

Maturation of the sensitivity for luminance and contrast modulated patterns during development of normal and pathological human children [☆]

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Abstract

Any object may contain at least two spatio-temporal components referred to as first- and second-order, respectively, defined by spatial-temporal luminance modulation or by contrast, texture or depth modulation. This study investigates form sensitivity of infants, normals, premature or strabismic. A two-alternative forced-choice preferential looking procedure was used in monocular and binocular condition. Maturation profile for both stimuli was similar in the control group. Strabismic infants showed a vertical offset in maturation, which affected the second-order more severely. The pre-term group showed a lag of second-order sensitivity. Our results underline differences between first- and second-order processing.

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1. Introduction

The visual system is a network of components devoted to the capture of individual elements of the scene. Serial and parallel interwoven channels work to extract size, location, orientation, form, contrast and chromatic content, and several types of motion (Livingstone & Hubel, 1987).

First-order form perception is defined by spatio-temporal luminance variations in the retinal image, while second-

order form perception is defined by variations in stimulus properties such as contrast, texture or depth (Cavanah & Mather, 1989; Chubb & Sperling, 1988). Second-order information is not readily visible in the Fourier domain and is therefore considered higher level or more complex given the additional computational load (Faubert, 2002).

In regards to motion perception, some psychophysical and physiological evidence suggests the existence of multiple processing channels for first- and second-order information. Nishida, Edwards, and Sato (1997) reported that adaptation to one kind of stimulus does not affect the threshold of the other. Some fMRI studies in humans (Smith, Greenlee, Singh, Kraemer, & Hennig, 1998; Smith & Ledgeway, 1997) report a strong activation of area V5 (MT) by the two types of stimuli tested but claim that the level of activation of other cortical areas allows differentiation of first- and second-order processing. Indeed, activation of areas V3 and VP was significantly higher

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for second-order than for first-order stimuli and this activation was related to motion perception. Accordingly, first-order motion activation appears first in V1, while second-order activation spreads later to V3 and VP, via V1, and both eventually converge in V5 (MT). In contrast, some fMRI (Nishida, Sasaki, Murakami, Watanabe, & Tootell, 2003; Seiffert, Somers, Dale, & Tootell, 2003) studies did not find activation differences between the two types of stimuli and pointed out that the direction of second-order motion is coded as early as V1. Clifford, Freedman, and Vaina (1998) and Clifford and Vaina (1999) have proposed a computational model in which two parallel channels are geared toward the perception of, respectively, first- and second-order motion. In this model, the first-order pathway is not sensitive to second-order motion, while the reverse is possible. This hypothesis is supported by some clinical observations describing specific alteration of second-order motion perception (Vaina & Cowey, 1996; Vaina, Makris, Kennedy, & Cowey, 1998). However, the same authors also observed patients who were insensitive to first-order motion while second-order motion sensitivity was spared.

While most studies tend to identify different pathways for the processing of these two types of motion perceptions, several investigations support the assumption of a single system, relying on a gradient-based analysis that displays the same pattern of activation (Benton, 2002; Dupont, Sary, Peuskens, & Orban, 2003). A detailed account of the different models of first- and second-order processing is included in Zanker and Burns (2001). In the context of form perception, recent studies on first- and second-order defined orientations support the notion that these textures are initially processed by separate mechanisms but that they probably share common mechanisms once the spatial configuration of the elements have been extracted from the image (post-rectification) (Allard & Faubert, 2006).

Motion sensitivity is one of the first visual functions to appear after birth and plays a fundamental role during visual development (Horridge, 1984). Newborns are able to track a target moving slowly and demonstrate a behavioural preference for dynamic stimuli (Regal, 1981). Discrimination of motion direction for more complex stimuli is only coded after two months of age and this sensitivity, restricted to a rather limited range of velocities, expands during development (Wattam-Bell, 1992, 1996). Some studies have dealt with the development of simple and complex motion sensitivity. Atkinson, Braddick, and Wattam-Bell (1993) reported that infants (between 8 and 20 weeks) are sensitive to first- and second-order stimuli, with a preference for the first-order. They did not show any variation of sensitivity between 8 and 20 weeks of age for a given amplitude of modulation of the stimulus. In a more recent study, Ellemberg et al. (2003) showed that motion sensitivity thresholds of 5-year-old children are significantly worse than those of adults. The difference is small for first-order stimuli and remains constant at the two velocities tested, 1.5 deg s^{-1} and 6 deg s^{-1} . However, the difference for second-order motion is much larger and is

increased by nearly an order of magnitude for the highest velocity.

Aging is another circumstance differentially affecting contrast thresholds for first- and second-order stimuli. In elderly persons, a greater elevation for the perception of second-order is observed as compared to the perception of first-order stimuli (Habak & Faubert, 2000). The authors suggest that age-related decline in sensitivity would be more prominent in complex environments regardless of whether they are static or dynamic (texture and motion, respectively).

The goal of the present study was to extend these results to different groups of infants and children to study the development of the sensitivity to these types of stimuli and to test the hypothesis that a visual disorder affecting binocularity, a prerequisite for optimal spatial perception, may specifically affect the mechanisms responsible for processing complex stimuli.

The normal development of the visual cortex is largely dependent on visual experience and eye alignment. Strabismus is a visual disorder characterised by ocular misalignment and usually leading to disruption of ocular dominance columns and to reduced vision in one eye, called amblyopia, if not properly treated. If binocular coordination is present from birth, binocular function may be demonstrated by evoked potential studies as early as 2 months of age (Atkinson & Braddick, 1981) and behaviourally at 4 months of age (Birch & Held, 1983). In comparison, spatial resolution increases steadily from birth to 2 years of age, and then asymptotes near the end of the first decade. A period of sensitivity to deprivation or any kind of optical or alignment disorder extends from about 6 months (Mohindra, Jacobson, Thomas, & Held, 1979; Vital-Durand, 1992) to a peak between 1 and 2 years and a recess after 5 years. During this critical period, the development of binocular depth perception relies on the availability of a retinal disparity signal whose cortical processing also depends on proprioceptive signals generated by the extraocular muscles (Buisseret, 1995).

Independently of amblyopia, several visual functions are affected by strabismus, including motion processing (Tychsen & Lisberger, 1986) and a recent study by Simmers taking into account the deficit in contrast sensitivity function in amblyope observers (Simmers, Ledgeway, Hess, & McGraw, 2003). The deficits are attributed to the extrastriate cortex and in particular to the dorsal pathway. As a consequence, strabismic observers are inaccurate when pointing to a target (Fronius & Sireteanu, 1994). Further, to investigate the extent to which a disorder of binocular function may affect second-order perception, Wong, Levi, and McGraw (2001) studied adult human amblyopes. They found that perception of a second-order static signal was more vulnerable as compared to first-order.

On this ground, we hypothesize that normal binocular vision is a prerequisite to develop optimal second-order processing. Once established, monocular viewing should not affect the performance of the subject. In the strabismic

patient, the sensitivity to second-order information should not be optimally developed, and should show an identical poor response in monocular and binocular condition. Therefore, we investigated if early deprivation of binocular vision impairs the development of second-order perception.

We also included a group of pre-term infants because this group is at risk of presenting various kinds of dysfunctions affecting the visual system, especially in very low birth weight and/or very pre-term birth (Hermans, Van Hof-Van Duin, & Oudesluys-Murphy, 1994; Pott, Van Hof-van Duin, Heersema, Fetter, & Schreuder, 1995; Van Hof-Van Duin & Evenhuis-van Leunen, 1989), as it is known that pre-term children present an increased risk of impairment on complex task processing such as reading or attentional performances.

2. Methods

2.1. Stimuli

Stimuli were generated by a Macintosh Power G4 by means of Vpixx® software (www.vpixx.com), like those introduced by Ledgeway and Smith (1994). First-order luminance artefacts were controlled with careful calibration and by using a stimulus with a carrier composed of small noises elements. They were displayed on a 21-in. monitor (832 × 624 pixels, 75 Hz refresh rate, internal correction routines from Vpixx including gamma correction). The carrier is maintained constant at a certain contrast value (50% of max) and the envelope is manipulated.

First-order stimulus. (Fig. 1a) consisted of luminance-defined, 0.5 c/deg vertical sine-wave grating (envelope) modulating static grey-scale noise (carrier), where the envelope and the noise carrier were added. The amplitude of the horizontal luminance modulation (Michelson contrast) was defined as:

$$\text{Luminance modulation depth} = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min}),$$

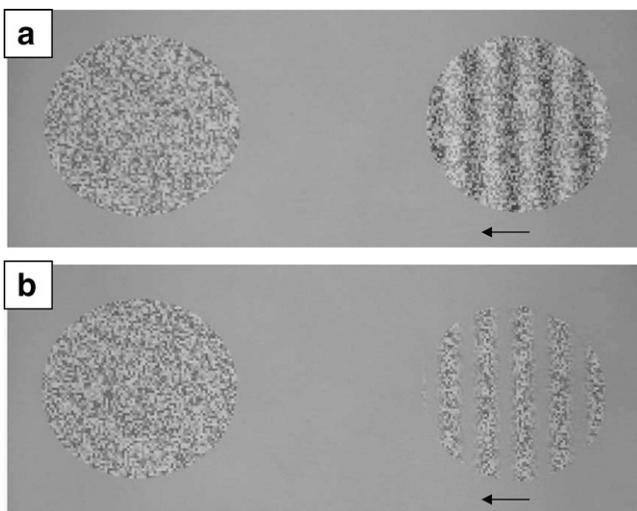


Fig. 1. Schematic representation of the stimuli presented to the observers. (a) The display for the first-order test. The first-order stimulus, luminance defined, is located on the right and the equivalent noise is on the left side. (b) The display for the second-order test. The second-order stimulus, texture defined, is located on the right and the equivalent noise is on the left.

where L_{\max} and L_{\min} are the maximum and minimum average of local luminance in the pattern. The luminance modulation was varied in steps of 25%, 12.5%, 6.25%, 3.12% and 1.56% (constant stimuli presentations).

Second-order stimulus (Fig. 1b) was created by multiplying the same noise carrier with the vertical sinusoidal grating of 0.5 c/deg. This produced a horizontal sinusoidal modulation of the contrast of the noise carrier. The modulation depth of the pattern’s contrast was defined as:

$$\text{Contrast modulation depth} = (C_{\max} - C_{\min}) / (C_{\max} + C_{\min}),$$

where C_{\max} and C_{\min} are the maximum and minimum average of local contrasts. The amplitude of the modulating sine-wave was varied in steps of 100%, 50%, 25% and 12.5%.

Two blocks of 20 trials each were prepared for first- and second-order stimuli. In each block, 4 (or 5) levels of luminance or contrast modulation were presented in a pseudo-random order. On each trial, two circular windows of 10 deg (degree) diameter, separated by 20 deg, appeared on a grey background. The mean luminance of the display was 30 cd m⁻² ($u' = 0.1883$, $v' = 0.4451$ in CIE color space), where L_{\min} and L_{\max} were 15 and 45 cd m⁻², respectively.

One window of the screen displays the dynamic stimulus (target), randomly located on the right or the left and an equivalent static noise is located in the opposite window. All noise elements were 3 × 3 pixels (approximately 4.17 cpd), which should be easily resolved by all infants even with low acuity. Each type of motion was presented with a temporal frequency of 2 Hz in the right or left motion direction.

2.2. Observers

A total of 182 infants and children observers (8 months to 7 years of age) were recruited with their parent’s informed consent. Most of them (162) attended the “Bébé Vision” unit of Lyon-Sud Hospital and underwent a complete ocular and visual assessment: binocular and monocular visual resolution tested by acuity cards or optotype for the older, static and dynamic ocular alignment tested by cover test, Hirschberg corneal reflex, ocular mobility, punctum proximum of convergence, smooth visual pursuit, stereoscopy tested by randot test, angle of deviation, cycloplegic refraction and fundus examination.

The observers are distributed as shown in Fig. 2, which shows that the groups are not age-matched:

Extra-clinical group. Twenty normal control individuals were recruited among friends and relatives of the main experimenter to be tested in a specially devoted room in a private home in order to determine the relationship between age and motion sensitivity. The best possible reference data

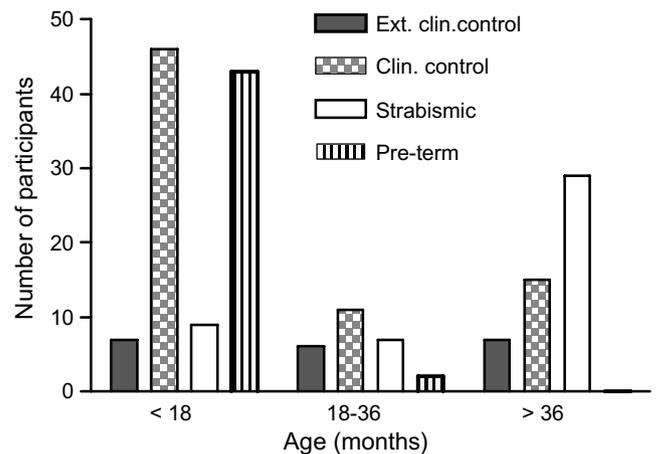


Fig. 2. Age distribution of the observer groups (Extra-clinical controls, clinical controls, strabismics and pre-terms). This graph shows that subjects of the Extra-clinical group were equally distributed in age, clinical controls and pre-terms were more numerous in lower ages and strabismics were rather older ages.

were expected from infants devoid of known risk of visual disorder who could, in addition, be tested in a familiar environment without time pressure. They were tested in binocular and each monocular condition. These observers did not undergo a thorough ocular and visual check-up, but they had no known history of visual disturbance and responded positively to the random dot stereoscopy test.

Clinical group. Seventy-two normal control children had their vision assessed as described above at the B  b   Vision clinic. Although they attended the clinic for alleged risk of visual disorder, they performed correctly on all tests including stereoscopy. Because of time pressure in the clinical set-up, they participated to the study only in the binocular condition.

Strabismic group. Forty-five strabismic observers (10 months to 7 years of age) affected by infantile esotropia (30), exotropia (2) and intermittent strabismus (13). Inclusion criteria included lack of stereoscopic vision. Their visual resolution in the non-deviating eye was within normal limits. Visual resolution in the deviating eye was also within normal limits for 40 observers. Five observers presented with amblyopia, defined as difference of resolution acuity of at least 2/3 of an octave between the two eyes. This small prevalence of amblyopia is explained by the fact that most esotropes were under treatment, or had been treated by patching. Thirty-two cases strabismic observers wore optical correction. Viewing of the motion test was binocular.

Pre-term group. Forty-five observers (8–24 months of age), born 24–35 weeks post-conception (580–2330 g), devoid of ocular or neurological history or heredity (Fig. 3). They had normal binocular and monocular visual resolution, and performed normally on random dot stereoscopic test. Testing was only binocular, and we used conceptional age for analysis.

Adult group. Sixteen adults observers (46.25-year-old \pm 3.25) were tested in the same condition. All had normal visual resolution and were devoid of ocular or neurological history. Viewing of the motion test was binocular.

This research adhered to the tenets of the Declaration of Helsinki.

2.3. Procedures

Children were tested using a two-alternative forced-choice preferential looking procedure (Fantz, Ordy, & Udelf, 1962; Teller, 1979) similar to the procedure used to test visual resolution (Vital-Durand, 1992; Vital-Durand & Ayzac, 1996) and chromatic sensitivity (Knoblauch, Vital-Durand, & Barbur, 2001). Infants were seated on their parent's lap, in a dimly lit room. The participant had a binocular view of the screen, which was approximately 57 cm from the screen. The experimenter viewed the child's eyes from behind the screen so that the display was not visible to him. The experimenter judged the location of the target stimulus (left or right side of

the screen) based on the infant's eye gaze. The data were recorded by the experimenter on the computer, trial after trial, without limitation of response time. A typical trial would last approximately 10 s.

Contrast modulation thresholds were measured for the two types of stimuli. The threshold is defined as the minimum contrast necessary (75% correct response criterion) to perceive a moving stimulus and it was calculated based on this following logistic function:

$$F(c) = \frac{1}{2}(c^\beta / (\alpha^\beta + c^\beta)) + \frac{1}{2},$$

where c is the contrast or luminance level, β is the slope and α the threshold at 75% of correct responses.

The statistical analysis was performed on each group as a whole. It did not consider that the groups were not strictly age-matched. An analysis of covariance was performed in which linear and quadratic terms were fit to the threshold (of first- and second-order, or monocular and binocular or controls and strabismics or pre-term) as a function of age. Comparisons of fits with the same or different terms were used to describe the data. Non-linear regression (polynomial second-order) was performed and $p < .05$ was considered statistically significant.

3. Results

3.1. Feasibility of the method

All 20 normal observers of the extra-clinical group tested in optimal conditions performed first- and second-order tests in binocular and monocular conditions. In the clinical condition, some children performed only the first-order test (28% of the 72 controls, 11% of the 45 strabismics, 14% of the 45 pre-terms), and some performed the second-order test only (9% of the controls, 11% of the strabismics, 18% of the pre-terms). So, the majority performed both tests (58% of the controls, 73% of the strabismics, 46% of the pre-terms). No data could be obtained from some infants who gave no reliable response for either stimulus even at maximum contrast (5% for the controls, 5% for the strabismics, 22% for the pre-terms).

T-test comparison of the control group thresholds obtained in optimal ($N = 20$) and clinical conditions ($N = 72$) did not show a significant difference ($p > .05$).

3.2. Normal development of first- and second-order perception

Fig. 4 shows the logarithm of the modulation depth thresholds for first- and second-order stimuli as a function of age (months) in a series of 20 control subjects from the "extra-clinical" group who could be tested monocularly and binocularly in optimal conditions. The results demonstrate that the decline of modulation depth threshold is correlated with the age of the observers. The data illustrate the improvement of sensitivity with increasing age. Comparison of monocular and binocular motion perception was performed and the results (ANCOVA) show no significant difference between first-order ($p > .05$), and second-order conditions ($p > .05$).

Contrast modulation thresholds for first- and second-order stimuli as a function of age was tested binocularly in the clinical group of 72 infants and children who were tested in the hospital. The results are compared to the mean

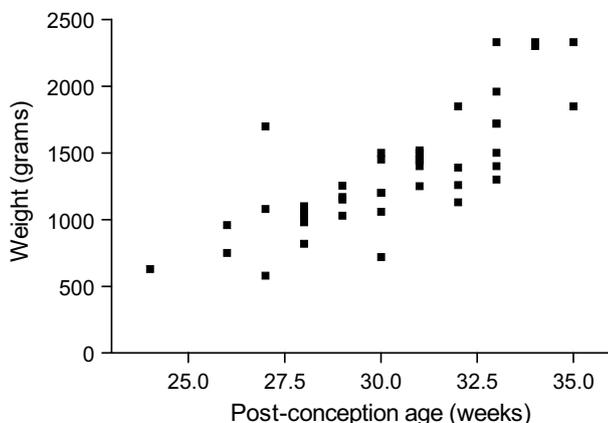


Fig. 3. Distribution of the pre-term population as function of post-conceptional age.

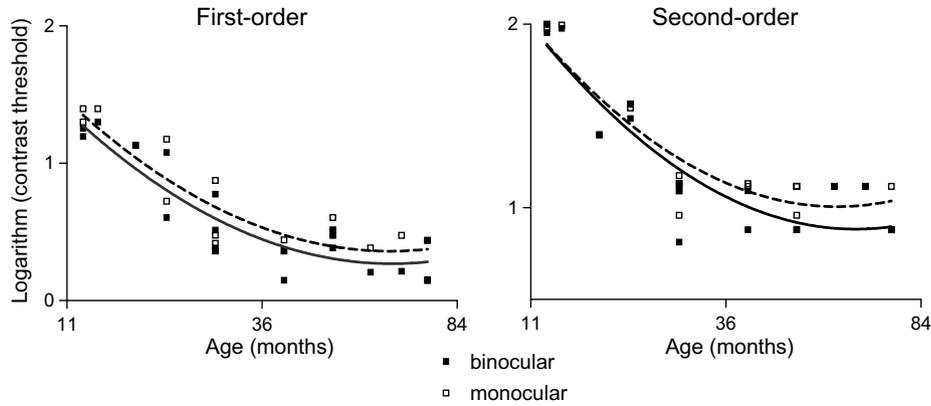


Fig. 4. Contrast modulation thresholds (transformed to base 10 logarithm value) for first- and second-order motion as a function of age, and binocular (■) or monocular (□) condition for the Extra-clinical control group (20 subjects). The polynomial regression lines are continuous for the binocular condition and dotted for the monocular condition.

adult threshold (Fig. 5) and show the same tendency toward adult values. An analysis of covariance was performed in which linear and quadratic terms were fit to the threshold as a function of age. Comparisons of fits with the same or different terms were used to describe the data. It demonstrates that the decline of modulation depth threshold with age shows the same trend.

The linear and quadratic coefficients were not significantly different ($p = .751$) and only the intercepts differ ($p < .0001$). This difference of intercept indicates a difference in sensitivity to the two types of stimuli and corresponds to a difference of 0.873 (nearly a factor of 8).

The interindividual spread of the data diminishes with age (<12 months to >48 months) for the first-order stimuli ($SD\ 6.5 \rightarrow .9$), and for the second-order ($SD\ 29.98 \rightarrow 4.53$). These results show that, although individual profiles were not exactly similar, the course of the maturation of the two stimuli appears parallel.

3.3. Development of first- and second-order sensitivity in the strabismic group

The modulation depth thresholds of strabismics and control observers are compared in Fig. 6. All regression

lines show a decline of the thresholds with increasing age, but sensitivity for first-order stimuli in the two groups differs significantly with $F(1, 56) = 5.38, p < .05$. Threshold for second-order motion between the two groups also differs ($F(1, 55) = 12.84, p < .001$). Although, thresholds from strabismic observers get closer to the normal value with increasing age, they remain higher than those from controls by the end of the age range.

Thus, processing of first-order stimuli is marginally affected by ocular misalignment, whereas processing of the second-order stimuli is more obviously impaired.

3.4. Prematurity and first- and second-order perception

Contrast modulation thresholds of control and pre-term infant groups have been compared for the two types of stimuli (Fig. 7). The fitted lines were not significantly different.

Indeed, comparison of the modulation depth fitted lines between the premature ($N = 45$) and clinical normal controls younger than 24 months ($N = 50$) does not show any significant differences for the perception of first-order stimuli, $F(1, 77) = 0.223, p = .637$, but a significant difference is observed for second-order stimuli, $F(1, 60) = 5.156,$

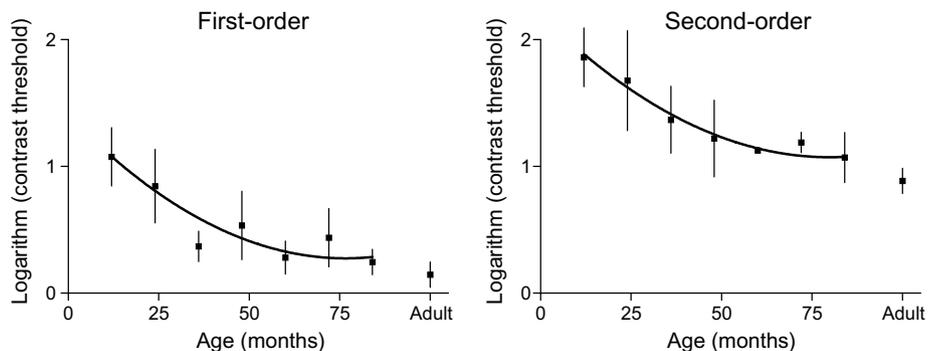


Fig. 5. Contrast modulation thresholds (transformed to base 10 logarithm value) for first- and second-order motion as a function of age, for the clinical group ($N = 72$). Polynomial regression line is performed on individual data points. The graph shows the means of the individual data points by age group with standard deviation.

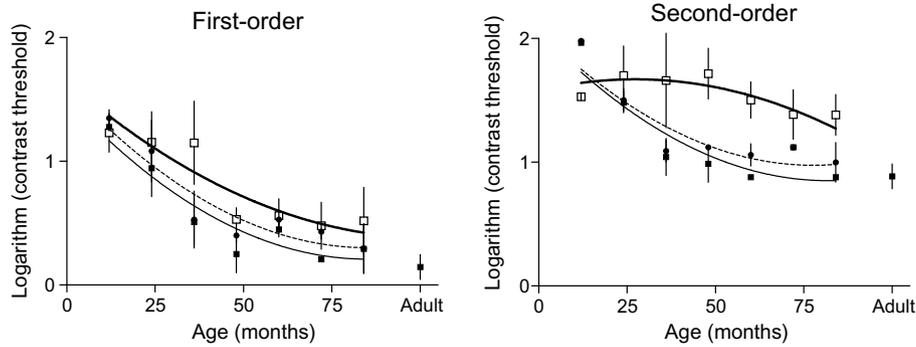


Fig. 6. Contrast thresholds for first- and second-order motion as a function of age for the strabismic group (□ and large solid line) in comparison with the control clinical group (■ and small solid line for binocular condition, ● and dotted line for monocular condition). Polynomial regression line is performed on individual data points. The graph shows the means of the individual data points by age group with standard deviation.

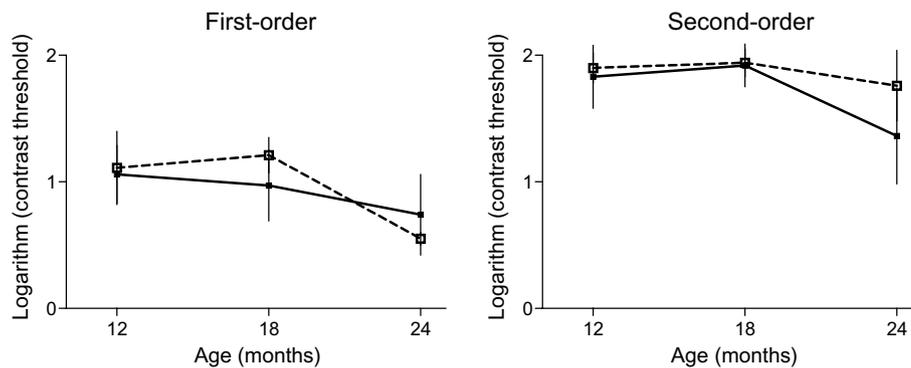


Fig. 7. Contrast modulation thresholds for first- and second-order motion as a function of corrected age for the pre-term group in comparison with the control clinical group ($N = 50$). The continuous lines correspond to the control group and the dotted lines to pre-term group. The graph shows the means of the individual data point by age group with standard deviation. The data from the control group are the same than those presented in Fig. 5. Because of a zoom effect due to restricted age range, the curve appears slightly bended rather than nearly linear.

$p < .05$. As demonstrated in the figure, the significance essentially comes from the later age levels.

This finding indicates that the control group and the group of premature infants corrected for gestational age do not reach similar threshold values for first- and second-order stimuli until about 18 months of age. At higher ages, the threshold of the premature group does not show the significant decrease observed in the control group for the second-order stimulus. This pre-term group presented the same spread of interindividual differences as the clinical control group (SD 7.9 and 6.8, respectively, for first-order and 21.56 and 34.05, respectively, for second-order).

4. Discussion

Experimentation with young infants and children is difficult for at least two reasons: (1) the attention span is short and difficult to maintain during the two consecutive tests (first- and second-order). It has been suggested that perception of complex stimuli requires a greater attentional load (Lu, Liu, & Doshier, 2000), a suggestion which could be interpreted as requiring more processing to extract a less salient stimulus, (2) with pre-verbal children, the judgement

of preference was less obvious because they tend to switch between the two stimuli and the responses were less clear-cut. In fact, there is some discussion about the contribution of alert attention in the processing of motion, which could rely largely on low-level processing (Thiele, Rezec, & Dobkins, 2002). Most children were cooperative during the study, although we observed large individual variability. This limitation has often been pointed out (Zanker & Mohn, 1993) stressing that, when no preference is expressed due to procedural and technical limitations, it can either mean that the stimulus is not salient to the point that it triggers a behavioural response or that the observer is not able to read the responses.

The results of our study suggest that, in the sample of the infants tested, the maturation of the sensitivity improves with increase age. Possible explanations for immature form processing can be related to any of five stages of the visual pathways: retinal immaturity of the fovea (Yuodelis & Hendrickson, 1986), progressive myelination of the neuronal pathways projecting to the lateral geniculate body and to the visual cortex and from area V1 to extrastriate areas and finally immaturity of the synaptic relays between cortical areas. On the opposite, the

pathways involved in the oculomotor response are fairly mature in our age range (Aslin, 1981; Harris, 1993).

The large variability of thresholds observed in all groups tested is a common constraint of infant studies and is more prominent when testing less visible second-order stimuli. A higher threshold could be genuine or result from an inappropriate judgment of the experimenter if the head of the observer is not straight ahead. This is sometimes the case as infants often detect the stimuli with their peripheral vision, which happens to be very sensitive to motion early on (Wattam-Bell, 1996). Lower thresholds could be due to early maturation of some individuals, in terms of neuronal characteristics or attentional capacities. Interindividual variations could also be due to specific constraints at the time of testing. In order to control this point, we had an opportunity to retest two strabismic infants and two control children at 3 weeks interval and the data did not vary significantly between sessions. In a related domain, Fraser and Wilcox (1979) described large, stable differences in adult observers' ability to see illusory motion. It has been proposed that perception of second-order stimuli requires more focused attention as compared to first-order (Ashida, Seiffer, & Osaka, 2001; Lu et al., 2000).

From the graph published by Ellemberg et al. (2003) it appears that the mean threshold of the log depth modulation of 5-year-old children is about 0.04 for first-order stimuli and 0.2 for the second-order stimuli. The two stimulus velocities tested were 1.5 and 6 deg s⁻¹. Our data were obtained at a velocity of 2 Hz (4 deg s⁻¹). We compared our own data with the interpolation of Ellemberg et al. data. Comparing values, our own data set the log contrast threshold at 0.4 for first-order and 1.12 for second-order. We have no explanation for this scaling discrepancy. However, in Ellemberg et al. experimental condition, the children were asked to indicate if the stimulus was moving up or down. They were specifically tested on motion detection. In comparison our experimental condition used a form in motion in competition with a stable noise. As a consequence we cannot determine that the babies responded to motion rather than to the form, although they probably responded to both, as motion cannot be perceived without the form extraction. In addition, it is known that babies respond better to moving things. Of course it cannot be compared to data of young children like the Ellemberg study where the subjects were asked to indicate the direction of the stimulus. In fact better comparisons are with studies using similar stimuli in both static and dynamic conditions with young normal and autistic subjects (Bertone, Mottron, Jelenic, & Faubert, 2003) and fragile × kids (Kogan et al., 2004). What transpires from these studies and one with aging (Habak & Faubert, 2000) is that both the static and dynamic thresholds show a difference of about 1 log unit between first- and second-order processes. These data in normals (Bertone & Faubert, 2003) and a recent ideal observer modeling of the internal equivalent noise and calculation efficiency of first- versus second-order processes (Allard & Faubert, 2006)

demonstrate that the main difference between these classes of stimuli is the rectification process. Therefore, the emphasis of this paper concerns the development of the second-order (rectification) process (not static versus dynamic). The argument for using motion is one of greater responsiveness of the babies.

Most previous findings fit with the existence of two different pathways for the processing of first- and second-order motion, and this segregation is supported by the architecture of connectivity among the cortical areas for both motion (Clifford et al., 1998; Clifford & Vaina, 1999; Smith & Ledgeway, 1997; Smith et al., 1998; Vaina & Cowey, 1996; Vaina et al., 1998) and orientation perception (Allard & Faubert, 2006; Schofield & Georgeson, 1999). In contrast, Benton (2002) favours a single gradient-based processing at least for motion systems. Our study shows that, although maturation of the first-order processing seems to follow the same developmental profile as the second-order, the threshold for second-order is systematically higher compared to that of the first-order, as it is also observed with adult data. This finding does not necessarily support the existence of two separate mechanisms in the perception of simple and complex motion, but indicates that second-order processing has specific requirements. To help unconfound this, we studied strabismic children, as a condition that affects at least one of the spatial components of vision, stereoscopy. We show that misalignment of the visual axes in the strabismic group goes along with an impaired sensitivity to complex form perception in contrast with the normal group who showed no difference between binocular and monocular conditions. Comparison of the performance of the control infants in the monocular condition to the performance of the strabismic group shows a significant difference that cannot be attributed to an attentional deficit, which has never been suspected in strabismic patients. It implies that binocular vision is associated with the development of first as well as second-order sensitivity even in the monocular condition of testing. This difference is more marked for second-order motion all along childhood. This result means that optimal perception of second-order motion depends on intact early binocular input during development, hence normal binocular neurons. These neurons could well be a common relay shared by the two functions. We speculate that the deficit observed in second-order perception in the strabismic group is a consequence of the deficit of binocular input affecting second-order specific neurons.

In summary, our results show that the developmental profile of thresholds for first- and second-order processing are parallel, and that there is no obvious difference between monocular and binocular viewing in normal observers. The parallelism of the development of first- and second-order sensitivities suggests that they are limited by a common critical factor. In the strabismic group, second-order sensitivity is more altered than first-order. This implies some contribution of stereopsis to second-order sensitivity, which could be independent of first-order processing.

Premature infants without incidental pathology and corrected for gestational age follow a normal developmental course of sensitivity for first-order processing but a lag is observed for second-order processing. Prematurity by itself seems to selectively affect complex processing but no other visual capacities. In any case, it implies that the early visual experience of the premature infants is not beneficial nor fostering their visual development.

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