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Development of the response AC/A ratio over the first year of life

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Abstract

This study investigated the development of the link from accommodation to vergence in infants by occluding one eye thus removing binocular cues. Occluded adults continue to converge partially demonstrating that the accommodative drive to vergence (the AC/A link) and proximal cues are sufficient to drive vergence. For infants of all ages, AC/A ratios were found to be in the normal adult range. We conclude that infants can use monocular cues to drive vergence and that this occurs before the age when there is a substantial increase in the accuracy of oculomotor processes. There is flexibility in the developing visual system which is able to produce early vergence responses by relying upon alternative cues.

Keywords: Accommodation; Vergence; Accommodative-convergence; Infant; Photorefraction

1. Introduction

While the AC/A ratio has been extensively studied in adults (e.g. Flom, 1960; Judge, 1996; Ogle & Martens, 1957; Plenty, 1988) the development of the links between accommodation and vergence has received less attention. Theories of the development of these links originate with Hering and Helmholtz in the 19th century (Wade, 1998). Hering argued that the links were innate and did not change developmentally while Helmholtz believed that the links were learned as a result of visual experience. This argument was extended by Fitton (1966) who proposed three possible theories for the origin of the accommodation vergence relationship: (i) The link is innate and invariant during the individual's life. (ii) There is a general genetic link between accommodation and vergence that is tuned by neo-natal experience. (iii) The repeated association between accommodation and vergence may establish a link. After more than a third of a century there is very little experimental evidence that allows these alternatives to be critically appraised. In this paper, we review what is known about the development of accommodation and convergence, and their linkages. We then report a study that looked at the development of this link.

1.1. Development of convergence

Several investigators have examined the development of vergence over the first few months of life. These studies suggest that convergence to moving targets matures around 3 months of age (Aslin, 1977; Ling, 1942; Thorn, Gwiazda, Cruz, Bauer, & Held, 1992). This maturation might be dependent on the development of the ability to use retinal disparities, as measured by the onset of stereopsis (Thorn et al., 1992). Behavioural and electrophysiological measures of sensitivity to binocular disparity suggest that stereopsis in the human infant has a sudden onset between 10 and 16 weeks of age (cf. Braddick, 1996; Gwiazda, Bauer, Thorn, & Held, 1986). It is after this time that infants appear to be able to converge accurately on a target moving in depth.

For static targets the results are somewhat different. Slater and Findlay (1975) found that newborn infants can converge appropriately to static targets between 10 and 20 in. but are less accurate when the target is at 5 in. Hainline and Riddell (1996) found that 40% of infants under 30 days have appropriate and, more or less, linear convergence to a set of static targets placed at distances between 25 cm and 2 m. The ability to converge accurately to static targets, therefore, develops before the emergence of functional binocular disparity detection and may be dependent upon processes such as bifoveal fixation (Braddick, 1996; Riddell, Horwood, Houston, & Turner, 1999).

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Taken together these results suggest that binocular vergence is present and relatively effective for a static target at birth and that during the first 3 months the ability to converge accurately for moving targets develops rapidly. If there are qualitative changes in the processes producing vergence these might be expected to be paralleled by changes in the association between vergence and related systems, such as accommodation.

1.2. Development of accommodation

The development of accommodation has been less thoroughly investigated than that of vergence. Accommodation increases in its range and accuracy over the first 6 months of life (Braddick, Atkinson, French, & Howland, 1979). Results suggest that infants under 1 month of age are able to change their accommodation in the appropriate direction but tend to over accommodate for distant targets. Responses at 1 month are not as accurate as those found at 2 months of age (Banks, 1980; Banks & Bennett, 1988; Haynes, White, & Held, 1965). Hainline, Riddell, Grose Fifer, and Abramov (1992) found that approximately 50% of infants under 2 months of age tended to demonstrate flat accommodation with a fixed plane of focus at about 30 cm. An additional 30% of the infants accommodated appropriately for near targets but fail to relax their accommodation for more distant targets producing a low gain response. The final 20% showed relatively accurate accommodative responses at all target distances. The available data suggests that, though there are quantitative changes in accommodation developmentally, for example, improvements in the gain of the response, there are no qualitative changes, such as a sudden change in the gain of the response at the onset of the ability to detect retinal disparities. If the link between accommodation and vergence is dependent on development of accommodation, it would be expected to improve gradually over the first 2 months of life with the gradual maturation of this system.

1.3. Development of accommodation and vergence measured simultaneously

The development of simultaneous, binocular accommodation and vergence has been examined by Hainline et al. (1992). They found that for 50% of infants under 45 days and for 30% of infants between 46 and 60 days convergence was appropriate but accommodation showed little change. They concluded that the development of accommodation lags behind that of vergence and that the link between vergence and accommodation is not fully developed in these infants. They also suggest that there can be little effect of accommodation upon convergence since accommodation in these infants does not change with target distance. This suggests that the proportion of infants who show linkages between accommodation and vergence might be expected to increase with age. Monocular accommodation and vergence were not measured in this study so this could not be tested directly.

Since infants as young as 1 month of age are able to converge to static targets and some of these infants can also accommodate appropriately, it is of interest to consider what cues they are using to produce this behaviour. The main cue for vergence in adults is retinal disparity. Since this cue is not thought to be available until the end of the third month of life, the youngest infants must be using alternative cues. The major cue for accommodation in adults is stimulus blur, however accommodation can also be driven by changing size or proximal cues (Erkelens & Regan, 1986; McLin, Schor, & Kruger, 1988; Regan & Beverley, 1978) and by vergence (the convergence accommodation/convergence or CA/C ratio). Currie and Manny (1997) found that infants also used multiple cues to drive accommodation. They found that for 1.5 and 3 month old infants blur alone was not a sufficient cue to accommodation but that it was also dependent upon proximal cues. Also for some infants at both ages vergence cues contributed to accommodation. By removing binocular cues from the image, we will be able to assess the importance of this cue to accommodation and vergence developmentally.

1.4. Development of the link between accommodation and convergence

While the developmental basis for the links between accommodation and vergence has been discussed, few experimenters have addressed empirically the question of whether such links are present in infants. A recent study has demonstrated that it is possible to measure vergence accommodation in some 3–6 month old infants (Bobier, Guinta, Kurtz, & Howland, 2000). In this study, accommodation was produced in response to the placement of a prism in front of one eye while infants viewed a non-accommodative target. This suggests that the vergence is able to drive accommodation by at least 3 months of age. However, vergence response was not measured in this study, so the size of the response CA/C ratio could not be measured. Aslin and Jackson (1979) studied the development of accommodative vergence by measuring binocular eye alignment for both binocular and monocular viewing conditions in 2–6 month infants. This allowed them to consider the linkage between accommodation and convergence in terms of the accommodative stimulus. They found that vergence was present for a near and distant target for most individual infants at all ages both for binocular and monocular viewing. They deduced that, during monocular viewing, as disparity cues were not present, vergence must be a consequence of the accommodative vergence link. They concluded that the accommodative vergence link is present at birth but proposed that it is modified by experience thus allowing for changes in interocular separation. Although Aslin and Jackson measured vergence changes, they did not simultaneously measure accommodation so it is not possible to confirm that accommodation is driving vergence. While their deduction that vergence and accommodation are linked is plausible, it is not directly supported by their evidence. An alternative explanation is that vergence is being driven by proximal cues.

Thus both Aslin and Jackson (1979) and Hainline et al. (1992) conclude that infants of 2 months can converge appropriately. However, the two studies have different conclusions when considering whether accommodation is being used to drive vergence during the first 2 months of life. In order to resolve this issue, it is necessary to measure both accommodation and vergence while infants of a wide range of ages view targets at different depths monocularly. The present experiment, therefore, compared binocular and monocular vision using a photorefractive technique that allowed accommodation and vergence to be measured simultaneously.

The presence of an occluder over one eye removes the cues to vergence which are given by binocular disparity. Proximal cues such as looming, and links from accommodation (accommodative vergence; Maddox, 1893), will still be present as possible means of driving vergence. It also leaves only proximal cues and blur as means of driving accommodation. Examining the changes in accommodative and vergence responses that result from removal of the retinal disparity cues then allow us to determine the relative importance of this cue to accommodation and vergence. If vergence in infants is highly dependent on binocular cues then the presence of the occluder might be expected seriously to reduce vergence. If, however, vergence can be driven by accommodation or by proximal cues then the presence of the occluder should have a relatively small effect. A qualitative change in the effect of the occluder might be expected to occur at the age when binocular interaction is known to have developed (10–16 weeks). Conventional wisdom is that accommodation in adults is relatively unaffected by occlusion and that about two-thirds of the monocular convergence response is driven by accommodation (Maddox, 1893). In a recent study, Horwood, Turner, Houston, and Riddell (2001) demonstrated that this is not always the case. In adult subjects, both accommodation and vergence were reduced on occlusion when the adults were naïve and uninstructed and the target was a picture of a clown which did not require accurate accommodation for identification. Since this is the type of target used when testing infants, and infants cannot be instructed, it is possible that there will also be a disruption in accommodation and vergence on occlusion in this group.

In the study reported here, an occluder was used to produce monocular vision. A split pathway photographic technique, using a remote haploscopic photorefractor (RHP) (designed by Abramov and Hainline, Infant Study Center, Brooklyn College of CUNY), allowed the vergence and accommodative behaviour of both the unoccluded and the occluded eye to be measured. The links between accommodation and vergence were examined for each individual subject by comparing the accommodative and vergence responses to a series of targets at different depths. The measure of linkage used was the standard calculation of the AC/A ratio. The existence of these links between accommodation and vergence were then analysed across age to assess whether developmental changes occur during periods when there are known increases in the accuracy of the two systems.

2. Methods

2.1. Apparatus

Photographs were obtained using a RHP. This apparatus was designed by Abramov and Hainline (see Fig. 1) and is described in detail elsewhere (Horwood et al., 2001). The RHP allows a series of photographs to be taken rapidly while the subject looks at a target presented at a range of distances. It consists of two optical pathways. The first is the photorefraction system which takes digital photographs of both eyes via a periscope with the camera 4.5 m from the subject. The photorefractor used in this study is identical to that described by Abramov, Hainline, and Duckman (1990). It uses a digital camera, a 1000-mm focal length catadiotropic lens and a flash gun mounted above the lens as close as possible to the lens edge.

The second pathway is used to present the fixation target. The target consists of an image on a video monitor mounted on a motorised beam. This image is presented to the subject via an optical pathway that passes through two concave mirrors and a beam splitter. Binocular photorefraction and target manipulation can, therefore, take place independently. This arrangement is important for occlusion. Just as the target appears in front of the infant via the two concave mirrors, there is an image of the infant's face projected onto the top concave mirror. Any optical change made between the virtual image of the infant's face and the real target is identical to an optical change between the real infant and the virtual target. We are therefore able to occlude infants by placing an occluder in front of the virtual image of the infant and the target. Adult subjects do not notice this occluder.

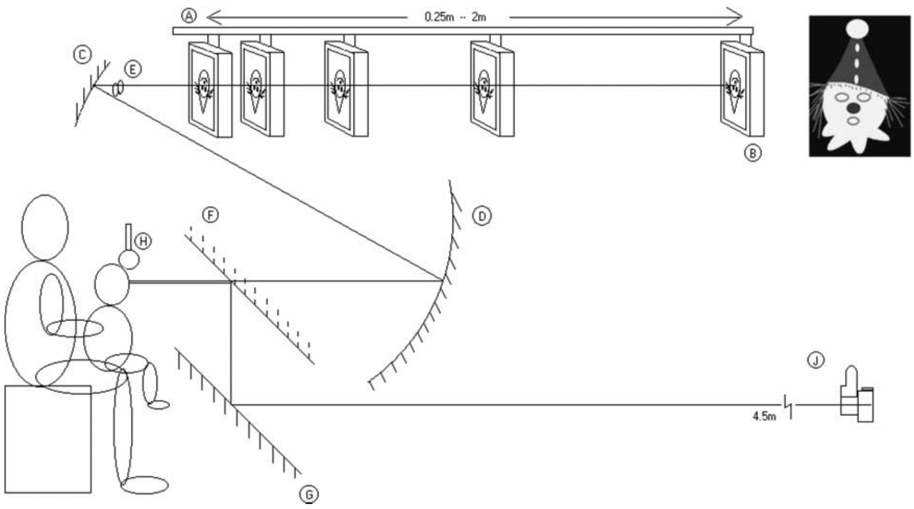

Fig. 1. The RHP: The diagram shows the two optical pathways. The upper pathway presents the fixation target to the infant via two concave mirrors and a beam splitter. The target moves along a beam and is presented at distances of 2, 1, 0.5 and 0.3 m from the infant. The lower pathway consists of the photorefraction system which takes digital photographs of both eyes via a periscope with a camera 4.5 m from the infant. The occluder was inserted between the target and the first concave mirror. Key: (A) motorised beam; (B) target monitor; (C) first lens mirror; (D) second lens mirror; (E) occluder; (F) half-silvered mirror; (G) first surface mirror; (H) head rest; (J) camera.

2.2. Target

The target was a brightly coloured picture of a clown subtending 7 cm × 10.5 cm at 2 m (see inset in Fig. 1). This was designed to act as an accommodative stimulus for infants and children but was not equivalent to the demanding accommodative targets (e.g. text which is at the lower end of adult acuity resolution; e.g. Dul, Ciuffreda, & Fisher, 1988). The clown's face alternated every second between two forms to maintain the infant's attention. This was the only stimulus visible to the infant during testing.

2.3. Subjects

Infants were recruited through antenatal classes and health care professionals. 307 infants of the appropriate age visited the laboratory over an 8 month period while the occlusion experiment was in progress. All infants were occluded if they remained in an appropriate state of alertness after completion of testing with an unoccluded target. Only infants who cooperated for four target distances while occluded were included in the study. 125 infants were not occluded: In some of these cases this is because they were either judged to be insufficiently alert since their eyes were closed or closing. In other cases the baby was uncooperative after the unoccluded photographs had been taken and would no longer look at the targets. A further 49 infants cooperated for only 1–3 target distances when occluded and therefore were excluded from the experimental data. There were 133 infants for whom occlusion produced sufficient data. Analysis suggests that infants cooperated with occlusion most readily between 9 and 16 weeks of age. The infants who did not cooperate consisted of individuals who disliked being occluded (they became wriggly or distressed as soon as the occluder was inserted but became cooperative again once it was removed) and those who's ability to attend was overtaxed by the prolonged testing period (they became wriggly at about the time the occluder was inserted but did not become cooperative again once it was removed).

The ages of the occluded infants ranged from 1 to 54 weeks. For the purposes of analysis, the infants were split into age bands as shown in Table 1. These age bands were chosen with reference to previous studies of vergence and accommodation. It has been shown that infants below 8 weeks of age have immature responses (Hainline et al., 1992) and so these formed the first group. The next group included infants who were not yet expected to have developed the ability to detect retinal disparity. This is thought to emerge between 12 and 16 weeks (e.g. Birch, 1993), and so this range was used for the third group. Since all infants over this age

Table 1
Demographic information: sample sizes and age data for the subject groups

Age (weeks)	Number occluded	Mean age (weeks) (s.d.)	% of infants occluded
0–8	26	6.1 (1.7)	31.1
9–12	36	10.6 (1.2)	54.1
13–16	23	14.6 (1.2)	52.1
17–26	17	20.1 (3.3)	43.9
27–54	31	39.8 (11.2)	42.5
Child	9	182.3 (20.8)	100

behave in a similar manner, we divided the remaining infants into those up to 6 months, and those above 6 months. Several of the infants were occluded on more than one visit to the laboratory as part of our on-going longitudinal study. All infants' ages are given relative to their gestational age rather than to their actual birthday. 9 siblings of the infants who were aged between 2 years 11 months and 4 years 1 month, and 16 visually mature individuals (children, students and postgraduates, aged between 9 and 44 years) were also tested.

2.4. Design

All participants took part in two conditions: binocular viewing and monocular viewing with the left eye occluded. The order of conditions for the two older subject groups was counterbalanced. While the order of conditions for the infants was not counterbalanced, a sample of 5 infants received binocular stimuli both before and after the monocular ones. No differences were found between the two sets of binocular photographs so differences between the binocular and monocular conditions could not be attributed to a lack of attention or fatigue.

2.5. Procedure

Infants were brought into the photorefractor room where the lighting was dimmed to produce dilated pupils for photorefraction and to allow the image to be seen through the beam splitter. Dim lighting conditions have not been found to severely reduce accommodative responses (Arumi, Chauhan, & Charman, 1997; Campbell, 1953). Infants were held by one of the experimenters with their forehead against a padded headrest. The infant was gently restrained by keeping the back of the head against the experimenter's chest. The infants looked into the photorefractor where the target was presented at eye level. No instructions were given to the infants. Adults and children sat on a chair in front of the photorefractor with their head on the headrest. They were told to look at the clown but were given no further instruction. The target was presented, and photographs taken, at 33, 50, 100 and 200 cm, representing accommodative demands of 3, 2, 1, 0.5 D. The order of presentation was pseudorandom (3, 0.5, 1, 2 D).

For the monocular conditions, an occluder (a piece of dark gray card) was inserted between the upper concave mirror and the target. This obscured the subject's view of the target in the same way as if an occluder had been placed before one eye. The occluder was not apparent to the subjects (as reported by the adults who participated in this study). When adult subjects looked for the occluder after testing, they were aware that the image in the occluded eye was gray and of about the same average luminance as the target.

In the photorefractor used here, the zoom lens produces a magnified image of the eyes that subtended approximately 12 cm. This almost completely filled the frame of the photograph. If the subject was off centre by as much as 2 cm, part of one eye was lost from the photograph. Since the occluder extended 2 cm to either side of the eye, this also ensured that the eye was always completely covered by the occluder.

2.6. Calculations

Vergence was calculated from the position of the corneal reflection in relation to the pupil centre. As convergence occurs the pupil centre moves nasally in relation to the corneal reflection (first Purkinje image) of the camera flash. By applying the Hirschberg ratio (1 mm corneal reflection change per 12.2° of vergence change, Riddell, Hainline, & Abramov, 1994; Slater & Findlay, 1975), we derived an angular estimate of vergence. An average value for the Hirschberg ratio was used throughout this study since we felt that the number of infants who did not complete testing would increase if we attempted to obtain individual Hirschberg ratios.

Accommodation was measured using a calibration of the equipment based on dynamic retinoscopy. A group of adult subjects were asked to look at a range of target distances while their accommodative plane was measured using both photorefraction and dynamic retinoscopy. The retinoscopy results were used to calibrate the size of the pupillary crescents produced by a given accommodative plane. We did this by plotting the accommodative plane given by dynamic retinoscopy against the crescents and pupil size measured from a photograph taken while the participant was viewing the same target. This was repeated for a series of targets across participants. The data were used to produce a smooth two-dimensional surface that could be applied to photorefraction data to give an estimate of accommodative response from a given pupil and fundal reflex crescent size. The function is non-linear and crescent size is found to asymptote when the accommodative plane is between 5 and 6 D, depending on pupil size. We are therefore unable to measure accommodation above this value.

Vergence and accommodation of each individual were calculated from their photographs (Fig. 2). All measurements were made by two experienced experimenters. In the small number of cases of disagreement, a third experimenter measured the photographs. Correlation between all measurements was extremely high, $r^2 = 0.9991$ for non-crescents and $r^2 = 0.9946$ for crescents. For infants over 8 weeks of age, a minimum pupil size of 4.6 mm (mean: 5.7 mm; range: 4.6–7.1 mm) was used. For infants below this age, a minimum pupil size of 4 mm (mean: 5.1 mm; range: 4.0–6.2 mm) was accepted.

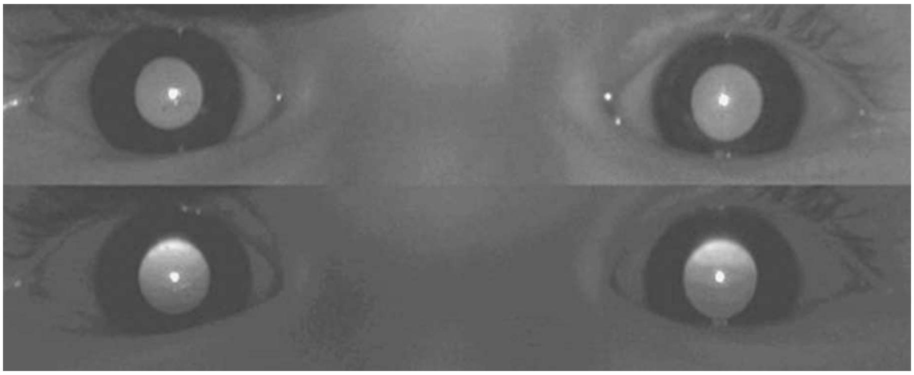

Fig. 2. Photographs of infant eyes produced by the RHP. The upper photograph is of an infant who is viewing a distant target (2 m): the pupil is a uniform gray. The lower photograph is of an infant who is focused upon a target at 0.33 m: the fundal reflex crescent is visible in the upper portion of the pupil. Accommodation is determined for a given pupil size by measuring the size of the fundal crescent, and vergence is measured as the distance from the corneal reflection to the centre of the pupil.

Birch and Held (1983) suggested that pupil sizes are smaller under binocular compared to monocular conditions. Since accommodative plane is related to both pupil and crescent size, it is possible that differences in pupil size between binocular and monocular conditions could result in systematic differences in calculated plane of accommodation between these conditions. A comparison of pupil sizes between the two conditions for both near and far targets showed, however, that there were no such systematic effects in this data (all F values < 1).

The response heterophoria AC/A ratio was calculated for the occluded data using the change in vergence over the change in accommodation between two target distances. Vergence is reported in metre angles with accommodative plane in dioptres to allow direct comparison to be made between these two measures.

3. Results

3.1. Binocular performance

Mean accommodation and vergence performances across age in both binocular and monocular conditions are shown in Fig. 3. The mean performance for infants up to 8 weeks when viewing with both eyes demonstrates accommodation which is related to the target demand between 1 and 3 D. A regression of accommodative response versus demand over this range produced a slope of 0.70 ($r^2 = 0.99$, $F = 146.61$, $P = 0.05$). For 0.5 D targets, this group over-accommodates and over-converges. Vergence response was not significantly related to demand at this age. Mean performance for infants of 9–12 weeks is more accurate than that of the youngest group for both accommodation and vergence. By 9–12 weeks, the accommodative and vergence responses were similarly advanced. Below this age, however, accommodation was related to target distance while vergence remained flat. This suggests that, in this population, accommodation develops before vergence. Vergence improves up to 13–16 weeks where it falls close to the ideal line and is as accurate as that of the adult group. Accommodation improves up to 17–26 weeks when it is more accurate than that of the adults. The 26–54 week infants perform less accurately at both accommodation and vergence than infants at 17–26 weeks. This result differs from previous findings in which infants of this age were found to accommodate appropriately (Atkinson, Braddick, Durden, Watson, & Atkinson, 1984). This might be due to the considerably longer testing sessions required for this study. Infants of over 6 months also appeared to find the target less interesting than the younger infants tested. Bobier et al. (2000) and Aslin and Jackson (1979), however, also found that infants of 6 months performed more poorly than those of 4.5 months. A similar poor performance is given by the 3 year olds who were cooperative but showed an accommodative response that suggests that they are not concerned about maintaining a clear image.

3.2. Comparisons of monocular and binocular performance

A 2×2 ANOVA (occluded/unoccluded; accommodation/vergence) was performed for each age group to compare mean accommodation and vergence for each individual with and without the occluder. There was no effect of occlusion upon infants up to 8 weeks, $F < 1$. Infants of this age showed no change in accommodation or vergence with occlusion. For all other age groups the occluder had a significant effect reducing both accommodation and vergence performance (9–12 weeks, $F(1,35) = 5.12$, $p < 0.01$; 13–16 weeks, $F(1,21) = 15.48$, $p < 0.001$; 17–26 weeks, $F(1,16) = 5.30$, $p < 0.05$; 27–54 weeks, $F(1,30) = 36.22$, $p < 0.001$; child, $F(1,8) = 10.38$, $p < 0.05$; adult, $F(1,15) = 36.85$, $p < 0.001$). The 9–12 week infants showed flat response curves when

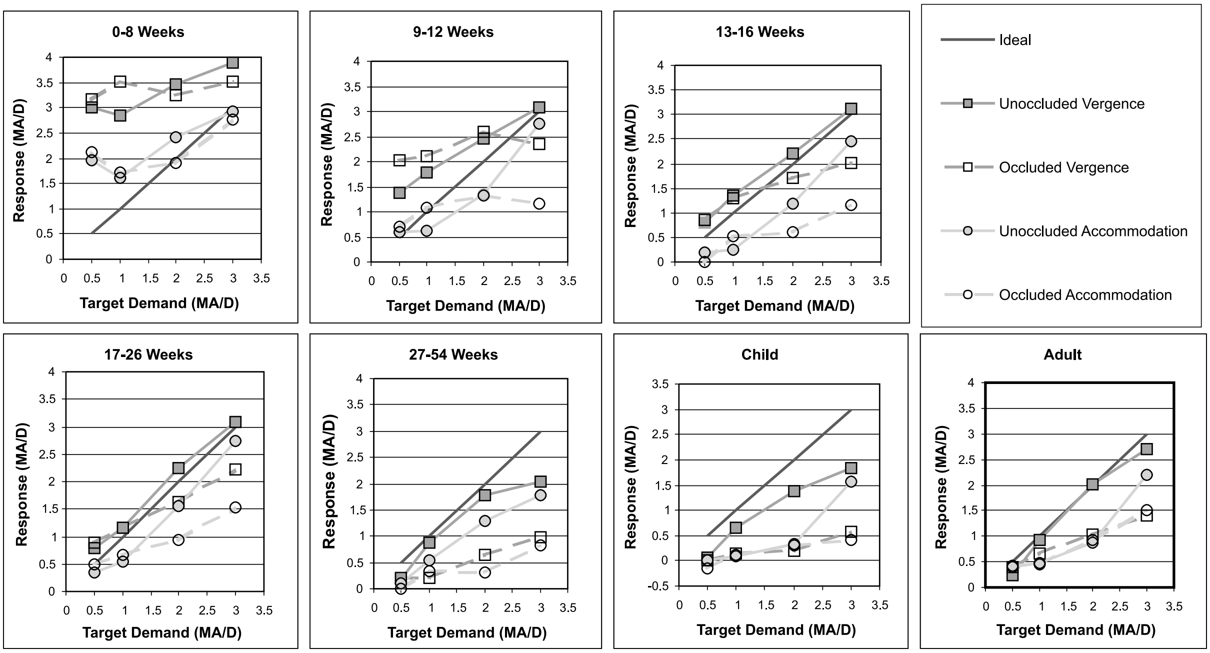

Fig. 3. The development of accommodation and vergence with age. Target distances varied between 2 m (0.5 D) and 0.33 m (3 D). Binocular performance is compared to monocular (occluded) performance. Accommodative response is linearly related to demand at all age groups tested. Vergence response is linearly related to demand from 9 weeks onwards.

occluded. For the older groups of subjects the occluder produced a reduction in gain with the largest effect upon accommodation and vergence occurring for the nearer targets (2 and 3 D).

For the adults the occluder had a greater effect upon vergence than upon accommodation. There was a significant interaction between the presence of the occluder and whether accommodation or vergence was being measured, $F(1,15) = 21.39$, $p < 0.001$. For all other groups of subjects the occluder had an equivalent effect upon accommodation and vergence (for 0–8 weeks, 13–16 weeks, 17–26 weeks, 27–52 weeks and child $F < 1$; for 9–12 weeks, $F = 1.82$, $p > 0.05$). The results for infants and children do not support the conventional wisdom from adult studies that occluding one eye disrupts the vergence more than the accommodative response (Maddox, 1893). Instead, occlusion affects both accommodation *and* vergence.

3.3. *AC/A ratios*

The mean stimulus AC/A ratio was calculated for the infants from Fig. 2. This was calculated by dividing the change in vergence between 0.5 and 3 D by the change in the stimulus to accommodation (i.e. 2.5 D). The youngest infants were found to have lower stimulus AC/A ratios than older infants. In turn, the infants over 6 months of age, children and adults tested had lower stimulus AC/A ratios than the 3–4 month old infants. Stimulus AC/A ratios were within adult range by the age of 13–16 weeks. This suggests that the stimulus AC/A ratios in the youngest infants are reduced due to the poor vergence response to target demand. This does not, however, show how vergence is related to accommodation. For this we need to measure a response AC/A ratio.

The first measure of response AC/A was computed by taking the ratio of the change in monocular convergence between 0.5 and 3 D and accommodation between the same demands as shown on Fig. 2. There is a developmental trend in the AC/A ratio calculated using this method; the youngest infants have a lower AC/A ratio which rises to within adult values by 13–16 weeks (Table 2).

We were attempting, however, to establish whether infants could be shown to have AC/A ratios in the adult range when performing to the best of their ability. To do this, we used the change in vergence (in metre angles) over the change in accommodation (in D) between two distances measured for individual participants. For adults and children a mean of the AC/A ratio for the change in vergence and accommodation between targets at 0.5 and 3, and 0.5 and 2 D was used. If either the accommodation or the vergence, or both, had no gain then an AC/A ratio was not calculated. When accommodation is flat the AC/A ratio approaches infinity and when vergence is flat it approaches zero. For individual babies, we excluded target distances where behaviour was judged to be erratic. We considered erratic behaviour in this instance to be when one single photograph, from a series of photographs which were otherwise monotonic, showed a response which was more than 1 D away from that predicted by the other photographs in

Table 2
Stimulus and response accommodative convergence/accommodation ratios calculated for each age group

Age (weeks)	Stimulus AC/A (Fig. 2)	Response AC/A (Fig. 2)	Non-flat response AC/A	% of subjects
0–8	0.14	0.52	0.93 (1.00)	56.5
9–12	0.13	0.72	0.89 (0.57)	60.6
13–16	0.46	1.00	1.23 (0.82)	80.0
17–26	0.54	1.30	1.06 (0.74)	78.9
27–54	0.30	0.91	1.09 (0.91)	63.6
Child	0.22	0.95	0.75 (1.23)	88.9
Adult	0.40	0.93	0.75 (0.70)	93.8

Stimulus and response AC/As were calculated from the mean change in vergence and accommodation between 0.5 and 3 D taken from Fig. 2 for infants at each age. Lower stimulus AC/A ratios reflect larger numbers of infants, children or adults who failed to converge in this situation. This is not seen in the response AC/A ratio measured in the same way. In this case, there is a developmental trend such that the response AC/A ratio increases with age as infants converge more appropriately, reaching normal adult values early in childhood. This can be compared to the response AC/A ratio calculated only for infants who accommodated and converged appropriately. Standard deviations are given in brackets. Here, there is no developmental trend in the AC/A ratio though more of the youngest infants were excluded from this calculation.

the series. In this situation, we discarded the erratic photograph, but used the other photographs from the series to calculate an AC/A ratio for this infant.

Using these principles, an AC/A ratio could not be calculated for 63/133 (47.4%) infants. For 38% of the infants, the AC/A ratio could be calculated in the same way as for adults with the qualification that if the behaviour at either 2 or 3 D was erratic a single measure of AC/A ratio was used rather than the mean. If behaviour at two or more of these distances was erratic then the change between 1 and 3 or 1 and 2 D was used (8% of the infants). For the final 7% of infants, AC/A ratios were calculated using any single pair of distances where behaviour was consistent. The AC/A ratios produced by each of these procedures were equivalent. The percentage of infants for whom an AC/A ratio cannot be calculated decreases with age up to 6 months when the general uncooperativeness of the infants leads to a marked increase in flat accommodation.

Using these criteria, it can be seen that, when an AC/A ratio can be measured, it does not change systematically with age. Although the AC/A ratios in our infant subjects were higher than normally found in adults, they fell within 1 SD of those found for adults in this study. Some adults also produce flat accommodation when occluded for this naturalistic target, giving high AC/A ratios, but do not do so when the target is text (Horwood et al., 2001).

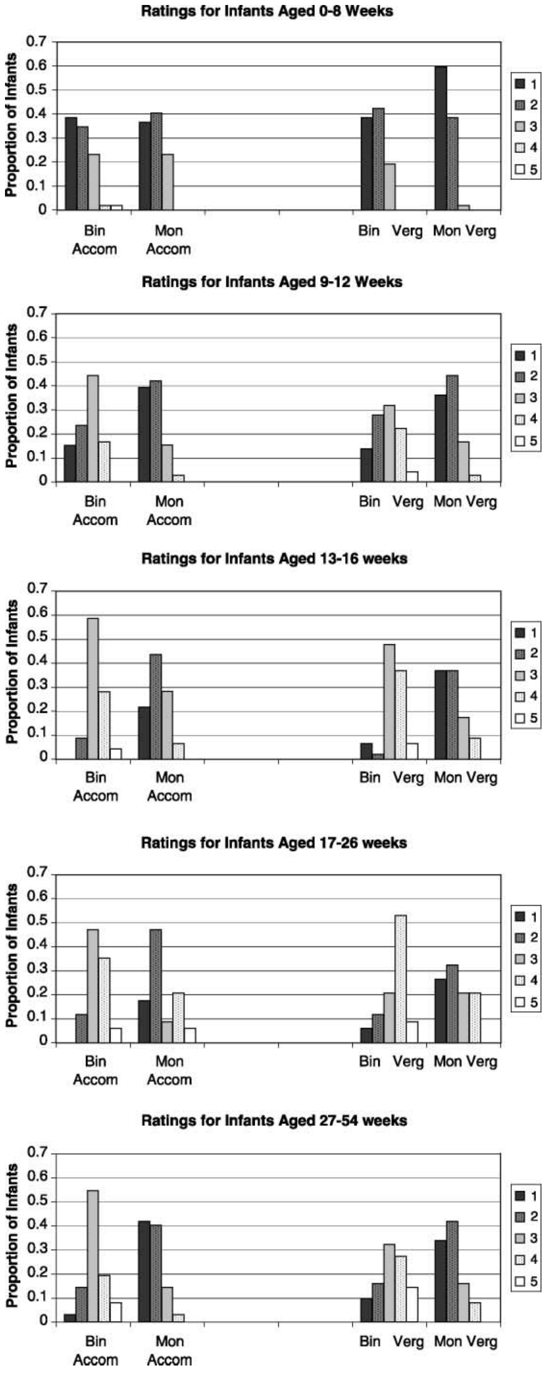

Fig. 4. A comparison of rated accommodation and vergence by age for monocular and binocular vision. Each graph shows the percentage of infants who achieved a particular rating at each age. *Rating scale:* 1—flat or erratic performance; 2—2 to 3 measurements on the ideal line other measurements appropriate; 3—all within 1–1.5 D of the ideal line with appropriate slope and most points linear; 4—within 0.75 D for all measurements; 5—within 0.25–0.5 D of the ideal line and linear. As the age of the infants increases, the modal rating increases for both vergence and accommodation. At all ages, occluded performance is worse than unoccluded performance.

3.4. Individual performance

In order to compare performance across individual infants, the graphs for the occluded and unoccluded data were rated on a 5 point scale where 0—an erratic response, 1—a flat response, 2—2–3 measurements on

Table 3
A comparison of the change in accommodation and vergence between binocular and monocular conditions

Relative changes in vergence and accommodation	(%)	Mean age (weeks)
Same reduction in A and V	23.3	17.6 (10.9)
V reduced more than A	30.8	19.0 (12.9)
A reduced more than V	27.8	22.8 (17.1)
No change	4.5	25.0 (7.9)
Zero A and V both unoccluded and occluded	2.3	6.6 (1.5)
Increases in A or V or both	11.3	13.1 (12.3)

Standard deviations are given in brackets. A—accommodation, V—vergence. Unlike the expected adult performance, infants are not found to reduce vergence more than accommodation when occluded.

the ideal line, 3—all points within 1 D or MA of the ideal line, 4—all points within 0.75 D of MA of the ideal line and 5—a response where all the points are within 0.25 D or MA of the ideal line. The development of rated accommodation and vergence with age when occluded and unoccluded is shown in Fig. 4. As the age of the infants increases, the modal rating increases for both vergence and accommodation. At all ages, occluded performance is worse than unoccluded performance. There is no significant difference between the ratings for accommodation and the ratings for vergence at any age either with or without the occluder. This suggests that when individual performance is considered, accommodation and vergence develop in parallel.

There were substantial individual differences in accommodative and convergence performance in the unoccluded and occluded conditions across infants. If accommodation is driving vergence via the AC/A linkage when monocular, we would predict that vergence would be more impaired by occlusion than accommodation. An analysis of the relative reduction of accommodation and vergence produced by the occluder in individual infants is shown in Table 3. The results suggest that accommodation and vergence are equally likely to be reduced by the occluder (which is consistent with the result of the ANOVA performed above in Section 3.2). There is no support for the suggestion that, for the majority of infants, vergence was reduced more than accommodation by occlusion. In fact, only 9 out of 133 infants (6.7%) conformed to the expected pattern with vergence decreasing more than accommodation during occlusion.

4. Discussion

We have described a method, remote haploscoscopic photorefraction, by which accommodation and vergence may be measured simultaneously in infants and by which comparisons may be made between binocular and monocular performance.

4.1. Measures of convergence

In this study, infants of 9 weeks and older were found to change their vergence response monotonically with target distance. This suggests that infants are able to converge to targets at some depths before they become sensitive to sensory retinal disparity cues at about 4 months (Birch, 1993). Previous studies have shown appropriate vergence responses in this age range and have suggested that this could result from bifoveal fixation of the target (Braddick, 1996; Hainline & Riddell, 1995; Riddell et al., 1999). There were improvements in the gain of the vergence response between 9 and 16 weeks of age suggesting that infants are able to converge more accurately as retinal disparity cues become available. This agrees with past research on the development of vergence responses to both static (Hainline & Riddell, 1996; Slater & Findlay, 1975) and dynamic targets (Thorn et al., 1992).

4.2. Measures of accommodation

Accommodation was related to target demand by 8 weeks of age in this infant sample. Accommodation improved in accuracy between 9 and 26 weeks and thus had a longer developmental time course than found for vergence. Early use of blur as a cue to accommodation might be limited by the infant contrast sensitivity function which has a lower sensitivity to high and middle frequencies than found in adults (Norcia, Tyler, & Hamer, 1990). This could result in reduced sensitivity to blur, as found using spatially filtered targets in adults (Green, Powers, & Banks, 1980). Thus, improvements in the gain of the accommodation response could be related to improvements in contrast sensitivity.

Hainline et al. (1992) found that, for emmetropic infants, accommodation was not linear but occurred at one of two levels: one for static, near targets and the other for distant targets. In the present study, not only was accurate accommodation found for younger infants but it was linearly related to target demand. It is possible that this earlier development of accommodation results from the differences between the targets used in the two studies. In the Hainline et al. (1992) study, the targets were a set of three-dimensional dolls that were placed at each target distance. For such stimuli there is a range of appropriate accommodative responses to each target and there are no cues to the change in distance between target presentations. In the present study, we used a two-dimensional target, thus reducing the range of appropriate accommodative responses. Our target moved to each new target position, and so looming and size change cues would also be avaiable.

4.3. Comparison of development of accommodation and vergence

In the infants tested here, accommodation started to develop before vergence. These results differ somewhat from those of Hainline et al. (1992) who found that, for the infants in their sample, vergence developed before accommodation. This difference is a consequence of an earlier development of the accommodation response in the present study. In the study by Hainline et al. (1992) there were no cues to change in distance between target presentations. By comparison, in this study, the target moved between target presentations, thus providing stronger proximal cues such as looming. The presence of these additional cues could explain the earlier accommodative development found in this study.

The results also showed that there were a variety of normal responses to the binocular target for each age group of infants. In any age group, responses varied from individuals with flat responses for both accommodation and vergence, to individuals with adult-like performance. The proportion of infants showing adult patterns of performance increased with age supporting previous findings (Hainline & Riddell, 1996). Many infants of 8 weeks and under showed some ability to accommodate and converge accurately for targets between 0.3 and 1 m. For more distant targets they over converged and accommodated resulting in a lower gain for both accommodation and vergence. Accommodation and vergence developed rapidly after 8 weeks and most infants achieved adult levels of performance by 16 weeks.

4.4. Convergence and accommodation with retinal disparity cues removed

The present technique is innovative in that it allows accommodation and vergence in both eyes to be examined while the target is viewed monocularly. When one eye is occluded, retinal disparity cues are removed, thus vergence responses must be driven by either proximal cues to depth or the use of blur cues which drive vergence via the AC/A link. If infants behaved like adults, occlusion should result in a greater reduction in vergence than in accommodation since two-thirds of the vergence response is produced as the result of accommodation (the AC/A ratio: Maddox, 1893). The results for adults in this study are consistent with this: the occluder reduced vergence to approximately two-thirds of the accommodative response.

Since retinal disparity is not available as a cue to vergence until the end of the third month, we expected that any vergence which was found in infants under this age would be dependent upon blur and proximal cues and therefore would be unaffected by occlusion. In the group of infants from 0 to 8 weeks old, monocular performance was as inaccurate as binocular performance. This result is consistent with the absence of an ability to use retinal disparity to drive vergence in this age group. In fact, vergence does not appear to be driven by any cue in this age group.

For all other age groups tested, the occluder produced an equal reduction in gain of both vergence *and* accommodation that was greatest for the nearer targets (2 and 3 D). This is a surprising result for two reasons. First, it is inconsistent with the prediction that vergence would be driven only by proximal and accommodative cues before the onset of retinal disparity detection. By 9–12 weeks, at least part of both the accommodation and vergence responses appear to be reliant on cues that are only available when the infant is viewing binocularly. Secondly, we did not expect a reduction in accommodation since blur and proximal cues are still available in the image and these are sufficient to fully drive accommodation in adults. This suggests that the CA/C link is important in driving accommodation early in development. This result is consistent with Currie and Manny (1997) who found that vergence cues helped to refine the binocular accommodative response in infants aged 1.5–3 months. It is also consistent with Bobier et al. (2000) who demonstrated a CA/C linkage in infants from 3 months of age.

In summary, blur and proximal cues appear to be sufficient to drive some but not all of the vergence response during the first year of life. By around 9–12 weeks of age, binocular cues are also important in driving this response. Thus, although infants of this age do not respond to sensory binocular cues (stereopsis), they do appear to be using binocular information to drive a motor response.

An examination of the behaviour of individual infants when occluded shows that the equal reduction in vergence and accommodation was a consequence of a mixture of behaviours. There was a group of infants for whom performance either improved or did not change when occluded (16%). This result would be expected if these infants are unable to make use of retinal disparity cues and therefore respond in an equivalent way to binocular and monocular stimuli. Most other infants (82%) show a reduction in accommodation, vergence or both. When these infants are grouped on the basis of which system shows the greater reduction, the infants divide more or less equally between each of the three possible outcomes. For 23% of infants there was an equivalent reduction in accommodation and vergence; for 31% of infants vergence reduced more than accommodation; for 28% of infants accommodation reduced more than vergence. It is important to note that this range of behaviours is not a consequence of inattention or erratic responses by the infants. Each infant is tested at four target distances and most of them show systematic responses across distance.

4.5. Linkages between accommodation and vergence

A major purpose of this study was to examine whether the links between accommodation and vergence develop or are innate. This requires measurement of the AC/A ratio. The stimulus AC/A ratio is a measure of the amount of vergence produced by a given change in the accommodative plane of the stimulus. In comparison, the response AC/A ratio measures the change in vergence produced by a given change in accommodative response. The remote haploscopic photorefraction technique allowed us to compare these measures.

Average stimulus and response AC/A ratios were calculated for infants in each age range from the measures of vergence and accommodation in Fig. 2 Comparison of these measures reveals that stimulus AC/A was less than half of the response AC/A at all ages tested. Since the vergence response is the same in both these calculations, the mean accommodative response must be less than demand at all ages. This could result from a small amount of accommodative lag in all subjects or a proportion of subjects with negligible accommodation. To test this, we calculated the AC/A ratio after excluding all infants with either flat accommodation, since the AC/A ratio approaches infinity in this case, or with flat vergence, since it then approaches zero. Infants were also excluded if their accommodative or vergence responses varied erratically around the zero level. Using these criteria, we were able to measure the response AC/A ratio for over half of the infants in the study. The proportion of infants who were excluded decreased over the first 6 months of life suggesting that both vergence and accommodation are developing over this time. However, the response AC/A ratios for infants with a measurable response at all ages were within the normal adult range for this stimulus (Horwood et al., 2001) and did not change systematically during the first year of life. This agrees with Aslin and Jackson (1979) who demonstrated that infants of 2 months of age produced a vergence change in response to a change in the accommodative plane of the stimulus even when the infants were monocular. Our response AC/A ratios are higher than the stimulus AC/A ratios reported by Aslin and Jackson (1979) since the accommodative response lagged the accommodative stimulus in this study.

We further predicted that, after the onset of the ability to use binocular disparity at the end of the third month, there would be qualitative changes in the AC/A ratio. This prediction was not supported since the occluder had an equivalent effect upon mean accommodation and vergence resulting in response AC/A ratios of about 1 at all ages tested. The developmental AC/A ratios are larger than those measured in adults (0.75) but ratios are within the upper end of the normal adult range. Infants and 3 year olds do not, however, appear to make the same use as adults of the blur and proximal cues since both accommodation and vergence decrease when retinal disparity is removed. It would be of interest to investigate the age at which adult-like behaviour emerges.

Fitton (1966) proposed three possible theories for the origin of the linkage between accommodation and vergence. The first possibility was that the link is innate and does not vary within the lifetime of an individual. Since our AC/A ratios were higher in both infants and young children than in the adults tested here, this theory does not appear to be supported by our data. Another possibility was that there was no initial link between accommodation and vergence but that repeated association between accommodation and vergence within the lifetime of the individual might be responsible for forming the linkage between these systems. Again, our data do not support this proposal since at least some infants of all ages had measurable AC/A ratios within the normal adult range. The final proposal seems to account best for our data: there appears to be a general genetic link between accommodation and vergence that is tuned by early experience.

Infants of all ages tested in this study were found to produce changes in the vergence response when only monocular cues were available in the stimulus. There was no relation between the size of the monocular vergence response and the maturity of the oculomotor responses after 8 weeks of age. Thus, we did not find a qualitative change in this response at the time when the binocular vergence response to moving targets is thought to be maturing due to the onset of sensitivity to retinal disparity cues. This suggests that there is flexibility in the infant oculomotor system that allows early vergence responses by relying on alternative, monocular cues.

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