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On the typical development of stereopsis: Fine and coarse processing

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ABSTRACT

Stereoscopic depth perception may be obtained from small retinal disparities that can be fused for single vision (fine stereopsis), but reliable depth information is also obtained from larger disparities that produce double vision (coarse stereopsis). While there is some evidence that stereoacuity improves with age, little is known about the development and maturation of coarse stereopsis. Here we address this gap by assessing the maturation of stereoscopic depth perception in children (4–14 years) and adults over a large range of disparities from fused (fine) to diplopic (coarse). The observer's task was to indicate whether a stereoscopic cartoon character was nearer or farther away than a zero-disparity reference frame. The test disparities were grouped into fine (0.02, 0.08, 0.17, 0.33, 0.68, 1.0 deg) and coarse (2.0, 2.5, 3.0, 3.5 deg) ranges based on an initial determination of the diplopia threshold for each observer. Next, percent correct depth direction was determined as a function of disparity. In the coarse range, accuracy decreased slightly with disparity and there were no differences as a function of age. In the fine range, accuracy was constant across all disparities in adults and increased with disparity in children of all ages. Performance was immature in all children at the finest disparity tested. We conclude that stereopsis in the coarse range is mature at 4 years of age, but stereopsis in the fine range, at least for small disparities, continues to mature into the school-age years.

1. Introduction

The conventional view of stereoscopic processing is that the visual input from the two eyes is fused to produce the percept of a single scene. In doing so, the stereoscopic system also provides extremely high-resolution information about the relative depth of objects in space. This 'fine' stereopsis has been well documented, and is assessed by clinical tests of stereoacuity (e.g. Randot stereotest). However, stereoscopic depth is also obtained when viewing images with very large disparities (horizontal offsets) that cannot be fused into a single image and hence appear diplopic. The existence of a 'coarse' disparity processing mechanism was studied in early investigations of stereopsis (Mitchell, 1969; Ogle, 1953; Tschermak & Hoefer, 1903), but remains poorly understood. More recently, Wilcox and Hess (1995, 1996, 1997, 1998) showed that different neural mechanisms seem to support fine (1st order) and coarse (2nd order) stereopsis. This distinction is upheld by other psychophysical (Kovacs & Feher, 1997; Langley, Fleet, & Hibbard, 1999; McKee, Verghese, & Farell, 2004, 2005) and physiological (Tanaka & Ohzawa, 2006) research. To date, investigation of stereoscopic dichotomies based on disparity range has been restricted to adult populations. However it is possible that the coarse and fine mechanisms have different developmental timelines, which leads us to evaluate the development of stereopsis in children.

Stereopsis is not present at birth, but appears by approximately 4 months of age in most infants (Birch & Petrig, 1996; Birch, Shimojo, & Held, 1985; Brown & Miracle, 2003; Fawcett, Wang, & Birch, 2005; Shea et al., 1980; Takai et al., 2005). Binocular fusion follows a similar time course (Birch & Petrig, 1996; Birch, Shimojo, & Held, 1985). Sensitivity to monocular pictorial depth cues appears later in development by 7 months of age (e.g. Arteberry, Yonas, & Bensen, 1989). Electrophysiological experiments with infant monkeys suggest that the development of stereopsis is limited not by a lack of disparity selective mechanisms in early visual cortex (V1/V2), but by their relatively coarse spatial frequency tuning, lower response rate and low contrast sensitivity (Chino et al., 1997; Maruko et al., 2008). This is consistent with human psychophysical experiments suggesting that the critical immaturity limiting infant stereopsis is contrast sensitivity (Brown et al., 2007). The development of stereopsis appears to be very dependent on visual experience because it appears at the same time after birth in both preterm and full-term infants (Jandó et al., 2012).

Most previous studies on the maturation of fine stereopsis have used commercially available tests such as the Titmus, Randot, Frisby or TNO. Estimates of the age at which stereoacuity reaches adult levels vary considerably and depend on the test used, however, most studies agree that fine stereopsis is still immature at 5 years of age and reaches adult levels between 6 and 9 years of age (Ciner

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et al., 1989; Cooper, Feldman, & Medlin, 1979; Fox, Patterson, & Francis, 1986; Heron et al., 1985; Leat et al., 2001; Romano, Romano, & Puklin, 1975; Simons, 1981; Tomac & Altay, 2000). In contrast, Birch and Petrig (1996) reported that VEP responses to stereoscopic stimuli approached adult levels by 6–7 months when assessed using dynamic random dot patterns. Note that in their work, Birch and Petrig (1996) refer to disparities greater than 20 arcmin as 'coarse' because they are large relative to their chosen disparity conditions; they did not use the diplopia-based classification applied here.[1] In fact, while they are very useful for avoiding the presence of monocular features, diplopia is not perceived in random-dot stereograms due to the presence of multiple false matches.

Very little is known about the development and maturation of coarse stereopsis. Our recent finding that disruption of binocular vision by amblyopia during childhood can spare stereopsis for diplopic stimuli (Giaschi et al., in press), could reflect the earlier maturation of coarse stereopsis relative to fine.

A number of potential roles for coarse stereopsis in human vision have been proposed (reviewed in Wilcox & Allison, 2009). For instance, most objects in a visual scene lie outside Panum's fusion zone and so are diplopic or double. Since fine stereopsis cannot signal depth for such stimuli, the coarse mechanism could be essential in providing depth information for a large region of visual space. Another possible role for coarse stereopsis is in the early development of coordinated binocular eye movements. As summarized by Simons (1993), a coarse stereoscopic mechanism could be used by the visual system to help align the two eyes, permitting the development of the high-resolution, fine stereoscopic system. The developing visual system initially faces enormous calibration challenges and considerable internal noise, these combined with relatively poor visual acuity and contrast sensitivity, will jeopardize its ability to make fine stereoscopic matches. Early development of a coarse stereoscopic signal may provide local depth information until the high-resolution information is available. This hypothesis has not yet been tested empirically. It follows, however, that if the coarse mechanism is used in this way, it must develop prior to the fine mechanism, and possibly mature earlier.

Here we assess the maturation of stereoscopic depth perception in children and adults using a computerized test. The aim is to determine the age at which performance reaches adult levels over a large range of disparities from fused (fine) to diplopic (coarse) in children aged 4–14 years with normal vision. We chose this age range based on the fine stereopsis studies summarized above, as well as previous studies showing that several other aspects of visual perception mature during the school age years (e.g. Gunn et al., 2002; Hadad, Maurer, & Lewis, 2011; Hayward et al., 2011; Levi & Carkeet, 1993; Parrish et al., 2005). As outlined above, the literature on the development of stereopsis has focused almost exclusively on the measurement of stereoacuity. While it is important to establish the minimum discriminable disparity, this approach leads to a focus on relatively small disparities. Here we assess accuracy of depth discrimination for a large range of suprathreshold disparities that are not typically included in threshold experiments. This will give us insight into the full range of stereoscopic depth perception, not just the lower limits.

2. Methods

2.1. Participants

Thirty-two adults, aged 18–40 years (mean 26 years) and 134 children, aged 4–14 years, were recruited. Prior to testing, informed consent was obtained from each adult or parent, and verbal or written assent was obtained from each child. Visual acuity was assessed by the Regan high-contrast letter chart (Regan, 1988), and stereoacuity was assessed by the Randot Circles test and the Randot Preschool test (Stereo Optical Co.). The Lighthouse picture chart (Lighthouse Low Vision Products) was used to assess visual acuity if a child had not yet mastered the alphabet. All participants had best corrected decimal visual acuity of at least 0.8[2] on the Regan chart or at least 0.67 on the picture chart (Chen et al., 2006; Dobson et al., 2009), stereoacuity of 60 arcsec or better on both stereo tests (Birch et al., 2008), and no known eye or vision problems. Six children and 2 adults were excluded from the data analysis because their best corrected visual acuity was poorer than the cutoffs specified above. Three children (age 7, 9 and 11) and 4 adults were excluded from the data analysis because their stereoacuity was poorer than the cutoff of 60 arcsec. The remaining children were divided into five groups according to age: 4–5 ($N = 25$), 6–7 ($N = 25$), 8–9 ($N = 27$), 10–11 ($N = 26$) and 12–14 ($N = 22$).

2.2. Apparatus

The stimuli were generated using a Macintosh G4 computer and presented on a ViewSonic Graphic series G225f CRT monitor with a resolution of 1024×768 and a refresh rate of 120 Hz. Stereoscopic images were displayed through liquid crystal shutter glasses (CrystalEyes 4) synchronized to the computer. Participant responses were collected using a Gravis game pad pro controller and the room was diffusely illuminated to avoid glare.

2.3. Stimulus

The display subtended 21.5×16.5 deg at a viewing distance of 1 m. The stimulus was a grey-scale Pokémon character (see Fig. 1) selected at random from a bank of nine characters presented at the centre of the display and surrounded by a rectangular, zero-disparity reference frame. The stimulus was presented on a grey background, at a moderate intensity to avoid crosstalk between the two eye's images. Two small black, zero-disparity squares were positioned above and below the reference frame to aid fusion. The width of the Pokémon stimuli was fixed at 2.2 deg while the height varied from 1.6 to 3.1 deg according to the character. To maintain a fixed distance of 0.6 deg between the outside edge of the stimulus and the reference frame, the width of the frame was scaled with the test disparity while the height varied with the character. Test disparities of 0.02, 0.08, 0.17, 0.33, 0.67, 1.0, 2.0, 2.5, 3.0, and 3.5 deg were used.[3]

2.4. Procedure

2.4.1. Measurement of the diplopia point

We began with an experiment to separate the disparity range into fine and coarse regions based on a quantitative measure, that is the proportion of trials on which the stimuli appeared fused (versus diplopic; Wilcox & Hess, 1995). Participants were instructed to indicate whether they saw one or two characters using an animated PowerPoint presentation. At the beginning of each trial a happy face image appeared for 500 ms to ensure fixation was at the zero-disparity plane. The Pokémon character was visible for 320 ms (the shortest duration that children would tolerate in pilot studies) and trials were self-paced. A mid-range subset of the test disparities was used and presented randomly on each

[1] The terms 'coarse' and 'fine' stereopsis have been associated with a variety of disparity ranges in the literature. Here we adopt a strict operational definition based on each observer's diplopia point.

[2] A decimal visual acuity of 0.8 is equivalent to a Snellen ratio of 20/25 or 0.1 LogMAR. A decimal visual acuity of 0.67 is equivalent to 20/30 or 0.2 LogMAR.

[3] For comparison with other tests, these disparities are 72, 288, 612, 1188, 2412, 3600, 7200, 9000, 10,800, and 12,600 s.

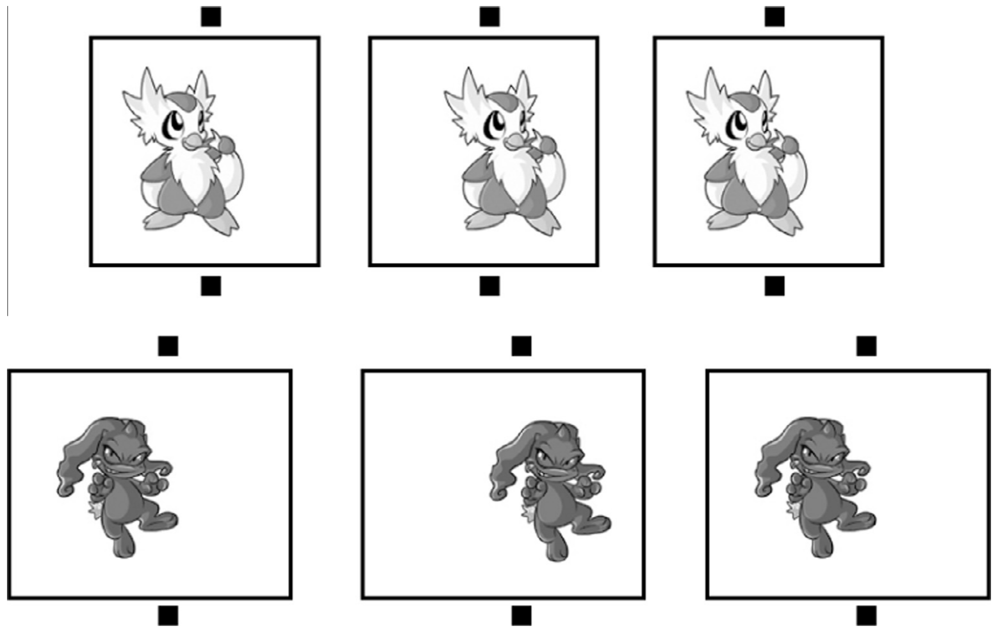

Fig. 1. Sample Pokémon stimuli are depicted as a stereopair. Crossed fusion of the left and middle pairs will cause the figure to lie in front of the fixation frame. Crossed fusion of the right and middle pair will cause the figure to lie beyond the frame (the depth order will reverse if uncrossed fusion is used). The stimuli in the upper and lower rows illustrate fine (fused) and coarse (diplopic) disparities, respectively. The rectangular and filled squares were fixed at zero disparity and served as a reference.

trial as crossed or uncrossed (0.08, 0.17, 0.33, 0.67, 1.0, 2.0, 3.0 deg). Each participant completed a total of 70 trials, 10 per disparity.

2.4.2. Depth discrimination

In the main experiment the task involved a conventional depth discrimination judgement, that is, observers were asked to indicate whether the Pokémon character appeared to be in front of or behind the reference frame. A new animated PowerPoint presentation was used to explain this task, and the full set of 10 disparities was used. Each participant began with a practice block of 20 trials with auditory feedback to ensure they could perform the task. Six participants were excluded for failing to understand the task (three 4–5; one 8–9; one 12–14; one adult). This was followed by the full experiment without feedback with 20 trials per disparity, separated into shorter blocks to permit rest breaks. A full data set was collected from six groups of participants: 4–5 ($N = 22$), 6–7 ($N = 25$), 8–9 ($N = 26$), 10–11 ($N = 26$), 12–14 ($N = 21$) and adults ($N = 25$).

3. Results

3.1. Diplopia assessment

The 'proportion diplopic' obtained for each participant as a function of disparity was fit with a Weibull function to obtain the slope and diplopia threshold. The diplopia threshold was taken as the point of maximum inflection on the psychometric function, which occurs at 63% for this type of "yes–no" procedure (Strasburger, 2001). The averaged data for each age category are plotted in Fig. 2. Analysis of variance showed a main effect of Age on the diplopia thresholds ($F(5,132) = 3.335$, $p = .007$; medium effect size, $f = 0.36$; Cohen, 1992). Tukey's HSD pairwise comparisons were used to examine differences between groups. The threshold for the 4–5 year olds was significantly higher than for the 10–11 year olds or for the adults ($p < .05$); no other group differences reached significance. A second ANOVA showed a main effect of Age on the diplopia slopes ($F(5,55.339) = 4.659$, $p = .001$; small effect size, $f = 0.25$). As Levene's test indicated that homogeneity of variance was violated, the degrees of freedom were adjusted with the Welch correction. Games–Howell pairwise comparisons were used to examine differences between groups. The slope for the 4–5 year olds was significantly shallower than for the 8–9 year olds ($p < .05$); no other group differences reached significance.

In spite of these small Age effects, each age group showed a clear transition from mainly fused at 1.0 deg to mainly diplopic at 2.0 deg. Based on this result, the disparities for the remaining analyses were divided into two sets, fine (0.02, 0.08, 0.17, 0.33, 0.67, 1.0 deg) and coarse (2.0, 2.5, 3.0, 3.5 deg).

3.2. Depth discrimination

The mean proportion correct as a function of disparity in the fine range is shown in Fig. 3. A repeated measures ANOVA with Age as a between subjects factor showed no main effect of Age ($F(5,139) = 0.737$, $p = .60$), but a significant main effect of Disparity ($F(5,695) = 49.33$, $p < .001$; large effect size, $f = 0.60$). This was qualified by a significant Age $\times$ Disparity interaction ($F(25,695) = 3.95$, $p < .001$; medium effect size, $f = 0.38$). This analysis was followed by tests of the simple effect of Age at each Disparity which showed a main effect of Age at the finest disparity only ($F(5,834) = 4.84$, $p = .001$, corrected); all other simple effects were not significant ($p > .25$). Tukey's HSD pairwise comparisons were used to examine differences between groups at the finest disparity. Here, adults performed significantly better than all other age groups ($p < .01$), while the 4–5 year olds performed significantly worse than all other age groups ($p < .01$). There were no significant differences among the 6–7, 8–9, 10–11 or 12–14 year old groups ($p > .05$). The power of the Age effect at the finest disparity, based on the large population effect size ($f = 0.43$), was 0.98. The sample size required to obtain an Age effect at the .05 level at the other disparities in the fine range, with the recommended power of 0.80 (Cohen, 1992), was determined to be at least 63 participants per group.

The mean proportion correct as a function of disparity in the coarse range is shown in Fig. 4. A repeated measures ANOVA with Age as a between subjects factor showed no main effect of Age ($F(5,139) = 1.38$, $p = .23$), but a significant main effect of Disparity

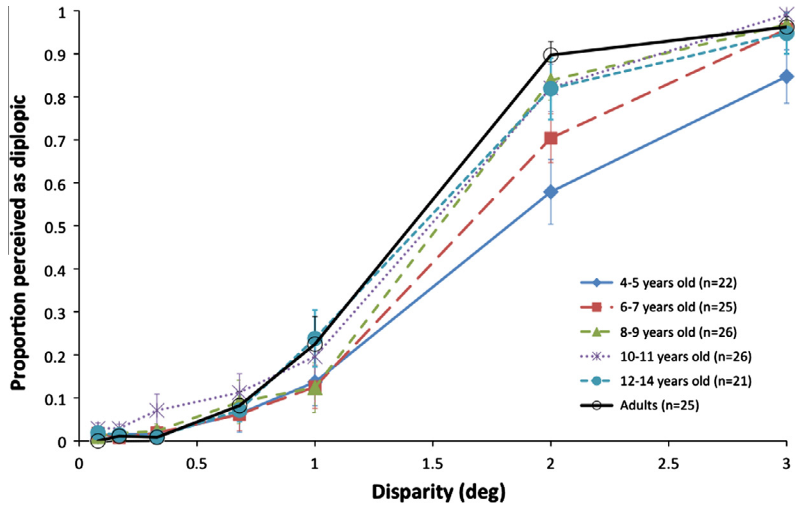

Fig. 2. The mean proportion of stimuli perceived as diplopic in each age group as a function of disparity. Error bars represent the standard error of the mean.

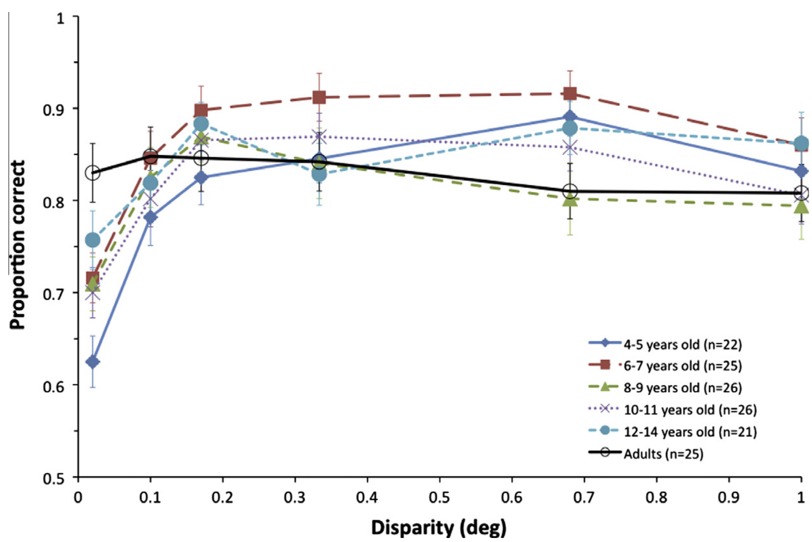

Fig. 3. Accuracy as a function of fine disparities for the different age groups. Error bars represent the standard error of the mean. The six different age groups are represented using different colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

($F(3,417) = 6.13$, $p < .001$; small effect size, $f = 0.21$). This was again qualified by a significant Age × Disparity interaction ($F(15,417) = 1.69$, $p = .05$; small effect size, $f = 0.25$). The simple effect of Age was not significant at any disparity ($p > .85$, corrected). The simple effect of Disparity was significant in the 4–5 year old ($F(3,417) = 2.83$, $p = .038$), 6–7 year old ($F(3,417) = 3.67$, $p = .012$), 10–11 year old ($F(3,417) = 3.52$, $p = .015$), and adult ($F(3,417) = 3.44$, $p = .017$) groups. Follow-up with Tukey's HSD pairwise comparisons showed that performance was better at 2.0 deg than at 3.5 deg in each age group (all $p < .05$). The initial Age × Disparity interaction was likely driven by a non-significant simple effect of Disparity in the 8–9 year old ($F(3,417) = .51$, $p = .68$) and the 12–14 year old ($F(3,417) = 0.75$, $p = .52$) groups.

Because the mean performance of the 4–5 year old group appeared to be consistently lower than that of the adults, a post hoc power analysis was conducted to determine if our design had enough power to detect an Age effect. The power of the Age effect with our sample size of 145 was 0.47. On the basis of the small Age effect size ($f = 0.22$) and the recommended power of 0.80, an N of approximately 46 per age group (276 total) would be required to obtain a significant Age effect at the .05 level.

We next expressed the mean depth discrimination accuracy for each child group as an immaturity ratio relative to the mean depth discrimination accuracy for the adult group (Table 1). These qualitative results are consistent with the statistical analysis and suggest that immaturity was greatest at the smallest disparity, particularly in the youngest group of children. At disparities between 0.17 and 1.0 deg, children were identical or slightly better than adults.

4. Discussion

We have determined that performance on our computerized test of stereopsis is at adult levels at the age of 4 years for disparities between 0.08 deg and 3.5 deg. This is the first report on the development of stereopsis across this large range of disparities. We found that performance at the finest disparity tested, 0.02 deg, was still immature at the age of 14 years. In support of this relative immaturity, the power analyses showed that while our sample size was large enough to detect the large effect of age at the finest disparity, the sample size would need to be doubled or tripled to detect the small effect of age at larger disparities.

In the coarse range, it is clear that all of our observers are performing less accurately than in the fine range. However, it is important to note that on average, performance for both adults

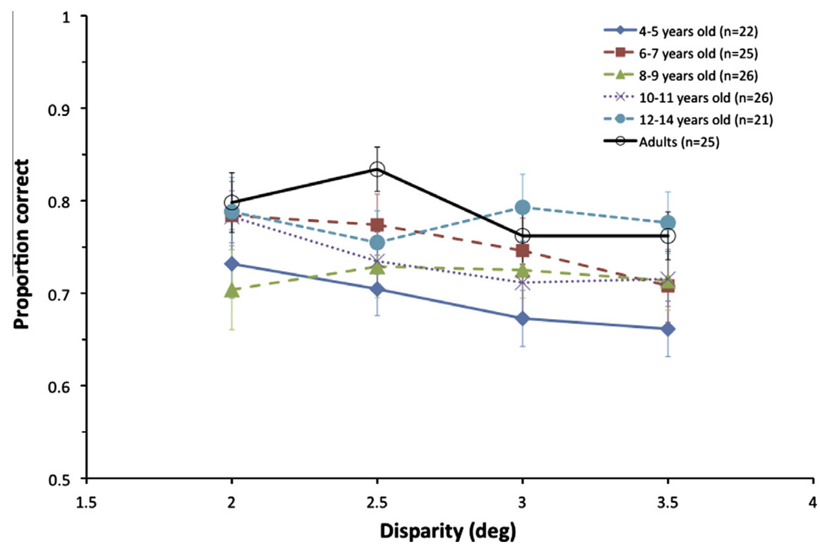

Fig. 4. Accuracy as a function of coarse disparities for the different age groups. Error bars represent the standard error of the mean. Each colour corresponds to a different age group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Immaturity ratios.

Group	Disparity									
	0.02	0.08	0.17	0.33	0.67	1.0	2.0	2.5	3.0	3.5
4–5	0.75	0.92	0.97	1.0	1.10	1.03	0.91	0.85	0.89	0.87
6–7	0.86	1.00	1.06	1.08	1.13	1.07	0.98	0.94	0.98	0.93
8–9	0.86	0.97	1.03	1.0	1.0	0.99	0.88	0.87	0.96	0.95
10–11	0.84	0.95	1.02	1.03	1.06	1.0	0.98	0.89	0.94	0.94
12–14	0.91	0.97	1.04	0.98	1.08	1.07	0.99	0.92	1.05	1.03

and children is well above chance levels. Therefore the similarity in performance across age groups cannot be explained by task difficulty (i.e. a floor effect). The decreased accuracy in the coarse range is probably due to the known degradation of depth information from disparities that appear diplopic (Ogle, 1952; Westheimer & Tanzman, 1956). This is consistent with our finding of a decrease in accuracy with increasing disparity for most age groups (Fig. 4).

4.1. Comparison with previous studies

Our finding that children were more accurate than adults at the larger disparities in the fused range (0.17–1.0 deg), although not statistically significant, is consistent with a previous study that reported faster reaction times in children compared to adults for identifying random-dot stereograms (Dowd et al., 1980). Dowd and colleagues attributed this age effect to differences in the size of Panum's fusional area. This interpretation is consistent with the results of our diplopia assessment (Fig. 2), but requires further investigation.

Most other studies of the development of stereopsis have measured stereoacuity, the smallest disparity that can reliably be discriminated, whereas here we used a suprathreshold accuracy task. Theoretically, given that even our smallest disparity is above traditional threshold estimates, one might expect that observers would perform near perfect within our fine range.[4] The reduced accuracy is probably due to the short viewing time (320 ms) and rapid pacing imposed by our computerized test versus the self-paced, unlimited viewing time of clinical tests such as the Randot tests. Instead, our results are consistent with a large number of studies that show that stereopsis for relatively small disparities is still immature at age 5 (Ciner et al., 1989; Cooper, Feldman, & Medlin, 1979; Fox, Patterson, & Francis, 1986; Heron et al., 1985; Leat et al., 2001; Romano, Romano, & Puklin, 1975; Simons, 1981; Tomac & Altay, 2000). The reported age at which performance on psychophysical tasks reaches adult levels for small disparities ranges from 6 to 9 years, and depends on the task and the stimulus used. A protracted developmental trajectory into adolescence has also been reported for other aspects of vision such as contour integration (Gervan, Berencsi, & Kovacs, 2011; Kaldy & Kovacs, 2003; Kovacs et al., 1999) and texture perception (Parrish et al., 2005).

An important difference between our experiment and the research cited above is that most studies have used random dot stereograms making it impossible to assess performance in the diplopic range. In such stimuli, the multiple false matches (available at disparities that would otherwise be outside the fusion range) provide solutions to the stereoscopic system at a fine scale. Therefore the coarse disparity detectors are not used. The percept of depth in such stimuli is not veridical, instead the random dot stereogram looks like a volume of elements at random depths.

While measures of stereoacuity cannot be directly compared with our suprathreshold task, they are not unrelated. That is, the majority of studies that assess the maturation of stereopsis report performance on their task or stimulus of choice over a range of ages and abilities. There is typically a criterion that is designated as the adult level for that task, for example 40 arcmin for the Randot stereotest (Romano, Romano, & Puklin, 1975). While the aim is to determine the age at which performance reliably reaches this criterion, most investigators also report the levels achieved prior to attaining adult performance. This information is potentially valuable because investigators rarely report that their young observers cannot do the task at all, just that they require very large disparities to perform the task. While stereoacuity thresholds improve with age, it appears that suprathreshold depth discrimination for large disparities is mature at an early age (at least by age 4 from our results). It will be necessary to test younger children with a modified methodology[5] to determine the developmental

[4] It is important to bear in mind that the scale of any given disparity should be considered in relation to the size (horizontal width) of the test stimulus. A relatively 'small' disparity applied to a narrow target may in fact be outside Panum's fusional area.

[5] The computerized task and methodology used here was designed specifically for children as young as 4 years, but is not suitable for testing younger ages.

time course and to test the hypothesis that the early development of a coarse stereoscopic signal may provide depth information until high-resolution information is available (Simons, 1993).

4.2. Fine versus coarse stereopsis

There has been debate in the literature as to whether fine and coarse stereoscopic processing fall along a continuum, or reflect the operation of two distinct mechanisms. Some authors have supported the presence of a continuum of essentially identical disparity detectors that process the full range of fine to coarse disparities (Ogle, 1953; Richards & Kaye, 1974). However, this work can be interpreted differently, and is also consistent with a large body of work suggesting that there are two distinct populations involved (Hess & Wilcox, 1994; Mitchell, 1969; Ogle, 1953; Schor & Wood, 1983). For example, Jones (1977) provided strong support for a distinct coarse disparity mechanism when he showed that observers with substantial deficits in processing large disparities typically performed at normal levels when presented with small depth offsets.

More recent psychophysical studies also provide compelling evidence for a disparity mechanism that is selective for coarse disparities (Hess & Wilcox, 1994, 2008; Kovacs & Feher, 1997; Langley, Fleet, & Hibbard, 1999; Lin & Wilson, 1995; McKee, Verghese, & Farell, 2004; Sato & Nishida, 1994; Schor, Edwards, & Sato, 2001; Wilcox, 1999; Wilcox & Hess, 1995, 1996, 1997, 1998). These studies typically present very different stimuli to each eye, forcing the visual system to extract a disparity signal from either the contrast envelope or the overall area of the stimulus, and to ignore the interior detail. The work of Wilcox and Hess (1996, 1997, 1998) and of McKee, Verghese, and Farell (2004, 2005) supports the proposal that these two systems operate in a synergistic manner in adults. The fine system is used when the binocular correspondance is unambiguous, while the coarse system serves as a type of back-up mechanism which is relied upon when the images in the two eyes have different luminance, are ambiguous (e.g. repetitive bars), or are presented at disparities that are beyond the fusion limit.

While not a test of this dissociation, our experiments are generally consistent with it, in that within the diplopic range performance is the same across all ages suggesting that coarse stereopsis matures before 4 years of age. However fine stereopsis continues to develop into the school-age years, at least at the finest disparity we tested.

4.3. Neural correlates

Studies of macaque neurophysiology (Uka & DeAngelis, 2006) and functional magnetic resonance imaging in humans (Neri, Bridge, & Heeger, 2004) have implicated the dorsal visual stream, specifically MT/hMT+ as part of the neural substrate underlying coarse disparity processing. The ventral visual stream may be more important for fine disparity processing (reviewed in Roe et al., 2007; Schiller, Logothetis, & Charles, 1990) though additional study is required to rule out variables such as task complexity and noise sensitivity. Kovacs (2000) attributed the protracted development of contour integration to the slower development of the ventral visual stream relative to the dorsal stream. The later maturation of fine stereopsis relative to coarse in the current study is consistent with this dichotomy.

Whether or not our data reflect a mechanistic dichotomy or the gradual development of a single neural substrate, it is important to recognize the presence and potential utility of these large disparity detectors in young children. This is particularly relevant to visual disorders such as amblyopia where the degree of binocularity is an indicator of treatment success (McKee, Levi, & Movshon, 2003), but conventional clinical tests of stereopsis focus on relatively small disparities and stereoacuity. The inclusion of large (even diplopic) disparities may provide a more complete picture of a patient's binocular status, and improve the clinician's ability to assess their suitability for treatment.

5. Conclusion

Performance on our computerized test of stereopsis was similar to that of adults at the youngest age tested (4 years) for large disparities that produce double vision. Performance for smaller disparities within the fusable range was poorer than that of adults even at 14 years of age.

Acknowledgments

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