state and accommodation ($P = 0.007$). Prone head position, drug instillation and maximum accommodation increased LT compared to upright head position, minimum accommodation, and no drug instillation, respectively. For the older group, drug state was significant ($F_{1,9} = 11.9$, $P = 0.007$) with drug instillation increasing LT compared to no drug instillation. Head position ($P = 0.064$) and accommodation ($P = 0.558$) were not significant. There was a
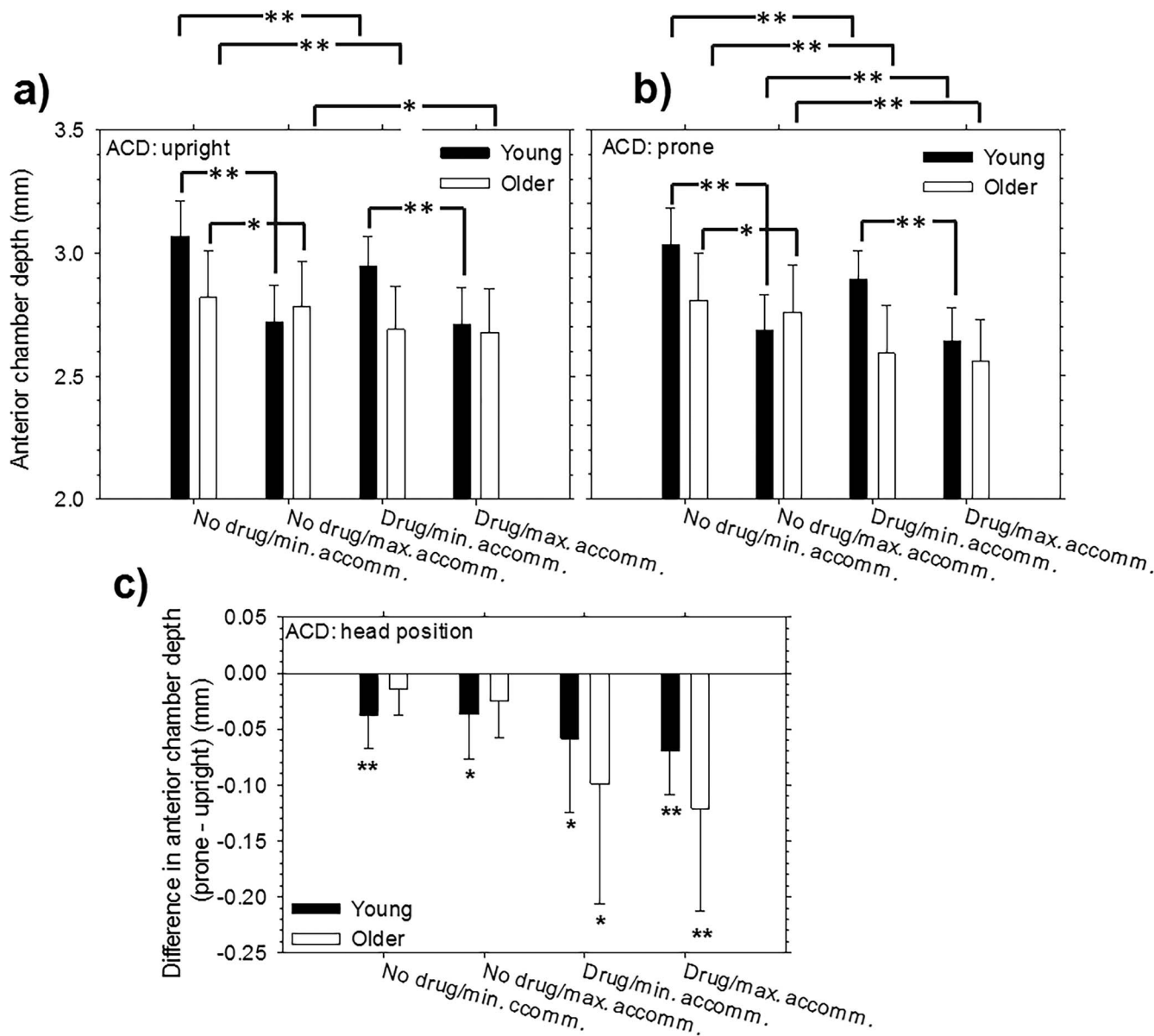
FIGURE 3. (a) Anterior chamber depth for the upright position for young and older groups for different combinations of drug and accommodation states. (b) Anterior chamber depth for the prone position for young and older groups for different combinations of drug and accommodation states. (c) Difference in ACD between prone and upright positions for young and older groups for different combinations of drug and accommodation states. *Single asterisks* indicate significance at 0.05 probability criterion and *double asterisks* indicates significance at 0.0125 probability criterion. *Error bars* indicate 98.75% confidence limits.

significant interaction between head position and drug state ($P = 0.042$).

The main finding for the young group was that head position affected LT for the no drug/minimum combination, but the mean effect was small at 0.04 mm and significance disappeared when a Bonferroni correction was applied (Fig. 4c). For the older group, as reported in the previous paragraph, head position did not affect LT (Fig. 4c).

DISCUSSION

We found that gravity, manipulated through head posture, affects ACD for young adult and older adult groups but the mean effects were only 0.04 to 0.12 mm and for the older group required the instillation of an accommodation stimulat-ing drug. As it is expected that there would be little change in lens shape between accommodation states in the older group,[30] due to lenticular sclerosis, the zonules might be slackening in both states and allowing the lens to move forward under the influence of gravity. Effects of gravity for LT have not been reported previously; there was a weakly significantly effect of gravity on LT for the young adult group without accommodation or a drug, but the effect was small at 0.04 mm. Results are summarized in the Table; because of the significantly weak effect mentioned above for the lens, the LT was considered not to be affected by gravity.

The results can be used to assess the theories described in the Introduction regarding the mechanism of accommodation. The Hess-Gullstrand variant of Helmholtz accommodation theory predicts that there is an excess of ciliary muscle contraction beyond that needed to get the lens to its maximum
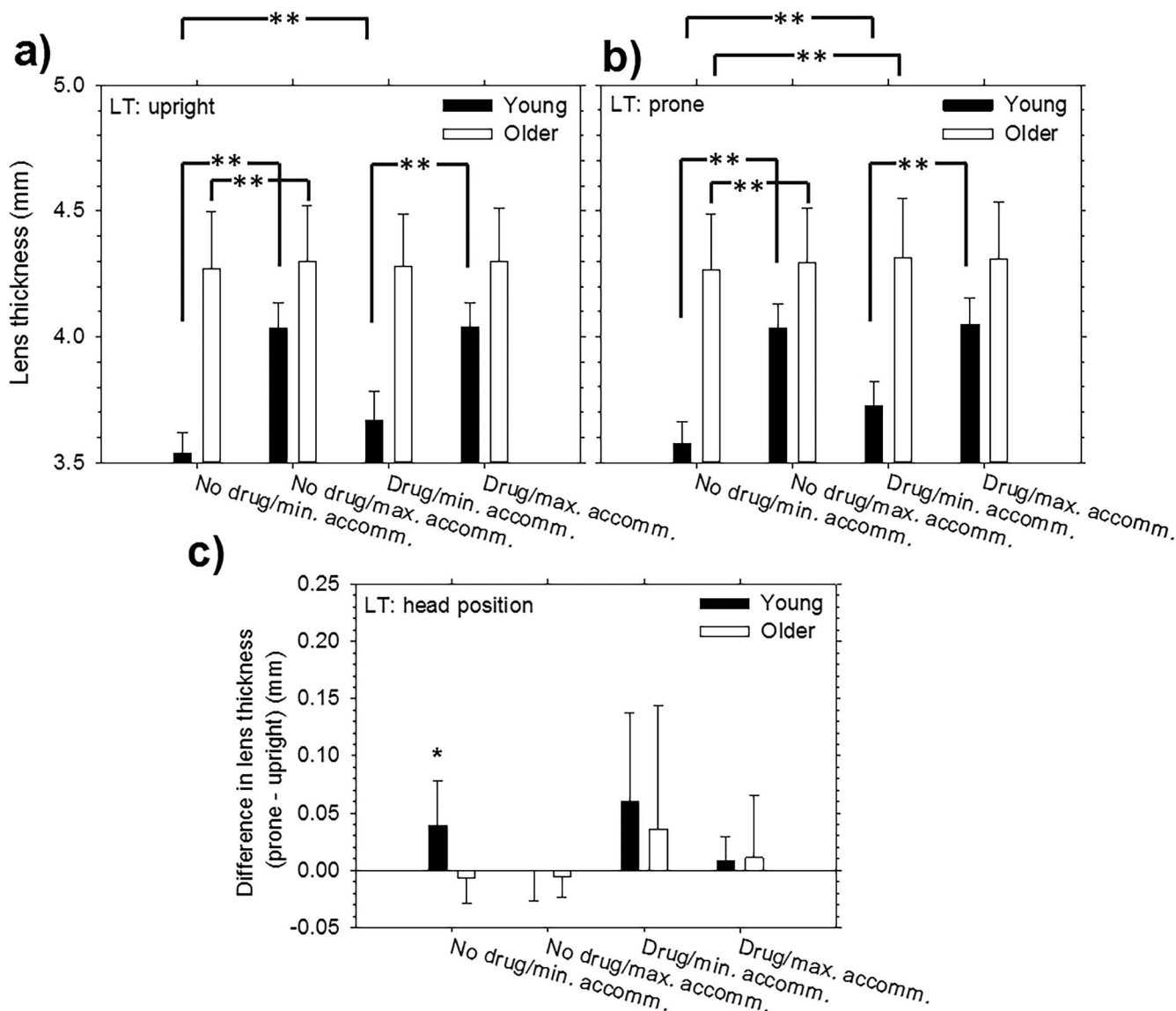
FIGURE 4. (a) Lens thickness for the upright position for young and older groups for different combinations of drug and accommodation states. (b) Lens thickness for the prone position for young and older groups for different combinations of drug and accommodation states. (c) Difference in LT between prone and upright positions for young and older groups for different combinations of drug and accommodation states. *Single asterisks* indicate significance at 0.05 probability criterion and *double asterisks* indicates significance at 0.0125 probability criterion. *Error bars* indicate 98.75% confidence limits.

shape, except possibly for very young eyes. As this excess contraction will increase with age, the slackness of the zonules at high accommodation effort should increase with age, and allow the lens to move under the influence of gravity more in the older group than in the young group. For the drug/minimum accommodation condition, it is likely that the accommodation resulting from the drug will be insufficient for gravity to affect lens position in the younger group. Predictions according to the theory are given in the Table, with ticks and crosses to indicate whether they accord or do not accord with study results, respectively.

The Duane-Fincham variant of Helmholtz accommodation theory predicts that the lens will not move in the direction of gravity in our age groups (Table). Schachar's theory predicts that, as the lens is under tension that will increase with accommodation, it will never be free to move according to gravity, and its predictions will be the same as those for the Duane-Fincham theory.

For the influence of gravity on ACD, the Hess-Gullstrand theory and Duane-Fincham/Schachar theories predicted the results correctly in 5/8 and 1/8 situations, respectively. While this favors the Hess-Gullstrand theory, we will again point out that the effects were small (≤0.12 mm). The Hess-Gullstrand theory predicts correctly that influence of gravity in the accommodated state should be greater for the older group than for the young group, but again the effects were small (0.06 mm). The data presented in this study showed a small but real effect of gravity on crystalline lens position, manifested as a reduction in ACD, at high levels of ciliary muscle contraction with the head in a prone position. This provided evidence of the ability of the zonules to slacken during high levels of accommodation effort.

The effects of gravity for ACD reported here (0.04–0.12 mm) are considerably smaller than those reported in the literature of 0.2 to 1.0 mm.[2,17–20] A possible reason is the lack of a supine/looking up condition in this study as reported by

TABLE. Effect of Gravity (Head Position) on ACD and LT According to our Findings and Theories of Accommodation

Factor Combination	Young Adult Group					Older Adult Group				
	Result	Hess-Gullstrand		Duane-Fincham, Schachar		Result	Hess-Gullstrand		Duane-Fincham, Schachar	
ACD										
No drug/min. acc	↓	–	X	–	X	–	–	✓	–	✓
No drug/max. acc	↓	↓	✓	–	X	–	↓*	X	–	X
Drug/min. acc	↓	–	X	–	X	↓	↓*	✓	–	X
Drug/max. acc	↓	↓	✓	–	X	↓	↓*	✓	–	X
LT										
No drug/min. acc	–	–	✓	–	✓	–	–	✓	–	✓
No drug/max. acc	–	–	✓	–	✓	–	–	✓	–	✓
Drug/min. acc	–	–	✓	–	✓	–	–	✓	–	✓
Drug/max. acc	–	–	✓	–	✓	–	–	✓	–	✓

↓, reduction in ACD; –, no change; ✓, accords with results; X, does not accord with results; min., minimum; max., maximum; acc, accommodation.

* Expected greater for older than young group.

some of the studies.[17–20] It might be argued that pupil miosis during accommodation will increase iris rigidity and support the lens, but this does not prevent the ACD decreasing much more than the vitreous chamber depth decreases in accommodation under upright conditions.[31,32]

Other possible reasons for the smaller effects of gravity found here than in the literature are a weaker cholinergic drug[1,17,19] or a lower dose of pilocarpine for the drug conditions,[20] the indirect nature of the Hess determinations,[17–19] the almost anecdotal nature of the Fincham report,[2] and the possibility that people not showing marked effects were ignored in the Hess and Fincham studies.

In conclusion, the data presented here show that gravity has a small but real effect on crystalline lens position; this being manifest as a reduction in ACD with the head in a downwards position and a concurrent high level of accommodation response. We deduced from this that the zonules are able to slacken sufficiently to allow the lens to move under the effect of gravity.

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