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Remote eye tracking assesses age dependence processing of coherent motion in typically developing children

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ABSTRACT

The aim of this study was to quantify processing of different types of coherent motion in terms of ocular motor response times in a group of normally developing children (age 0-12+ years old) using remote eye tracking. Motion coherence was applied in three different types of Random Dot Kinematograms (RDKs): vertical (RDK1) and diagonal (RDK2) motion and expansion (RDK3). Orienting eye movements were quantified using the Reaction Time to the first Fixation (RTF). The children were divided into two groups: the 'youngest group' between 0-3+ years and the 'oldest group' between 4-12+ years old. The results showed that RTF was significantly prolonged in the 'youngest group' compared to the 'oldest group' for each RDK. In the 'oldest group', RTF was significantly affected by the type of RDK shown. The presented results suggest that based on ocular motor responses age dependence of processing different types of coherent motion may be revealed.

Key words: Eye movements; Random Dot Kinematograms; coherent motion; reaction time; eye tracking

INTRODUCTION

Processing of motion is one of the most fundamental aspects of vision. Visual motion sensitivity originates from retinal ganglion cells that convey their information via the magnocellular pathways to the lateral geniculate nucleus (LGN). From here, the stream of motion signals leads via the primary visual cortex (V1) to the posterior and anterior parietal cortex, including V3a, V5+ (encompassing V5, MST and other alleged motion areas) and/or hMT+[1-3] and extends towards the anterior parietal and the posterior frontal cortex. This path-way that is used for motion processing, spatial cognition and visual-motor planning is also known as the dorsal network.[4] Motion processing has been extensively investigated at the functional level using Random-Dot-Kinematograms (RDKs). RDKs mostly consist of a black background combined with white moving dots displayed on a monitor, either to trigger optokinetic nystagmus (OKN) or to test coherent (or global) motion. RDKs with full field coherently moving dot's mostly trigger OKN. RDKs with two or distinct target areas have been commonly used in behavioural discrimination tasks in very young children e.g. preferential looking (PL). Here, the stimulus consists of a target area in which the dots move in opposite direction compared to the majority of the dots in the back-ground.[5,6] It has been shown that the sensitivity to motion is already present from birth[7] or shortly after a few weeks of age[8] and that different visual pathways are involved in processing OKN compared to PL during development.[9] Therefore, measurement of coherent motion sensitivity in relation to age may provide valuable information about maturation of the visual pathways in healthy children and in children with visual processing dysfunctions.

Quantification of processing coherent motion presented in an RDK may be done by a button press, a verbal response or by observing eye movements. Also, psycho-physical thresholds can be assessed, e.g. by using a stair-case procedure during a true/false method in which the number of coherent moving white dots in the target area is gradually reduced. There is, however, a large variability in RDKs used in clinical and scientific studies, i.e. stimulus type, direction of coherent motion, dot size and speed. This makes it difficult to compare studies available in literature on individual thresholds and reaction times across different RDK tasks. Additionally, in most RDKs, the dots in the target area move in opposite direction to the dots in the background. This induces a motion discontinuity at the intersection of both areas. Here, the relative speed of passing dots in opposite direction is twice the average dot speed. This creates a strong transient edge effect, which is absent in optic flow stimuli like expansion. In so-called motion-defined form stimuli, these edges are used to make different forms visible.[10] However, it is still unknown to what extent these edge effects contribute to coherent motion detection. Finally, most RDK tasks require subjects to understand the specific test instructions and to be able to give verbal or motor responses. In children under the age of 3-4 years or children with intellectual disabilities, these tasks cannot be performed adequately. Moreover, the outcome measures depend on the skills of an observer who assesses orienting responses as a measure for correct motion detection.

To overcome (part of) these problems, we developed a method to quantify visual orienting responses to RDKs in children using remote eye tracking technology.[11] Visual stimuli are presented on an eye tracker monitor. The stimuli that are shown test basic eye movements (saccades and pursuit), lower order visual functions (visual acuity and contrast) and higher order visual functions (form and motion coherence and competitive dots and non-competitive dots). Upon presentation, orienting behaviour in response to these stimuli is measured. This approach requires no specific verbal instructions prior to the test or active cooperation in terms of pointing or pressing a button. In addition, it allows objective quantification of orienting responses in terms of reaction time and fixation areas.[11] The first aim of this study was to compare processing of coherent motion in terms of reaction times to three different types of RDKs in children between 0-13 years of age: coherent motion in vertical (RDK1) and diagonal (RDK2) motion and expansion (RDK3). Our second aim was to investigate if the presence of motion edges in RDK1 and RDK2 affected orienting behaviour.

MATERIALS AND METHODS

Study population

We approached 430 healthy children between 0-13 years old in the region Rijnmond, Rotterdam, The Netherlands. The children aged 0 till 4 years (0-3+), the so-called ‘youngest group’ attended a regular day-care centre and the children aged 4 till 13 (4-12+) years, the so-called ‘oldest group’ attended a regular primary school. Parents were informed about the study by letter and 188 (~44%) written consents were received. Children had normal or corrected-to-normal vision. We included for this study 104 females, 6.2 (*SD* = 3.5) years and 84 males, 5.7 (*SD* = 3.6) years. The experimental procedures were approved by the Medical Ethical Committee of Erasmus University Medical Centre, Rotterdam, The Netherlands (METC-2006-055). The study adhered to the Declaration of Helsinki for research involving human subjects.

Measurement setup and procedure

The setup consisted of a 17-inch monitor with an integrated 50 Hz infrared eye-tracking system (Tobii 1750, Tobii Corporation, Sweden). The measurements were conducted in a quiet room. Children sat on their parents lap or on a comfortable chair at ~60 cm in front of the eye tracker. The system's latency was 30ms. First a standardized 5-point calibration procedure of both eyes was performed. Next a sequence of short movies was shown. The objective was to randomly present short movies of visual stimuli for testing higher visual functions, e.g. form and motion coherence. Each stimulus contained a specific area with a higher salience defined as the target area. In the present study, we analysed three different types of coherent motion stimuli, see Figure 1.

In Table 1, an overview is presented of the main characteristics of each stimulus. During one trial, the stimulus RDK1 (vertical motion) was shown two times (the target area on the left and on the right monitor side) and the stimuli RDK2 (diagonal motion) and RDK3 (expansion motion) were each shown 4 times (the target area in all 4 monitor corners), for a duration of 4 s. All dots had a limited lifetime of 0.4 s. We started with including the 'youngest children' and prepared two different sequences (sequence I and sequence II) of movies, each with a duration of ~10 min. Note that in this initial phase of our research, sequence I only contained RDK1 and RDK2 and sequence II only contained RDK1 and RDK3. In total, we included 78 children in the 'youngest group'. Sequence I was shown to 56 children, sequence II was shown to 42 children. To a subset of 17 children, both sequences were shown for a test-retest. Thus, RDK1 was shown to all 78 children, RDK2 to 56 children and RDK3 to 42 children. Next, we included the 'oldest children', and we prepared one sequence that contained all three RDK's, with a duration of ~15 min. In total, we included 110 children in this group. Orienting eye movements were stored on the hard disk and manually analysed off-line using custom Matlab programs (Mathworks Inc., Natick, MA, USA).

Table 1. An overview of the main characteristics of the three types of RDKs shown to healthy subjects of 0-12+ years old; see also Figure 1 for a schematic illustration of each RDK.

	Coherent Motion		
Dot	**RDK1**	**RDK2**	**RDK3**
direction	vertical	diagonal	Expansion
velocity (degree/s)	11.8	11.8	11.8
size (degree)	0.25	0.25	0.25
density (dots/degree^2)	2.6	1.3	2.6

RDK = Random Dot Kinematogram

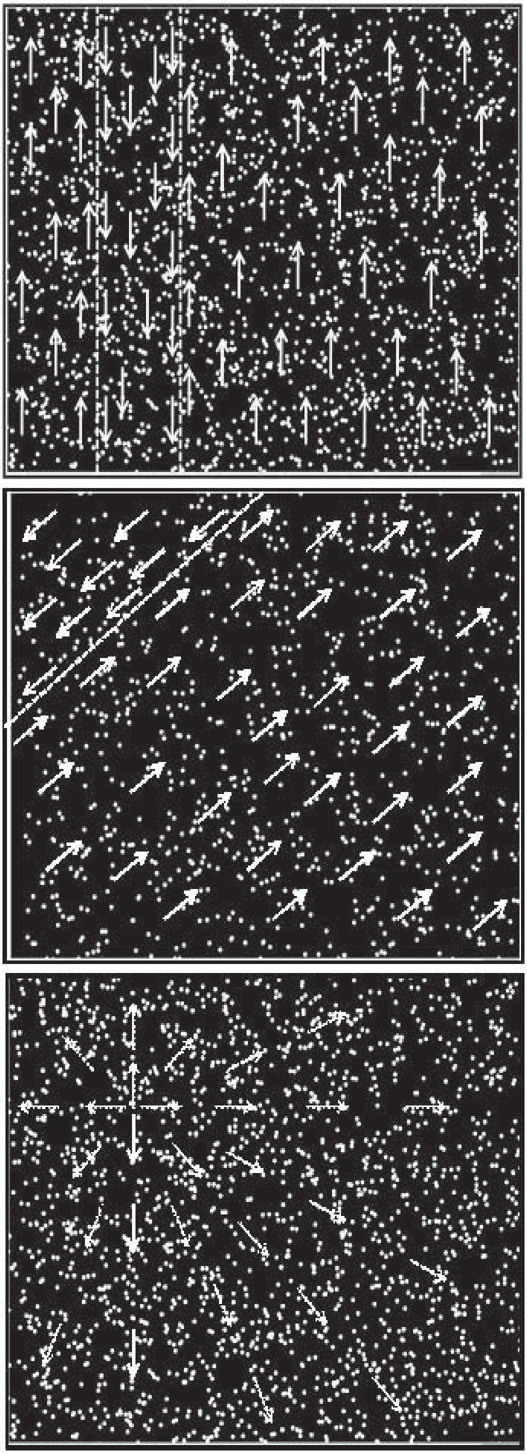

Figure 1. The top panel illustrates the vertical coherent motion (RDK1). White dots in a 5 degree width vertical bar on the left side of the monitor (the target area indicated with the dashed lines) moved in upward direction, while the dots in the remaining areas moved downwards. The middle panel illustrates the diagonal coherent motion (RDK2). In the target area, the top left corner, the white dots moved in coherent diagonal direction, while in the remaining areas, the white dots moved in opposite diagonal direction. The bottom panel illustrates coherent expansion motion (RDK3). White dots moved from the centre of the target area, the top left corner) to the borders of the monitor. All dots had a limited life time of 0.4 s.

Data analysis and statistics

Data analysis started with the calculation of the visual angles between gaze point and the edge of a target area. For RDK1 this edge was defined as two vertical lines, positioned at three degrees to the left and to the right of the target area midline. For RDK2, this edge was defined as a diagonal line, positioned at six degrees from the target area midpoint. For both RDKs, this resulted in a target with a margin at the edge of 0.5 degrees. For RDK3, this was an 8 degrees circle around the expansion point in the centre of the target area. For each RDK presentation, we selected the time values that gaze crossed the preset border. The reaction time to an RDK was calculated as the 15th percentile of the two-time values obtained for each RDK. This reaction time was denoted as the Response Time to Fixation (RTF), defined as the time between showing a stimulus and landing of gaze within the predefined target areas. The focus of gaze analysis was to assess reflexive orienting eye movements to the target area as a best estimate of visual processing time. If gaze was already in the target area of an RDK at presentation, eye movements were not included for analysis. In addition, an eye movement response was excluded for analysis if (1) no gaze data was available within the first 500 ms after presentation of the stimulus, (2) a reaction time was deter-mined within 120ms after presentation of the stimulus, (3) more than three saccades were made to reach the target area, or (4) the duration of fixation prior to an eye movement was more than 1500 ms and (5) the duration after reaching the target area was less than 200 ms. Finally, author JP checked by visual inspection whether the first or second saccade fixated the edge of motion discontinuities (using a margin of about 1 degree) caused by dots moving in opposite directions, see Figure 1, top and middle panel for a schematic illustration. The percentage of edge fixations was calculated by dividing the total number of edge fixations divided by the total number of correctly analysed RDKs for the complete group. Two separate age groups were defined: the 'youngest group' of children were the preschoolers between 0-3+ years old and the 'oldest group' of children went to primary school and were aged between 4-12+ years old. A Kolmogorov-Smirnov test was done to test parameter values for a normal distribution. It revealed that a normal distribution for the RTF values per RDK existed in the 'oldest group'. A Mann-Whitney U-test was applied to test between groups (age group). In the 'oldest group', a one-way repeated-measures analysis of variance (ANOVA) was used to test within subjects effects (RDKs). Bonferroni posthoc testing was used for pairwise comparison of RTF-values within these subjects. All statistical analyses were performed in SPSS-17 (SPSS, Chicago, US) and significance levels of $p < .05$ were considered statistically significant.

RESULTS

Figure 2 top panel illustrates, superimposed, orienting gaze starting at the onset of the presentation of the two types of RDK1, i.e. the target area on the left side and on the right side of the eye tracker monitor. After detection of the coherent motion (either on the left or right side), the subject made an eye movement into the target area. Figure 2, bottom panel, illustrates, again superimposed, orienting gaze starting at the onset of presentation of each of four types of RDK2 stimuli. After detection of the coherent motion, this subject fixated the motion edge three times and one time the centre of the target area was fixated (the upper right target area).

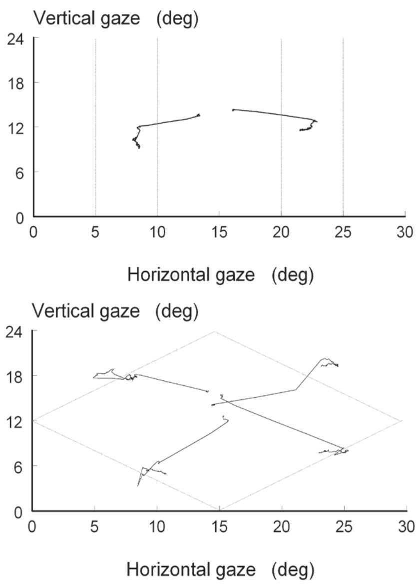

Figure 2. The top panel illustrates superimposed the orienting gaze to the two target areas (one on the left side and one on the right side) of RDK1. After detection of the vertical coherent motion, the subject made an eye movement into the target area. The bottom panel illustrates superimposed the orienting gaze starting at the onset of presentation of the four types of RDK2. After detection of the coherent diagonal motion, three of the eye movements of this subject resulted in transient edge fixation, while one time, a saccade was made into the target area (the top right monitor corner).

Figure 3 shows for RDK3 the distance between the gaze point and the midpoint of expansion and the preset eight degree borderline (the dashed line). From the time values at which gaze crossed the 8 degrees border, the Reaction Time to Fixation was calculated. Note that the duration of presentation is 4 s. We plotted the first 2.0 s for illustration purpose only.

Figure 4 shows the RTF-values of the children to respectively RDK1, RDK2 and RDK3 against age. In each panel, a power line was fitted to the data to illustrate the decrease of RTF-values with increasing age (dashed lines). Orienting responses to the RDKs showed a development over age, see Figure 4. Large variability in reaction times was found in children between 0-3+ years

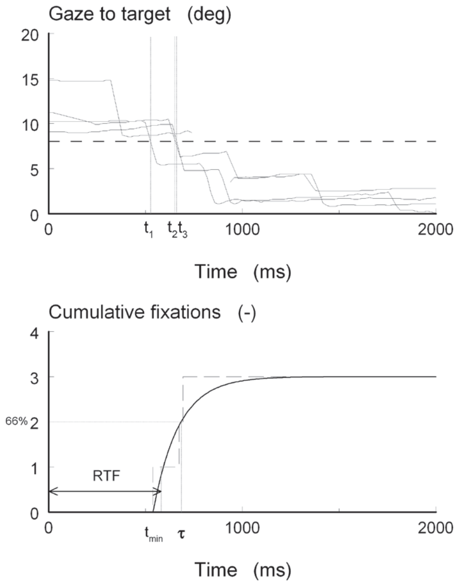

Figure 3. The top panel shows the visual angles between gaze and centre of the target area against time of 4 coherent expansion motion stimuli presented in RDK3. The bottom panel shows the cumulative plot of the time values that gaze crossed an 8 degrees border (dashed line) of the target area. An exponential curve with time constant tau was fitted to this cumulative plot to quantify the Reaction Times to Fixation (RTF).

old. The fastest reaction times with small variability were found in children between 8-12+ years.

In Table 2, an over-view is presented of the orienting responses to the three RDKs. The results are presented in two subgroups: children between 0-3+ years old (n = 78) and children between 4-12+ years old (n = 110). The success rate in assessing RTF-values in the 'youngest group' was highest when using RDK1 and RDK3 (vertical and expansion motion) and in the 'oldest group' this rate was almost equally high for all three RDK's. The Kolmogorov-Smirnov test showed normal distribution for the RTF values per RDK in the 'oldest group'. In addition, only 9 children in the 'youngest group' delivered an RTF value for all RDK's, whereas this figure was 92 in the children of the 'oldest group'. Based on the Mann-Whitney U-test, RTF values were significantly prolonged in the 'youngest group' compared to the 'oldest group' for each RDK. For the 'oldest group', the Mauchly's test, as part of the one-way repeated-measures ANOVA, indicated that the assumption of sphericity was not violated, $X^2(2) = 2.46$, $p = .293$ (epsilon=.64). The results showed that RTF was significantly affected by the type of RDK shown, $F(2,182) = 14.66$, $p < .001$. Pairwise comparison within subjects revealed significant differences between RDK1-RDK2 (mean difference -80 ms (SD 15 ms); $p < .001$) and between RDK1-RDK3 (mean difference -70 ms (SD 15 ms), $p < 0.001$). Finally, we found that 7% of all subjects fixated edges of motion discontinuities in RDK1. In RDK2 this percentage was increased to 64%.

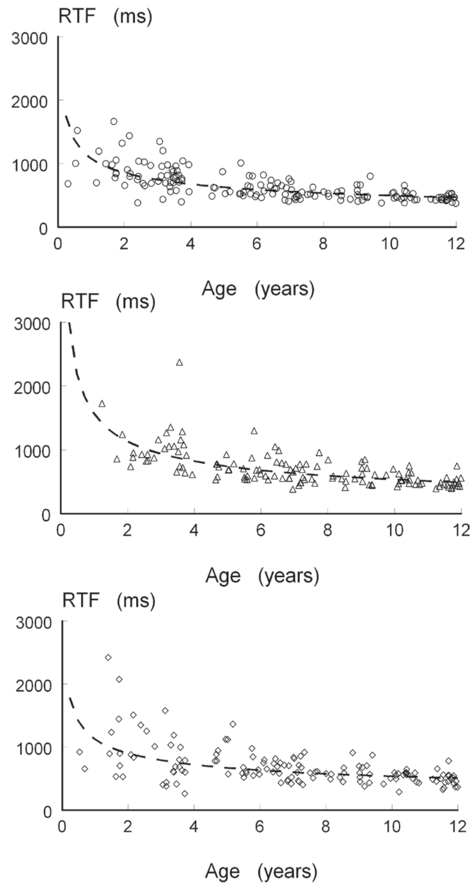

Figure 4. In the top, middle and bottom panel, RTF-values of the control group to respectively RDK1, RDK2 and RDK3 are plotted against age. In each panel, an age-related power line was fitted to the data (dashed lines).

Table 2. An overview of the objectively assessed orienting responses to three types of coherent motion tasks results presented in two subgroups: children aged 0-3+ years (*n* = 78) and children aged 4-12+ years old (*n* = 110).

		Coherent motion values		
Age group	**Parameter**	**RDK1**	**RDK2**	**RDK3**
0-3+ years	Successes % (number)	72 (56/78)	53 (28/53)	81 (34/42)
	Median RTF-values ms (25-75 percentiles)	810 (695-980)	940 (830-1160)	820 (600-1200)
4-12+ years	Successes % (number)	93 (102/110)	94 (103/110)	96 (106/110)
	Median RTF-values ms (25-75 percentiles)	505 (450-580)	560 (480-705)	575 (490-690)
0-12+ years	Edge fixations %	7	64	-

RTF = Reaction Time to Fixation; RDK = Random Dot Kinematogram

DISCUSSION

The aim of the present study was to quantify the processing of motion of three different RDKs in normally developing children by means of orienting responses. In the 'oldest group' the RDKs with vertical coherent motion induced significantly faster ocular motor responses, up to 70 ms, than the RDKs with diagonal and expansion motion. One explanation might be that the diagonal motion stimulus contained only half the number of dots displayed on the monitor making this stimulus less pronounced compared to the coherent vertical and even the expansion motion. Differences in RTF-values might also relate to differences in target areas used, since each target area was different in size and screen location. We tested the influence of target area size on RTF by increasing and decreasing each area by 25%. We found that the RTF-values differed on average not more than 30 ms (i.e. a maximum of less than two sample values given a sample frequency of 50 Hz), indicating that area size only partially could explain the difference found in RTF-values. Previously, it was shown that cells in hV5+, located in the inferior temporal sulcus (ITS), are highly sensitive to directional motion.[12-16] Processing of optic flow stimuli like rotation or expansion, predominantly activate cells in MST.[17-21] The presented results suggest that, based on the reaction times to fixation, age dependence exists in processing different types of coherent motion.

Performance of motion processing is mostly based on psychophysical threshold methods or visual event-related potentials (VERPs). Based on thresholds, it was found in healthy children aged 4-11+ that motion processing reached adult levels at the age of 10-11+ years.[22] Based on VERPs, processing of expansion motion showed a similar time course, i.e. reaching of adult levels at the age of 8-10+ years.[23] The present data not only support these previous findings, but in addition show quantitative differences in processing different types of coherent motion. As stated, orienting eye and/or head responses are reflexively induced towards visual stimuli when its information is processed by the brain. At this level of processing visual information, processing of (visual) perception to name the shape of the form or to indicate the direction of a motion, like in psychophysical threshold methods, might not even be completed yet. In a future study, it would be interesting to test the RTF-values as a function of decreasing coherent threshold levels. It might be that timelines of maturation become different when levels of coherent motion decrease.

In the present study, we remotely assessed gaze while the RDKs were presented on the monitor of the eye tracker. Gaze responses can be analysed in two different ways to quantify the performance of a preferential looking based RDK. Firstly, the outcome may be a simple classification of a target area as seen or unseen based on eye movements, instead of a verbal or motor response. When the RDKs are extended with stepwise reduction of the number of coherent moving dots in combination with a staircase procedure, objective individual thresholds can even be assessed. We are currently developing these RDKs in our lab to assess thresholds for coherent form, motion and contrast levels based on eye movements. Secondly, as presented in this paper, the outcome can be a reaction time. In previously published papers, we showed development over age of orienting responses to cartoons.[24] Small variations in response times were found in younger as well as older children (on average RTF-values of ~200 ms), while data presented in the present paper show large variability in response times in children between 0-3+ years old and relatively high RTF-values. This may relate to the fact that the cartoons are high contrast and colourful images whereas the coherent motion stimuli are low contrast and complex of shape. Recent theories argue that the brain constructs an internal saliency map based on features such as colour, form and movement.[25-27] A salience map represents the most conspicuous area in a visual scene. It is suggested that a saliency map guides visual attention and triggers orienting behavioural responses. Presumably, the cartoon stimulus has a much higher saliency compared to the coherent motion stimuli, explaining the relatively fast orienting responses to cartoons. The more delayed reaction times to the coherent motion stimuli may reflect the difficulty of processing these types of stimuli in the tested children.

The RDK with coherent diagonal motion had the largest area in which dots moved unidirectional and only a small portion of dots that moved in the opposite direction. For this stimulus, we found a high number of edge fixations compared to both other stimuli. We suggest that the one edge of motion discontinuity in this RDK with coherent diagonal motion presumably represents the most conspicuous area of this stimulus. This edge might trigger comparable visual attention in young as well as elderly children, resulting in edge fixations in 64% of cases. In the RDK with coherent vertical motion, two edges of motion discontinuity exist. Here, the most conspicuous area may not be a line, but a large vertical block of rectangular shape. Presumably, visual attention is now drawn to the centre of this block rather than to its edges, resulting in only 7% of edge fixations.

We believe that quantification of typical orienting behaviour in childhood represents a reference of neurological development. Future studies may assess abnormal development and diagnosis of visual processing dysfunctions in a case control experiment. The children that have our special attention include (very) preterm born children with a high risk of having visual processing dysfunctions and children diagnosed with a loss of visual function without damage to the ocular structures. The latter group is diagnosed with cerebral visual impairment (CVI), a very broad diagnosis of exclusion and based on anatomical landmarks.[28] With the current eye tracker method, the wide range of visual impairments that might occur in these children may be quantified in terms of functional deficits. Testing the effectiveness of processing different types of e.g. contrasts, colours and form and motion coherences enables the construction of a unique visual profile per child. Such profile could support specific rehabilitation or visual stimulation programs in children with CVI.

CONCLUSIONS

In the present paper we showed that orienting responses to three types of coherent motion had a development over age. Large variability in reaction times was found in children between 0-3+ years old. The fastest reaction times with small variability were found in children between 8-12+ years, suggesting adult-like responses around this age. Measurement of coherent motion sensitivity in relation to age may provide valuable information of processing motion in patients with visual processing dysfunctions and typically developing children.

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DECLARATION OF INTEREST

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