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The accommodative pupil responses of children and young adults at low and intermediate levels of ambient illumination

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Abstract

Accommodative pupil constrictions were compared between 27 children (9–10 years) and 13 young adults (22–26 years) in order to clarify the issue whether or not children have such a response. Accommodative stimuli of 4 and 7 diopters were used to elicit the response and experiments were performed at 5 and 100 lux in order to investigate whether the level of ambient light has different effects on developing and mature visual systems.

The accommodative pupil response is present in children, but weaker than in adults. Different levels of ambient light lead to only minor additional differences between children and adults.

The weaker accommodative pupil response of children may be a consequence of their superior accommodative ranges, which make it unnecessary to close the pupil to increase depth of field. Adults, in contrast, may do better with smaller pupils that reduce accommodative demand because of increased depth of field. A mature human visual system may furthermore be better tuned to handle dimmer and thus noisier images in the photopic range than the developing visual system of a child.

Keywords: Children; Adults; Accommodation; Pupil response; Light level

1. Introduction

In the adult human visual system, accommodative effort leads to a constrictive response of the pupil (Davson, 1990). However, little information is available in the literature concerning this reflex in children and the reported results are inconsistent. In one of the studies performed it was found to be hard to elicit any pupil constriction at all by accommodative effort in children up to 10 years of age (Schaeffel, Wilhelm, & Zrenner, 1993). In another study by Wilhelm and co-workers (Wilhelm, Schaeffel, & Wilhelm, 1993) accommodative pupil constriction in young children was observed, but the reaction was harder to elicit and considerably weaker than in adults. Schäfer and Weale (1970) found pupil constriction in children in response to accommodation, but the number of children in this study was very low. All of the above mentioned studies were performed under low-light conditions. Giunta, Peck, and Howland (1996) found small, but significant pupillary near responses in children aged 3–16 years under lighting conditions that are not reported.

In two earlier studies in which two of us participated, we observed that children of the Moken tribe of Thailand (sea nomads), who have superior underwater visual resolution, constricted their pupils when diving (Gislén et al., 2003). We also observed that European children, who by practicing had learned to achieve about the same underwater resolution as the Moken children, also constricted their pupils when they were submerged and confronted with a demanding visual task (Gislén, Warrant, Dacke, & Kröger, 2006).

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In both cases, the underwater visual capabilities of the children could be fully explained only if one assumed that they not only constricted their pupils, but also used maximum accommodation to improve image quality (Gislén & Gislén, 2004).

Underwater the unaccommodated human eye is defocused by about 40 diopters (D), because the refractive power of the cornea is neutralized. When fully accommodated, children should be able to compensate for up to 15 D of this defocus (Westheimer, 1986). However, severe defocus does not usually elicit an accommodative response (Heath, 1956), and underwater the images may thus be too blurry to elicit accommodation. Our earlier findings nevertheless strongly suggest that the Moken and trained European children had learned to control accommodation and used the maximum amount they were capable of in order to improve image quality as much as possible (Gislén & Gislén, 2004). The observed pupil constrictions in diving children could therefore have been induced by this accommodative effort.

The children in those studies (Gislén et al., 2003, 2006) have been between 7 and 14 years of age. In the current study, we investigated the pupillary near response in children aged 9–10 years in order to clarify whether accommodative miosis is a plausible explanation for the observed pupil constrictions in the diving children. We furthermore wondered whether the visual signals influencing pupil constriction, i.e., light level and accommodative demand, might be weighted differently in adult and juvenile visual systems. One crucial factor may be that accommodative range and average pupil size decrease with age (Kadlecova, Peleska, & Vasko, 1958; Winn, Whitaker, Elliot, & Phillips, 1994). Reduced pupil size in adults increases depth of field and thus reduces accommodative demand, which partially compensates for the progressive reduction of accommodative range with age. Because of their lenses' superior elasticity, children may instead prefer to rapidly accommodate between different near-targets (Wilhelm et al., 1993).

Could it be that in dim light the signal to open the pupil is stronger in children than the signal from accommodative effort to close the pupil? Adults may constrict their pupils under the same conditions, presumably to reduce accommodative demand. In moderate to high levels of ambient light, the difference in the reaction may be smaller, so that accommodative effort leads to strong pupil constriction even in children. This would resolve at least some of the conflicting reports in the literature.

2. Materials and methods

In this study participated children without known visual defects from two schools in Lund, Sweden (Svenshögsskolan and Vårfruskolan). The children were brought to the laboratory in groups of eight by minibus and returned to their school about two hours later. The children and their parents had given informed consent. Young adults without known visual defects were recruited from students at the Department of Design Sciences at Lund University and had also given informed consent to participate in the study by individual appointment. The subjects were examined with the Cover Test, Titmus Fly Test, and for Near Point Convergence to ensure normal binocular vision. All measurements were taken by J.G. assisted by A.G. in the Vision Enabling Laboratory at CERTEC (Center for Rehabilitation Engineering Research) at Lund University. The study was approved by the Lund University Ethics Committee, DRN 13/2005.

Three levels of ambient illumination were used; 5, 100, and 200 lux. Light levels were adjusted by dimming fluorescent tubes and measured close to the eyes of the subject under investigation with a digital luxmeter (Hagner, Stockholm, Sweden).

Measurements of refractive state and pupil size were performed with a PowerRefractor (Multi Channel Systems, Tübingen, Germany). This instrument measures refractive state by eccentric slope-based infrared photorefraction (Choi et al., 2000) and similar instruments have been used in the earlier studies (Giunta et al., 1996; Schaeffel et al., 1993; Wilhelm et al., 1993). The instrument was positioned 1 m in front of the eyes of the subject, which has previously been found to induce little or no accommodative response (Choi et al., 2000). The accommodative stimulus (the visual target) consisted of two thin wires crossing at 90 deg in the middle of an open frame through which the subject could see the instrument. The subject's head position was fixed by a chin and forehead rest, and the optical axis of the instrument, the visual target, and the midpoint between the eyes of the subject were aligned. The target was positioned at 0.25 and 0.14 m in front of the eyes of the subject to generate accommodative stimuli of 4 and 7 diopters (D), respectively. The subjects were told to rest their eyes by looking at the instrument and to briefly, but steadily fixate the visual target for measurements in the accommodated states. All measurements were taken on the right eyes of the subjects and results could be obtained if pupil diameter was at least 3 mm.

The PowerRefractor has a dynamic range of +5 to −5 D relative to the position of the instrument, and +4 to −6 D relative to infinity (Choi et al., 2000). We nevertheless used an accommodative stimulus of 7 D, because we were primarily interested in the pupil response, and not accommodation. We made sure that all measurements on children and adults were performed under identical conditions and only compared relative values of refractive state obtained in the accommodated states. Another feature of photorefraction is that the method cannot produce reliable results if the subject's eyes are exactly focused on the instrument (Roorda, Campbell, & Bobier, 1995). We therefore did not use the results obtained in the resting position, unless a refractive error exceeding 1 D was detected, which led to the exclusion of the subject.

3. Results

The main reason for the exclusion of a subject from the analysis was small pupil size (<3 mm in diameter) as the PowerRefractor does not return results if pupil size is smaller than this. Other reasons to exclude subjects were refractive error exceeding 1 D and not fully normal binocular vision. The numbers of subjects from which results were obtained are listed in Table 1 for all conditions of measurement.

Two facts are immediately obvious from the values in Table 1. Firstly, at 200 lux many of the adults dropped out of the analysis because their pupils were too small. Secondly, at 200 lux even a sizable number of children dropped out because of small pupil sizes when the accommodative stimulus was 7 D. The analysis was therefore limited to the 27 children who up to 100 lux of ambient illumination and 7 D of accommodative stimulus had pupils of 3 mm or more in diameter and the 13 adults who fulfilled the same criterion upto 100 lux and 4 D. The average ages in the analyzed groups were 9.3 years with a standard deviation (SD) of 0.6 years and 23.9 years, SD 1.2 years.

Table 1
Numbers of juvenile and adult subjects from which results were obtained per condition of measurement

	Condition of measurement								
Level of illumination (lux):	5			100			200		
Accommodative demand (diopters)	1	4	7	1	4	7	1	4	7
	No. of subjects								
Children (total no. in study: 32)	31	31	31	31	31	27	31	28	17
Adults (total no. in study: 21)	20	20	15	19	16	9	16	11	5

At 100 lux and especially at 200 lux, many adults dropped out of the analysis because pupil diameter was smaller than 3 mm. At 200 lux and 7 D of accommodative stimulus, even a sizable number of children dropped out by the same reason.

Within the groups of children and adults, the accommodative responses to the presented stimuli were of about the same magnitudes at 5 and 100 lux (Table 2). Between the groups, however, there were differences. At 5 lux, for which a complete data set is available, accommodative gain was significantly higher in children than in adults (Fig. 1 and Table 2). Although the accommodative responses of children to a stimulus of 7 D at 5 lux were on average about 1 D stronger than in adults (Fig. 1 and Table 2), pupil sizes in adults were significantly smaller (Fig. 2 and Table 2). If the changes in pupil diameter in response to the accommodative stimuli are expressed in percent of the resting pupil diameter to make the results independent of the individual resting pupil size, differences between children and adults persist (Table 2). For the 4 D stimulus at 5 lux, the 5% significance criterion was barely missed ($p = 0.0501$), while for 7 D at 5 lux the significance criterion was fulfilled ($p = 0.035$). For the 4 D stimulus at 100 lux, there was no significant difference in the change of pupil size between children and adults (Table 2).

If compared within the groups of children and adults, the accommodative stimulus of 4 D did not lead to a significant amount of pupil constriction in neither children nor adults at 100 lux (Fig. 2 and Table 2). At 5 lux, however,

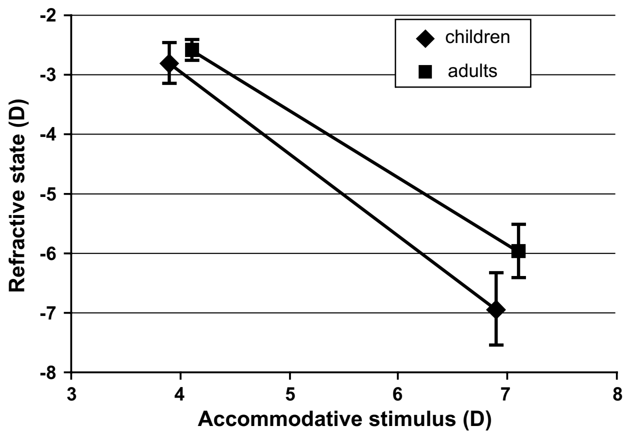

Fig. 1. Measured refractive states of children and adults as functions of accommodative stimulus. The x-values of the data points were shifted by ± 0.1 D to avoid overlap between the symbols. Note that the children accommodated stronger than the adults. Error bars are standard deviations.

Table 2
Refractive states, pupil diameters, and pupil constrictions in children and adults

	Condition of measurement					
Level of illumination (lux):	5			100		
Accommodative stimulus (D)	1	4	7	1	4	7
	Refractive state (diopters ± SD)					
Children ($n = 27$)	—	2.81 ± 0.61	6.94 ± 1.11	—	2.92 ± 0.67	7.37 ± 1.31
Adults ($n = 13$)	—	2.60 ± 0.44	5.96 ± 1.08	—	2.73 ± 0.37	—
Refractive state C. vs. A.	—	n.s.	$p < 0.01$	—	n.s.	—
	Pupil diameter (mm ± SD)					
Children	6.58 ± 0.73	6.18 ± 0.78	5.11 ± 0.84	5.01 ± 0.71	4.77 ± 0.61	4.02 ± 0.54
Adults	6.38 ± 0.86	5.81 ± 0.96	4.55 ± 0.86	4.72 ± 0.72	4.32 ± 0.59	—
Pupil diam. C. vs. A.	n.s.	n.s	$p < 0.05$	n.s.	$p < 0.05$	—
Pupil diam. within C. vs. 0 D	—	$p < 0.05$	$p < 0.001$	—	n.s.	$p < 0.001$
Pupil diam. within A. vs. 0 D	—	n.s.	$p < 0.001$	—	n.s.	—
	Pupil constriction (% resting diameter ± SD)					
Children	—	11.4 ± 11.3	37.5 ± 18.9	—	7.5 ± 18.6	33.8 ± 15.6
Adults	—	17.4 ± 10.0	48.1 ± 15.6	—	14.1 ± 17.8	—
Pupil constriction C. vs. A.	—	$p = 0.0501$	$p < 0.05$	—	n.s.	—

The performed t-tests were one-sided with equal variances between groups if F-tests did not detect any significant differences in variance between the compared groups. In two cases (refractive state at 5 lux, 0 D and at 100 lux, 4 D) the F-tests detected unequal variances and one-sided t-tests for groups with unequal variances were performed. C, children; A, adults; n.s., not significant; —, not applicable.

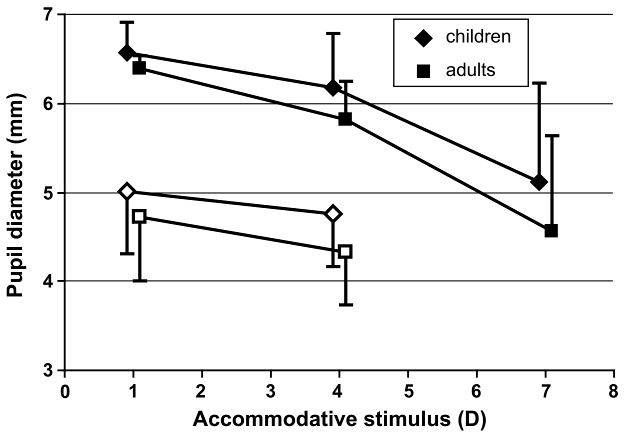

Fig. 2. Pupil diameters in children and adults as functions of accommodative stimulus. The x-values of the data points were shifted by ±0.1 D to avoid overlap between the symbols. Children have larger pupils in the resting state (1 D) and constrict their pupils less than adults in response to accommodative stimuli in both dim and moderately bright light. Closed symbols: 5 lux, open symbols: 100 lux. Error bars are standard deviations.

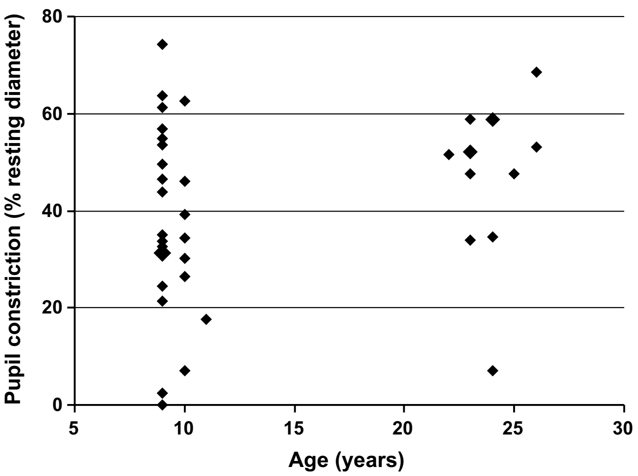

Fig. 3. Accommodative miosis in children and young adults in response to 7 D stimuli at 5 lux of ambient illumination. Note the wide range of pupillary near responses in children. The larger symbol among the 9 year olds represents three data points that were too similar to be resolved individually. The larger symbols among the adults represent two similar data points each.

there was a significant reduction in pupil size with a stimulus of 4 D in children, but not in adults. When a stimulus of 7 D was presented, pupil constriction was highly significant in both groups (Fig. 2 and Table 2). The individual responses to the 7 D stimulus at 5 lux are shown in Fig. 3. Pupil constriction was also highly significant in children exposed to the 7 D stimulus at 100 lux (Table 2).

4. Discussion

Our results lend no support to the initial hypothesis that the accommodative pupil response of children is weakest and most dissimilar to the response in adults under dim light. Although there have been statistically significant differences in pupil constriction between children and adults at 5 lux, but not at 100 lux (Table 2), the effects of lighting level are minor (Fig. 2). Furthermore, children showed significant amounts of accommodative miosis at 5 lux with the 4 D stimulus, while this was not the case in adults (Table 2).

However, the effects of illumination level could not be investigated in detail, since at 200 lux most adult pupils were too small to obtain readings of refractive state, such that the accommodative response could not be determined at 200 lux and at 100 lux only up to 4 D of accommodative stimulus. Children and adults may actually differ more than our data indicate, because we had to exclude all subjects (mainly adults) with pupil diameters smaller than 3 mm. The differences in the accommodative responses to stimuli of 7 D are also rather under-than overestimated since the PowerRefractor tends to underestimate refractive errors that exceed −6 D (Choi et al., 2000). Such highly accommodated refractive states were most common among the children.

There was considerable individual variation in the accommodative pupil responses of both adults and children (Fig. 3). Some subjects actually opened their pupils when a moderate accommodative stimulus (4 D) was presented. This illuminates the need for sufficiently large sample sizes.

Comparison of the results at 5 lux of the study by Wilhelm et al. (1993) and our study reveals a surprising effect of the choice of visual target. Wilhelm et al. used a small image of a well-known athlete, while we used crossing wires. In the Wilhelm et al. study, the about 10 years old subjects accommodated substantially more at a 7 D stimulus (up to about 12 D compared to max. 9 D in our study), but constricted their pupils substantially less (about 5% compared to 37.5%). This indicates that the presented target has a decisive effect on the performances of the subjects and suggests that the accommodative and pupillary responses may be at least partially independent of each other. This target-dependency of the responses is another factor that may explain some of the confusion in the literature about the strength of the accommodative pupil response in children.

Stronger pupil constriction in adults induced by accommodative stimulation reduces accommodative demand and effort, because depth of field is longer with a smaller pupil. This appears to be well-adapted, since accommodative range decreases with age. If depth of field is increased, an adult has to spend less effort on accommodation and still sees a sharp image. The cost is a darker, i.e., noisier image. This may be compensated for by better fine-tuning of the neural circuitry in a mature human visual system, which may be able to cope with more image noise—at least in the photopic range—than the developing visual system of a child. A smaller pupil may therefore be the optimal solution for an adult, even if he/she is young enough to be able to fully accommodate to the visual target.

The results presented here support the earlier assumption that the observed pupil constrictions in diving Moken and trained European children (Gislén et al., 2003, 2006) were induced by strong accommodation, as was predicted by an optical analysis of underwater vision in humans (Gislén and Gislén, 2004).

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