Graefes Arch Clin Exp Ophthalmol (2008) 246:1–7
DOI 10.1007/s00417-007-0632-3

CLINICAL INVESTIGATION

Performance of a new, 3D-monitor based random-dot stereotest for children under 4 years of age

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Received: 1 November 2006 / Accepted: 14 June 2007 / Published online: 3 August 2007

Abstract
Background The aim of this study was to determine the performance of a new, 3D-monitor based, objective stereotest in children under the age of four.
Methods Random-dot circles (diameter 10 cm, crossed, disparity of 0.34°) randomly changing their position were presented on an 3D-monitor while eye movements were monitored by infrared photo-oculography. If ≥3 consecutive stimuli were seen, a positive response was assumed. One hundred thirty-four normal children aged 2 months to 4 years (average 17±15.3 months) were examined.
Results Below the age of 12 months, we were not able to obtain a response to the 3D stimulus. For older children the following rates of positive responses were found: 12–18 months 25%, 18–24 months 10%, 24–30 months 16%, 30–36 months 57%, 36–42 months 100%, and 42–48 months 91%. Multiple linear logistic regression showed a significant influence on stimulus recognition of the explanatory variables age ($p<0.00001$) and child cooperation ($p<0.001$), but not of gender ($p>0.1$).
Conclusions This 3D-monitor based stereotest allows an objective measurement of random-dot stereopsis in younger children. It might open new ways to screen children for visual abnormalities and to study the development of stereovision. However, the current experimental setting does not allow determining random-dot stereopsis in children younger than 12 months.

Keywords Binocular vision · Depth perception · Spatial vision · Stereopsis

This study was sponsored by OPOS-Foundation, St. Gallen.

The authors have no financial interest concerning this study.

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Introduction

Several psychophysical and electrophysiological stereotests have been reported for infants [1–5, 11, 15]. They allow study of the development of stereopsis and the sensory outcomes following the treatment of ophthalmopediatric disorders [10, 13, 18]. Many of these tests use random-dot stereo stimuli because they convey no visual information other than random noise, if seen monocularly. However, if binocularly fused, vivid depth perceptions occur. This lack of monocular cues makes this type of stereogram ideal for stereovision testing. The most frequently used random-dot tests for clinical routine testing include the TNO test, the Lang I and II tests, and the Radom-dot E test [14]. All these clinical tests need verbal capabilities of the subject tested. Tests which can be used for preverbal children are the infant random dot stereoacuity cards [5], random-dot stereogram evoked potentials, and random-dot correlogram evoked potentials [12, 15]. Infant random dot stereoacuity cards may be difficult to use because of the need for polarizing glasses. The procedure is based on a two-alternate forced-choice paradigm. Random-dot stereogram and correlogram evoked potentials represent objective testing procedures [12, 15]. However, their use is limited because of the need for dissociating glasses and because the response recording is technically difficult and excellent child cooperation is needed.

In order to detect failures early in infancy in the development of the visual system, it would be desirable to have an appropriate objective test for random-dot stereopsis.

Such a test would be helpful for screening of visual dysfunctions in young children and to study the development of stereovision. Over the past 4 years, such an examination technique has been developed in our Laboratory for Experimental Oculography. The test is based on two components. A 3D monitor is used for the random-dot stimulus presentation, allowing natural viewing conditions because no dissociating glasses are needed. An infrared video-based oculography system is used for the objective assessment of stimulus recognition by monitoring the eye movements.

In two previous studies, which mainly included older children with an average age of about 5 years, we were able to show that the new test is able to objectively measure random-dot stereopsis [6, 7].

The aim of this study was to evaluate the performance of the test in children younger than 4 years.

Subjects and methods

This research followed the tenets of the Declaration of Helsinki and was approved by the Ethical Committee of Kantonsspital St. Gallen. Written informed consent was obtained for all children. One hundred thirty-four children were tested with the new method based on a random-dot stimulus presentation with an autostereoscopic monitor and a response measurement by infrared photo-oculography.

Subjects Healthy children were recruited by offering a free eye examination through the Dept. of Neuro-Ophthalmology and Strabismology, the Dept. for Obstetrics and Gynecology, the paediatric hospital of Kantonsspital St. Gallen, and paediatric private practices in the region of St. Gallen. All children had an orthoptic examination including the Hirschberg ocular alignment test, cover test, four-prism diopter base out fusion test, and pupillary reaction. Visual acuity was usually measured with LH-symbols in each eye and had to be at least 20/40. In older children, as soon as testing was possible, Landolt-rings were used. With Landolt-rings visual acuity had to be at least 20/30. In babies and young toddlers visual acuity was measured with two-alternate forced choice preferential-looking gratings and for each eye had to be within the 95% age-corrected confidence intervals as soon as possible. Stereovision was assessed with the Lang I stereotest. Children with abnormal findings were excluded from this study. The following were regarded as abnormal findings: visual acuities in one or both eyes below the limits mentioned above, manifest or intermittent strabismus, abnormal direct or indirect pupillary reactions, no reaction to the Lang I figures for ages >18 months, and anterior chamber or fundus abnormalities. Only children with abnormal findings had cycloplegic refraction; in all other children no objective refraction was performed. Infants were examined in Prechtl’s [16] state III (calm wakefulness with open eyes, regular breathing, absence of gross body movements), because more reliable results are obtained from infants in this behavioural state. In total, 134 normal children (average age 17±15.3 months, age range 2 months to 4 years) were included in the study.

Autostereoscopic display The stimulus was visualized on an autostereoscopic display (display 2018XLQ, DTI, Rochester, NY) allowing vision of full-color 3D images without special eyeglasses at a rate of 60 frames per second. The principle of the autostereoscopic display is as follows: a liquid crystal display consisting of 1,208 columns and 1,024 rows is illuminated from behind, a short distance away, by a light source panel consisting of an array of 604 narrow vertical bright lines (Fig. 1a). These vertical bright lines are spaced apart in such a way that when a subject is at a particular distance from the display screen, a vertical bright line will illuminate a vertical column of pixels as seen by one eye, while the other eye viewing that same vertical column will see darkness because it corresponds to a dark vertical band between the vertical bright lines on the light source panel behind the screen. In this way, the odd pixel columns are illuminated for the left eye, while the even pixel columns are illuminated for the right eye. This provides a 3D perception of the image (Fig. 1b). The best distance (allowing similar displacements towards or away from the screen until no 3D image can be perceived) depends on the interpupillary distance of the observer and can be calculated trigonometrically (e.g. for an interpupillary distance of 66 mm the distance is 80.0 cm). The distance between the screen and the child’s head rest was always optimized according to the interpupillary distance. Before and during each experiment, it was ensured that the head was optimally placed in the center of the head rest. There is a tolerance of about 20 cm towards or away from the display, which still allows vision of the 3D image. A displacement of the head (towards or away from the screen, or sideways) never allowed monocular vision of the stimulus.

Random-dot stimulus Random-dot circles with a diameter of 10 cm and a crossed disparity of 0.34° were generated in four different locations with the coordinates +10 cm/+10 cm,

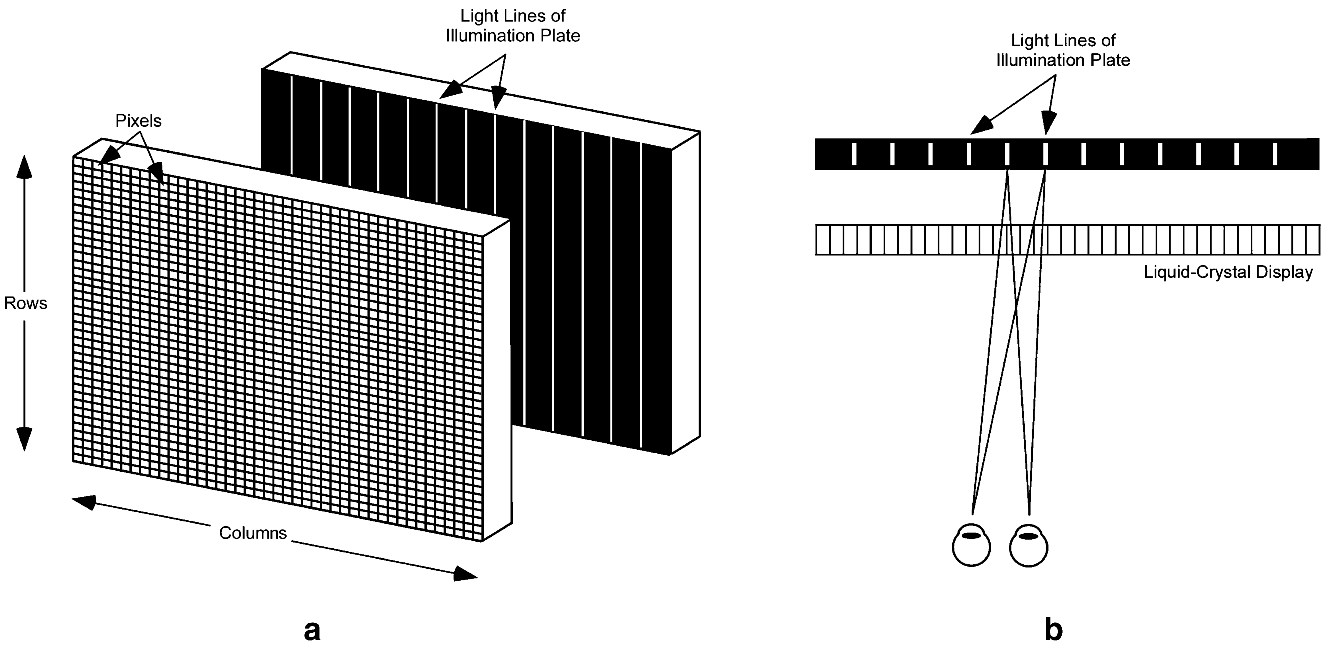


Fig. 1 **a,b** Principle of autostereoscopic display

+10 cm/−10 cm, −10 cm/+10 cm, −10 cm/−10 cm. The pixel size of the random dots was 5.5 mm. Since the displays image separation between the right and left eye of our screen is not complete, it would be possible to perceive the other eye's image very faintly. This inconvenience is nonproblematic if the monitor is only used to show equally luminant images to both eyes in order to visualize 3D images. However, in our experimental setting it may have allowed vision of the random-dot stimulus monocularly. Therefore, a faint counter-image of the same intensity was generated, which neutralized the imperfection of the autostereoscopic screen. This counter-image was a reverse-intensity image of that in the adjacent column. This also allowed elimination of any luminance shift when moving the head. The stimulus randomly changed its position between the four possible locations. The stimulus was presented monocularly and binocularly to ten cooperative children older than 6 years and to ten adults. When asked, all were able to see the stimuli binocularly, however, under monocular conditions none of them, even if allowed to displace the head, was able to see the stimuli. The visual acuity necessary to see the stimulus was tested in four normal adults using Bangeter occlusives (Ryser Optik, St. Gallen, Switzerland). Each eye needs to have a Snellen visual acuity of 20/400 (decimal 0.05, logMAR 1.3) to clearly see the stimulus.

Eye movement recordings An extensive description of the experimental setting of the infrared video-based oculography system has been published previously [8, 9, 17, 19]. The stimulus generator and recording system is provided by Metrovision (Perenchies, France). Calibration was performed by determining age-related correction factors from repeated presentations to 20 children of vertical and horizontal steps with the following x/y-axes: horizontal steps 0°/−10°, 0°/0°, 0°/+10° and vertical steps −10°/0°, 0°/0°, +10°/0° [8]. The vertical and horizontal eye positions were recorded at a 30 Hz sampling rate. The duration of recording of the stimulus response was always identical and was 38 s. It resulted in 1,140 lines in the data file. The algorithm for data analysis to extrapolate missing values due to blinking and to exclude outliers using the robust mean and standard deviation has been described previously in detail [17].

Stimulus presentation Infants and toddlers up to the age of 1 year were seated in a infant car seat (Maxicosy) with an

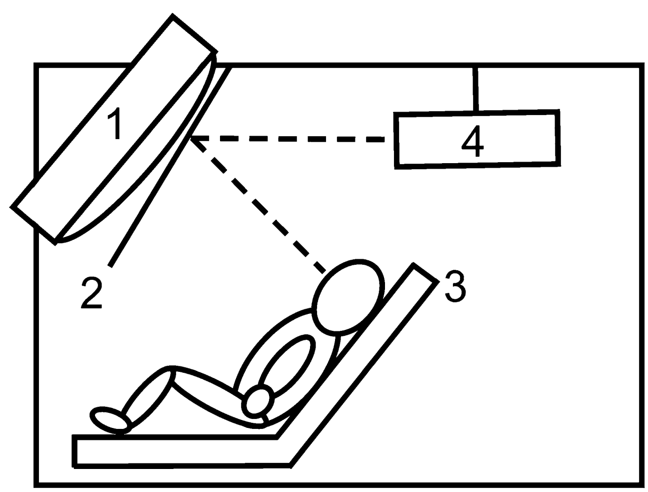


Fig. 2 Experimental setting for children <1 year: *1* autostereoscopic monitor for stimulus presentation, *2* hot mirror, *3* infant car seat (Maxicosy) with an inclination of 45°, *4* infrared illumination and infrared photo-oculography camera

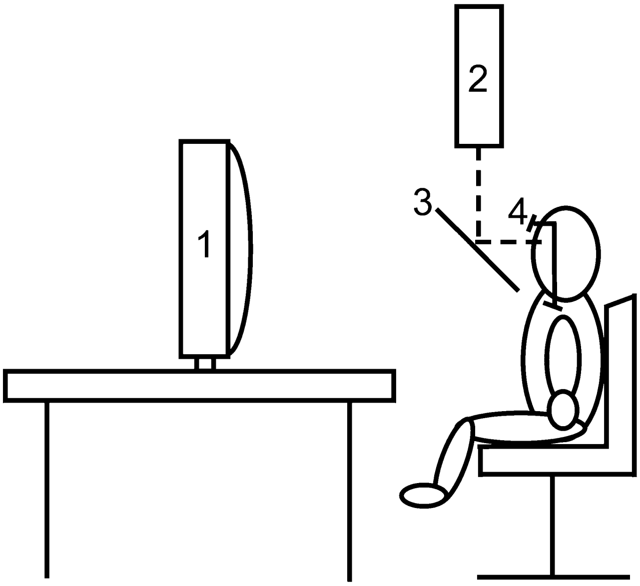


Fig. 3 Experimental setting for children ≥1 year: *1* autostereoscopic monitor for stimulus presentation, *2* infrared illumination and infrared photo-oculography camera, *3* hot mirror, *4* chin and front rest

inclination of 45° (Fig. 2). This inclination minimizes pupil masquerade by the eyelid [19]. Their heads were not stabilized. Children between 1.5 and 4 years were sitting, kneeing, standing on a chair, or sitting on the lap of the mother. Their heads were stabilized by a chin and front rest (Fig. 3). In both settings, the monitor for stimulus presentation was placed in a fronto-parallel position at a distance of 40 cm from the eyes.

The distance from the eyes was calculated according to the instructions of the 3D monitor provider. Eye position was determined by measuring the position of the corneal reflex with respect to the center of the pupil. The display was viewed binocularly while eye movements were recorded monocularly in the right eye. An infrared illumination of the eye (880 nm) was used to produce the corneal reflex and the pupil image. The system operated with a sampling rate of 30 Hz and achieved a resolution of 10 arc minutes [8, 9]. Illumination source and camera were installed above the children's heads. A hot mirror (dichroic filter separating visible light and infrared light) was used to illuminate the eye, record the eye position, and to align the camera. Optimal alignment during recording was achieved looking at an image of the child's eye on a computer screen. If necessary, the head position of the child was adjusted during the recording period. In smaller children attention towards stimuli was increased by a music box placed behind the screen.

Child cooperation After each recording, without knowledge of the recording results, the cooperation of the child was graded in three categories: poor, average, and good cooperation.

Analysis of the curves Two plots graphically visualized the ocular response: time against x-coordinate and time against y-coordinate. The following coordinate system was used: x-coordinate corresponds to horizontal and the y-coordinate to vertical eye movements. Negative values corresponded to displacements to the left or inferior to the centre, positive values to the right or superior to the centre. On each child's curve a line plotted with identical coordinates of the expected eye movements if all stimuli would be followed was superimposed. One of the authors (B.S.) determined which saccade ends corresponded to presented stimulus position. A positive response was assumed if during the whole recording period four or more consecutive saccades corresponded to the stimulus coordinates.

Performance of the new test In a previous study including children with an average age of about 5 years (some of them with normal Lang I stereovision, some with Lang I negative because of congenital esotropia), the sensitivity was found to be 92.3%, the specificity 96.7%, the positive predictive value 0.96 (95% CI 0.79–0.99), the negative predictive value 0.94 (95% CI 0.78–0.99), and the overall accuracy 0.95 (95% CI 0.85–0.99) [6].

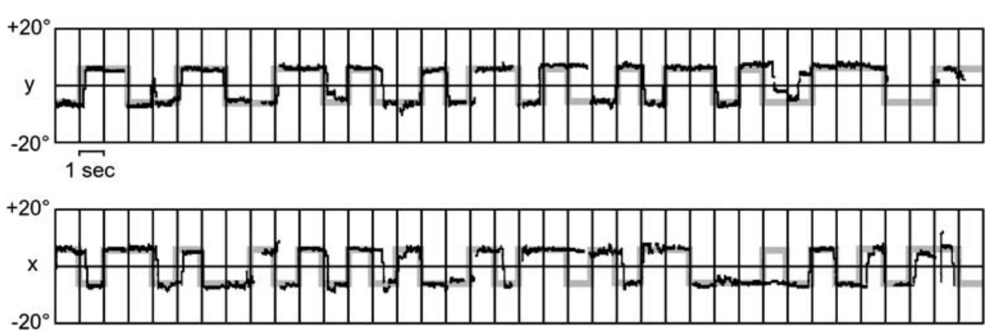


Fig. 4 The recording in a 48-month-old child is shown. The upper plot corresponds to the horizontal eye positions (y-axis in degrees) plotted against time (seconds). The lower plot shows the vertical eye positions (x-axis in degrees) against time (seconds). Negative values are to the left or below center, and positive values are to the right or above center. The *black line* corresponds to the eye positions, the *gray, transparent line* to the position of the stimuli. There is an excellent correspondence of eye positions for both axes with the stimulus position. Therefore, the stimulus has been recognized during nearly the whole recording period

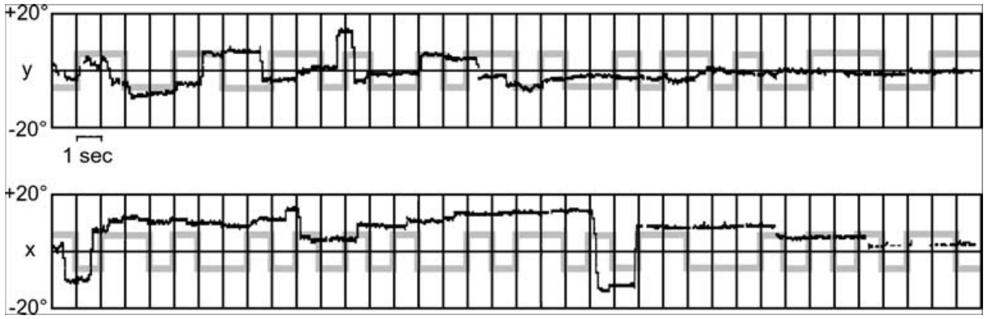


Fig. 5 The recording in a 36-month-old child is shown. The upper plot corresponds to the horizontal eye positions (y-axis in degrees) plotted against time (seconds). The lower plot shows the vertical eye positions (x-axis in degrees) against time (seconds). Negative values are to the left or below center, and positive values are to the right or above center. The *black line* corresponds to the eye positions, the *gray, transparent line* to the position of the stimuli. There is nearly no correspondence between the stimulus location and the eye position. Therefore, the stimulus has not been recognized

Statistical analysis For each proportion of positive responses in each age group the 95% confidence interval was calculated. The influence of different variables on recognition of the stimulus was studied using a multiple logistic regression with the dichotomic target variable positive or negative test recognition and the following explanatory variables: age, gender, and child cooperation. Analysis was performed using the software R, version 2.1.0. The power to detect a gender difference of 25% would have been 0.8, assuming alpha=0.05.

Results

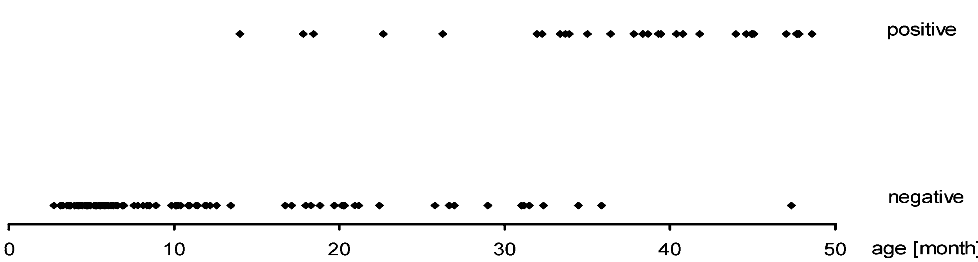
Figure 4 shows the horizontal and vertical eye movement recordings of a 48-month-old child with very good cooperation during one recording period of 38 seconds. The black lines correspond to the eye positions, the gray, thicker ones to the position of the stimuli. There is a very good correspondence of the eye positions in the horizontal and vertical with the stimulus position showing that the 3D random-dot stimulus has been seen during nearly the whole recording period. Figure 5 shows a negative response in a 36-month-old child. There is no correspondence between the stimulus positions and the eye positions.

Figure 6 shows the overall performance of the new test in different age groups. With increasing age the number of positive responses increased. Below the age of 12 months, we were not able to prove the presence of random-dot stereovision. For older children the following rates of positive responses were found: 12–18 months 25%, 18–24 months 10%, 24–30 months 16%, 30–36 months 57%, 36–42 months 100%, and 42–48 months 91%. Figure 7 shows these rates including the 95% confidence intervals. Multiple linear logistic regression showed a significant influence on stimulus recognition of the explanatory variables age ($p<0.00001$) and child cooperation ($p<0.001$), but not of gender ($p>0.1$).

Discussion

We present the results of the performance of a new, simple 3D-monitor based random-dot test in children younger than 4 years of age. The test has been developed by the authors, and it has been found to be potentially useful in two previous studies [6, 7]. In one previous study including a large number of older children with normal and abnormal random-dot stereovision we found good sensitivity, specificity, and high positive and negative predictive values [6]. In this study, we found that the test is well suited for children older than 36 months. In this age category the sensitivity was over 90%. In the age group between 12 and 36 months it was also possible to determine the presence of random-dot stereovision; however, the sensitivity was lower. Children younger than 12 months always tested negative. There was no major difference between girls and

Fig. 6 Performance of the new test in the different age groups. Plot of positive and negative responses against age. With increasing age the number of positive responses increased



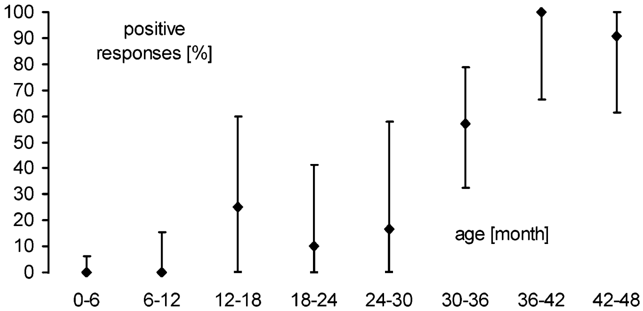


Fig. 7 Performance of the new test in the different age groups. Rates of positive responses for different age groups. Bars represent 95% confidence intervals for proportions

boys in stimulus recognition capabilities. However, the restricted sample size might not have allowed detection of small differences between gender. As expected, apart from age, child cooperation significantly influenced random-dot stimulus recognition. The factors most probably responsible for the lower sensitivity in the age group below 3 years are: larger spontaneous head displacements, less interest in a circular stimulus changing its position between four locations, and for the age group between 1 and 3 years, difficulties in placing the head in the head-rest. For a better recording of lively and very young children, the use of an eye-head-tracking camera system should be considered. Additionally, a more interesting stimulus, e.g. like a face, should be used in order to increase attention in the age group below 3 years. Such an improvement would be necessary in order to allow studying the development of stereovision under natural conditions from birth on.

What is the advantage of our new test? The use of a 3D-monitor allows natural viewing conditions and avoids the dissociation induced by the use of polarizing or other types of glasses. Stimulus recognition can be assessed with increased objectivity using infrared photooculography. Previous techniques like random-dot stereogram and correlogram evoked potentials also represent objective testing procedures; however, such techniques are technically complex and request dissociating glasses and excellent child cooperation [12, 15]. Therefore, our test might be especially helpful for clinical outcome studies in which a more objective random-dot stereovision assessment is important. However, our new test will not replace the most frequently used random-dot tests like the TNO test, the Lang I and II tests, and the Radom-dot E test for clinical routing examination of random-dot stereopsis [14]. Although all these tests request verbal capabilities of the subject tested and may also be passed monocularly, they remain cheaper and easier to be applied. We did not compare our new test to tests in use for preverbal children like the infant random dot stereoacuity cards [5], random-dot stereogram evoked potentials, and random-dot correlogram evoked potentials [12, 15]. Therefore, a direct comparison of these methods is not possible. What are the limitations of our study? Although the faint counter-image generated to eliminate the imperfection of the 3D monitor seems to avoid luminance shifts, which may occur if the head is moved, we cannot fully exclude that in some situations a luminance shift might have induced a positive response. In addition to that, we cannot exclude that disparity alone and not depth might be sufficient to induce a positive response.

In conclusion, we found that our new examination technique allows an objective assessment of random-dot stereopsis in children older than 1 year, and reaches high sensitivities from the age of 3 on. The method might open new ways to screen children for visual abnormalities and seems to be useful for the objective measurement of the sensory outcome following the treatment of ophthalmo-pediatric disorders.

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