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Do infants have the horizontal bias?

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ABSTRACT

A robust set of studies show that adults make more horizontal than vertical and oblique saccades, while scanning real-world scenes. In this paper we study the horizontal bias in infants. The directions of eye movements were calculated for 41 infants (M = 8.40 months, SD = 3.74, range = 3.48–15.47) and 47 adults (M = 21.74 years, SD = 4.54, range = 17.89–39.84) while viewing 28 real-world scenes. Saccade directions were binned to study the proportion of saccades in the horizontal, vertical and oblique directions. In addition, saccade directions were also modeled using a mixture of Von Mises distributions, to account for the relatively large amount of variance in infants data. Horizontal bias was replicated in adults and also found in infants, using both the binning and Von Mises approach. Moreover, a developmental pattern was observed in which older infants are more precise in targeting their saccades than younger infants. That infants have a horizontal bias is important in understanding infants' eye movements. Future studies should account for the horizontal bias in their designs and analyses.

1. Introduction

Eye movements are frequently used to study infant cognition (Wass, Forssman, & Leppänen, 2014) in both experimental and free-viewing paradigms. Traditionally, looking time measures have been extremely important in studying infant cognitive development (Aslin, 2007) and new eye tracking techniques can further enhance our knowledge in this area (Aslin, 2012). Understanding infant cognitive development starts with knowing what information is available for infants to process. Especially in free-viewing paradigms, infant eye movements reflect natural exploration behavior and provide a relative unbiased measure of attention. Understanding what guides infant eye movements is therefore of key importance to study infant cognitive development.

Adult eye movements are series of short fixations and rapid saccades. Approximately three fixations and saccades are made every second (Rayner, 2009). Saccades are targeted at salient regions (Itti & Koch, 2000; Itti, Koch, & Niebur, 1998) influencing eye movements in a bottom-up way, but top-down processes (e.g. knowledge) also influence where we fixate (Henderson, 2003). Apart from these bottom-up and top-down influences, general biases also play an important role in

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guiding eye movements (Tatler & Vincent, 2008, 2009). Most early fixations fall in the center of the scene (Clarke & Tatler, 2014) and saccades are predominantly targeted in the horizontal direction (Foulsham, Kingstone, & Underwood, 2008; Gilchrist & Harvey, 2006; Tatler & Vincent, 2008). In this paper we examine the possibility of a horizontal bias in infants.

At birth, eye movements are less efficient than in adults, because the first few weeks of postnatal life infants have relatively little control over their eye movements (Atkinson, 1992). However, the visual system develops rapidly and 1- to 2-month-old infants start to fixate visual stimuli (Bronson, 1994; Hunnius & Geuze, 2004). These fixations are often long (>500 ms), as infants may have trouble shifting their gaze. At 3- to 4-month of age fixations become shorter (<500 ms, Bronson, 1994) and control over eye movements is more stabilized (Hunnius & Geuze, 2004). The fixation systems continue to develop until adolescence (Luna, Velanova, & Geier, 2008) and fixation durations are known to decrease until at least 10 years of age (Helo, Pannasch, Sirri, & Rämä, 2014).

Also for infants there is evidence of top-down and bottom-up processes guiding eye movements. Three-month-old infants have a preference for looking at own-group faces versus other-group faces, whereas this preference is not present at birth (Kelly et al., 2005) and 3- to 4-month-old infants have a preference for faces of the gender of their primary caregiver (Quinn, Yahr, Kuhn, Slater, & Pascalis, 2002). These findings indicate that top-down processes influence eye movements. There is also evidence of bottom-up processes guiding infants' eye movements, while watching a Charlie Brown video clip, 3-month-old infants' fixations were best predicted using saliency, whereas 6- and 9-month-old infants' fixations were best predicted by the location of faces in the video (Frank, Vul, & Johnson, 2009). The influence of bottom-up factors on eye movements continues to decrease until adolescence (Açık, Sarwary, Schultze-Kraft, Onat, & König, 2010; Helo et al., 2014).

Although the development of top-down and bottom-up visual processes in infancy has been investigated in some detail, the early development of many general biases remains largely unexamined. Tatler and Vincent (2009) showed that models accounting for general biases gave a better description of where adult fixations are located than models based on top-down and bottom-up processes alone. As these general biases play an important role in guiding adult eye movements (Tatler & Vincent, 2008), it is likely infant eye movements are also guided by these general biases.

To our knowledge, the horizontal bias has yet to be examined in infants. Studying the horizontal bias in infants is important to gain a better understanding of what guides infants' eye movements. If the horizontal bias is present in infants, future studies can improve models to explain infant looking behavior and can account for the bias in experimental studies. For example, before concluding infants have a preference for some stimuli or object in a scene, it must be ruled out that this preference is due to general biases.

1.1. Horizontal bias in adults

In the adult literature there is overwhelming evidence of the horizontal bias (e.g., Foulsham et al., 2008; Gilchrist & Harvey, 2006; Tatler & Vincent, 2008). Although the origin of the bias remains unclear, there are some factors that may contribute to it. First, biomechanical factors may partially drive the bias. Horizontal saccades require only the use of one pair of muscles (the lateral and medial rectus), whereas saccades in the other directions requires more than one pair of muscles (Viviani, Berthoz, & Tracey, 1977). For instance, oblique saccades require coordinated horizontal and vertical muscle activity (Becker & Jürgens, 1990) and even vertical saccades require extraocular muscle activity (Henn & Cohen, 1973). Second, physiological factors may guide the bias. The spatial density of rods and cones in the retina is higher along the horizontal direction than the vertical direction (Curcio, Sloan, Kalina, & Hendrickson, 1990). Najemnik and Geisler (2008) found that an ideal observer model based on this asymmetry produced a distribution of saccade directions with a horizontal bias. Third and lastly, the distribution of objects in the environment may contribute to the bias. We may learn that interesting objects are often located along the horizon. In order to maximize our information uptake in the shortest timeframe, therefore, we start to move our eyes along the horizon.

1.2. Current study

The horizontal bias is a well established phenomenon in adults and an important factor in the guidance of eye movements as saccades are made more often in the horizontal directions, than in the vertical and oblique directions. To fully understand adult eye movements it is important to consider bottom-up and top-down factors, but also more general eye movement biases (Tatler & Vincent, 2009), such as the horizontal bias. The research question of this paper is: "Do infants exhibit the horizontal bias in saccade direction, while scanning real-world scenes?" Furthermore, the bias may be different for older than younger infants. To answer the question if the bias changes with age, we observed a wide age range (3- to 15-month-olds). This enabled us to test if the horizontal bias develops with age. Answering these questions will help us to understand what guides infants' eye movements and thus enable us to learn more about infant cognitive development.

1.3. Analytical approach

The direction of eye movements is usually analyzed by a binning approach (e.g., Foulsham & Kingstone, 2010; Foulsham et al., 2008), in which saccade directions are binned in pre-defined categories (i.e. horizontal, vertical, oblique). However, this may introduce a confound in this study as the pre-defined ranges of the binning approach may not be applicable to infants. Infants' eye movements are likely to be noisy compared to adult eye movements. Therefore, saccade directions

Fig. 1. Five of the real-world scene stimuli used in this study.

may not be appropriately captured in the binning approach (i.e. bins may be too small). We overcome this problem by also using the continuous Von Mises distribution (cf. Rolfs, Knapen, & Cavanagh, 2010) to analyze saccade directions. Since saccade directions have a circular distribution, the Von Mises distribution, that can be thought of as the normal distribution on a circle, provides an excellent continuous alternative to the binning approach. The Von Mises approach allows saccade directions to be classified in a data-driven manner, accounting for the amount of variance in the data. Furthermore, common problems of binning approaches, such as loss of information (MacCallum, Zhang, Preacher, & Rucker, 2002) and decreasing power (Cohen, 1983), are also overcome by the continuous Von Mises approach.

2. Methods

2.1. Participants

Initially, 46 infants participated, but 5 infants were excluded due to inattention or inability to calibrate the point of gaze. After excluding these participants, 41 infants (mean age = 8.53 months, SD = 3.71, range = 3.48–15.47) and 47 adults (mean age = 21.74 years, SD = 4.54, range = 17.89–39.84) were included in the final analyses. Infants were distributed evenly over the age range. The gender ratio in infants (14 males, 27 females) was independent of the gender ratio in adults (19 males, 28 females), $\chi^2(1) = .15$, $p = 0.699$. Research was conducted in accordance with the Declaration of Helsinki, all adult participants and infant caretakers gave their informed consent.

2.2. Stimuli, design and procedure

Twenty-eight real-world (3 indoor) scene stimuli were selected from the LabelMe database (Russell, Torralba, Murphy, & Freeman, 2008), see Fig. 1 for five examples. Except for one image which was 576 pixels width, all images were 1024 pixels width. The heights of the images differed between 606 and 896 pixels. Eye movements were recorded with an EyeLink eye tracker (SR Research Ltd., Ontario, Canada) that sampled at 500 Hz. Infant participants were seated on a parent's lap approximately 55 cm from a 17-in. computer monitor, which subtended an approximate $27^\circ \times 34^\circ$ visual angle. Parents were asked not to talk or direct their child's attention during stimuli presentation. Adult participants were seated at the same distance from the monitor. Lights were dimmed and black curtains were drawn such that only the stimuli presented on the computer monitor could be seen. Prior to data collection, a five-point calibration scheme was used to calibrate each participant's point of gaze. The calibration procedure was repeated if necessary until the recorded point of gaze was within 1° of the center of the target. The experimental session only began after the calibration criterion had been reached. The 28 picture stimuli were shown one at a time for 4 s each. A dynamic 'attention-getter' stimulus preceded each trial to attract attention and center the gaze.

2.3. Gaze analysis

Infant and adults differ in their mean fixation durations and saccade speeds (Hainline, Turkel, Abramov, Lemerise, & Harris, 1984). It may be advisable, therefore, to employ different thresholds to classify fixations and saccades in infants and adults. However, this can make comparing infant and adult eye movement data difficult, because differences can emerge simply due to the different pre-processing methods. In order to avoid these problems we used a slightly modified version of the data-driven algorithm described by Mould, Foster, Amano, and Oakley (2012), as implemented in the R-package gazepath (van Renswoude & Visser, 2015). This algorithm makes it possible to derive the optimal speed and duration threshold data-driven and per individual, applying one method to all participants, while accounting for individual differences.

The algorithm of Mould et al. (2012) exploits the fact that the speed of eye movements is low during fixations and high during saccades. First, local maxima in speed of eye movements are found by selecting the eye movements that are faster than the previous and following eye movements. There are many local speed maxima in fixations, but few local speed maxima in saccades. Second, these local maxima are used to separate saccadic and non-saccadic movements. This is done by comparing the distribution of local speed maxima exceeding the threshold (black histogram, Fig. 2), with a uniform distribution of local maxima exceeding the threshold (dotted line), see the left panel of Fig. 2. The difference between these two distributions is given by the gap statistic (red line in the left panel of Fig. 2); the optimal speed threshold is where this gap statistic reaches a maximum. Eye movements with speeds below the threshold are classified as non-saccadic eye movements and eye movements with speeds above the threshold are classified as saccadic eye movements.

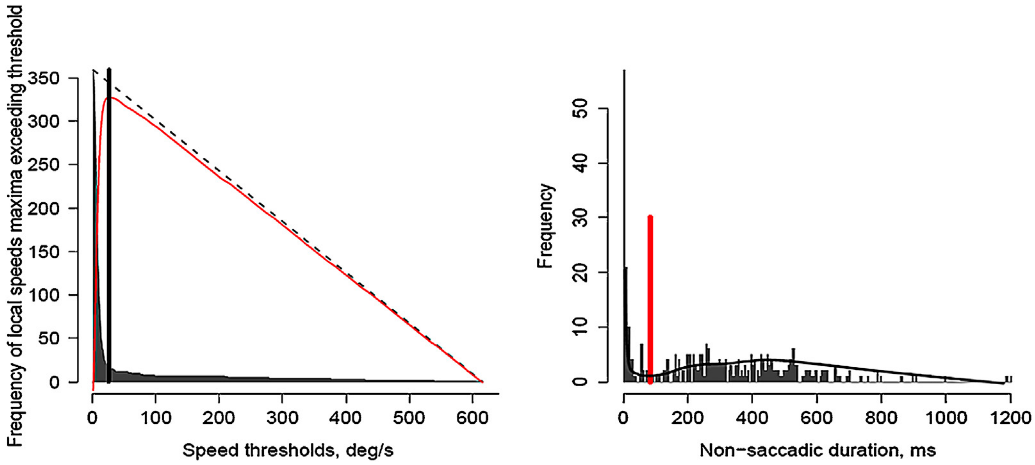

Fig. 2. illustration of the procedure to derive the speed threshold (left panel) and the duration threshold (right panel). The left panel shows the histogram of local maxima exceeding the threshold, where the threshold ranges from 0 to the maximum speed, i.e., all local maxima exceed the threshold of 0, only a few the threshold of 100 and none exceed the maximum speed. The dotted line represents a uniform distribution of local maxima exceeding the speed threshold and the gap statistic (red line) is the smoothed difference between the two. The maximum of the gap statistic is selected as speed threshold. The right panel shows the distribution of possible fixations. This distribution has 2 peaks, one at 0 ms and one around 400 ms, the duration threshold (red line) is the minimum between these two peaks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

After this first step the non-saccadic eye movements still consist of noise and fixations. To separate fixations from noise, a duration threshold is used. The right panel of Fig. 2 clearly shows two distributions; one with many short non-saccadic durations (noise) and one with longer non-saccadic durations approximately normally distributed around 400 ms (fixations). To separate these two distributions the minimum between the two local maxima of the histogram of non-saccadic durations is calculated (see the right panel of Fig. 2). This minimum is the optimal threshold (red line in right panel of Fig. 2) to separate fixations from noise. All points above this threshold are classified as fixations.

Because infant eye-tracking data have some specific characteristics, the original algorithm was modified in three ways. The first and largest adjustment was that speed thresholds were estimated per trial, whereas Mould et al. (2012) used multiple trials of the same person. Although this worked well in our data set for the speed threshold, this approach resulted in too few data points to reliably estimate the duration threshold. Therefore 28 trials (all images) per person were combined to estimate the duration thresholds. Second, saccades with velocities that exceeded the 1000 deg/s were excluded from the analyses. Inspection of the data showed that these velocities often occurred before and after missing data points, some which were incurred by blinking. This is in line with the study of Pedrotti, Lei, Dzaack, and Rötting (2011) who also found that eye-trackers produce unreliable measures before and after blinks. Third, fixations that were separated by saccades shorter than 10 ms were combined. The infant data in this study were too noisy to reliably detect such short saccades.

2.4. Calculation of saccade directions

The direction of saccades was measured in degrees relative to the pictures, ranging from 0° to 360°, covering the full range of the circle. Saccades in the 0° direction were to the right, in the 90° direction up, in the 180° direction to the left and in the 270° direction down. The direction of the straight line from the first *x* and *y* coordinate of the saccade to the last *x* and *y* coordinate of the saccade was defined as the saccade direction.

2.4.1. Binning approach

To use the binning approach, the proportion of horizontal, vertical and oblique saccades that infants and adults made was calculated for each trial. Saccades made along the 0° axis (±30°) and the 180° axis (±30°) were classified as horizontal saccades, saccades made along the 45° axis (±15°), the 135° axis (±15°), the 225° axis (±15°) and the 315° axis (±15°) were classified as oblique saccades and saccades made along the 90° axis (±30°) and the 270° axis (±30°) were classified as vertical saccades. These proportions were chosen so every direction covered the same range (33.3%, i.e. 120°) of the circle. This was done to be able to make fair comparisons between the three directions.

2.4.2. Von Mises approach

The Von Mises distribution can be thought of as the normal distribution on a circle. Because multiple peaks in the distribution were expected, for instance at zero and 180° representing horizontal saccades, a mixture of Von Mises distributions was fitted on the data of the infants and the adults. The movMF package (Hornik & Grün, 2011) in R (R Core Team, 2014) was used to fit this mixture of Von Mises distributions.

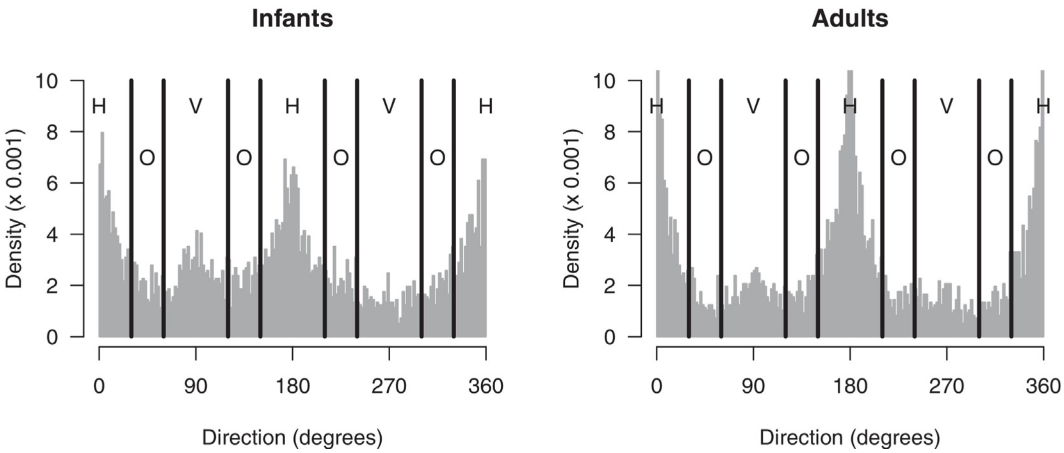

Fig. 3. The distribution of saccade directions overlaid with the cut-off points of the binning approach to classify horizontal (H), vertical (V) and oblique (O) saccades.

2.5. Data pre-processing

The data-driven algorithm of Mould et al. (2012) was used to classify fixations and saccades. This algorithm adjusts the thresholds to data quality; noisier data results in more conservative thresholds. Mean velocity (M = 35.48 deg/s, SD = 12.82) and duration (M = 85.81 ms, SD = 28.43) thresholds were higher in infants relative to adults (M velocity = 21.62 deg/s, SD = 7.15; M duration = 58.74 ms, SD = 15.92). This is what would be expected, as infant data are noisier than adult data. Furthermore, the thresholds do not deviate much from commonly used fixed thresholds, such as the standard Eyelink velocity thresholds of 35 deg/s and the often used 100 ms duration threshold.

A common problem in infant eye-tracking is that key dependent variables, for example, fixation durations, correlate with noise levels (Wass et al., 2014). Wass et al. (2014) defined two sources of noise, robustness (the mean length of usable data segments per trial) and precision (the differences between the raw data and smoothed data). Lower robustness and higher precision scores indicate higher noise levels. Wass et al. (2014) showed that these measures correlated with fixation durations; infants who had noisier data appeared to have shorter fixation durations. The Mould et al. (2012) algorithm used in this study overcame these problems by adjusting thresholds to the noise levels. There was no correlation between robustness and median fixation duration (r = −0.06, $t(39)$ = −0.39, p = 0.701) and the correlation between median fixation duration and precision was also non-significant (r = −0.26, $t(39)$ = −1.71, p = 0.094).

3. Results

3.1. Descriptives

The infants made 5529 fixations (M = 434 ms, SD = 258 ms, range = 44–2744 ms) and the adults made 13,283 fixations (M = 275 ms, SD = 171 ms, range = 30–3198 ms). These values are in line with fixation durations others report (e.g., Johnson, Slemmer, & Amso, 2004). The infant fixation durations are typically longer than the adult fixation durations, the mean fixation durations were also correlated with the age of infants (r = −0.42, $t(39)$ = −2.86, p = 0.007), such that younger infants had longer fixation durations than older infants, which is what would be expected. There were 4832 infant saccades and 12,367 adult saccades available for analyses. The distribution of saccades directions for infants and adults can be found in Fig. 3.

3.2. Binning approach

Fig. 3 shows the distribution of saccade directions with the cut-off points for horizontal, vertical and oblique saccades.[1] The mean proportions in these three directions were compared between infants and adults. The left panel of Fig. 4 shows these proportions for infants and adults grouped over images. Horizontal saccades are made more often than vertical and oblique saccades, in both infants and adults, indicating that infants have the horizontal bias. However, adults show the bias to a larger extent.

[1] We also analyzed the data using four bins of 90° each, instead of three 120° bins, this did not change the results.

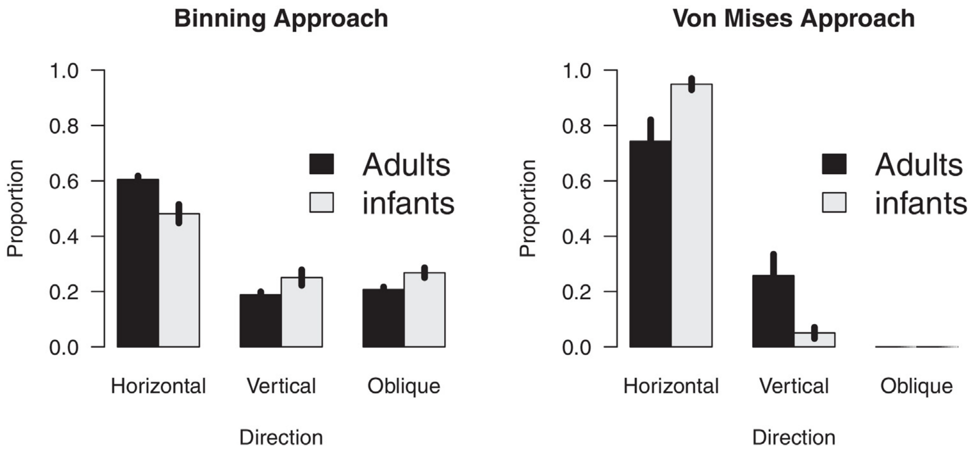

Fig. 4. Proportion of horizontal, vertical and oblique classified saccades by the binning (left panel) and Von Mises (right panel) approach (bootstrapped). Error bars lie two standard errors around the means in the binning approach and two standard deviations in the Von Mises approach.

Table 1
AIC, BIC and corresponding Akaike weights for models with 1–12 components fitted on the infant and adult data.

	Infants				Adults			
	AIC	Weight	BIC	Weight	AIC	Weight	BIC	Weight
1	−48.74	.00	−35.77	.00	−53.47	.00	−38.63	.00
2	−663.50	.00	−631.08	.00	−3860.34	.00	−3823.22	.00
3	−842.79	.00	−790.92	.00	−5180.34	.00	−5120.96	.00
4	−870.92	.00	−799.61	.29	−5217.88	.00	−5136.23	.00
5	−892.11	.49	−801.34	.70	−5269.73	.00	−5165.81	.00
6	−890.68	.24	−780.47	.00	−5336.58	.00	−5210.40	.97
7	−884.85	.01	−755.19	.00	−5351.57	.76	−5203.11	.03
8	−878.85	.00	−729.75	.00	−5346.85	.07	−5176.12	.00
9	−890.85	.26	−722.29	.00	−5340.91	.00	−5147.92	.00
10	−869.70	.00	−681.69	.00	−5334.98	.00	−5119.72	.00
11	−879.55	.00	−672.10	.00	−5329.04	.00	−5091.51	.00
12	−873.56	.00	−646.66	.00	−5348.43	.16	−5088.63	.00

To test for developmental differences within the infant group, the age of infants was correlated with the proportion of horizontal saccades. This correlation was significant, $r = 0.37$, $t(39) = 2.53$, $p = 0.016$, such that the proportion of horizontal saccades was larger for older than younger infants.

3.3. Von Mises approach

Because of the multiple peaks in the distribution of saccade directions, a mixture of Von Mises distributions was used to describe the data. The question of, how many Von Mises distributions should be mixed, was addressed by fitting several mixtures of the Von Mises distribution with an increasing number of components on the data of the infants and adults. Table 1 shows that five components were sufficient to fit the data of the infants according to the AIC, BIC and their Akaike weights (Wagenmakers & Farrell, 2004). The number of components for the adult data was less clear. The AIC suggested seven components, whereas the BIC suggested six components (see Table 1). Ideally the infant and adult data are fitted with the same number of components, to ease comparison. The five (infants) and six (adults) component models were selected, because five of the six components in the adult model were comparable with the five components of the infant model (see Fig. 5). The colors in Fig. 5 correspond to the component in that model. It can be seen that only the yellow component with the mean around 270° was not comparable between infants and adults.

A direct comparison between the parameters of the fitted models in infants and adults was not possible, because standard errors were not estimated. To compare the μ, κ and α parameters of the mixture of Von Mises distributions between infants and adults, confidence intervals were bootstrapped around these parameters. This was done by simulating data 100 times based on the parameters and refitting the model. The bootstrapped means and standard deviations of the parameters are displayed in Fig. 6. As Fig. 6 shows, the μ parameter was estimated very accurately and was almost the same for infants and adults. Both infants and adults had two components looking to the right (around 0°), one component looking up (around 90°) and two components looking to the left (around 180°). The κ parameters of adults were higher on all components, except for the vertical up component. This implies that overall there was lower variance in the adult data than in the infant data. The α parameter showed differences in component three and four. Adults made more saccades upwards, whereas infants made

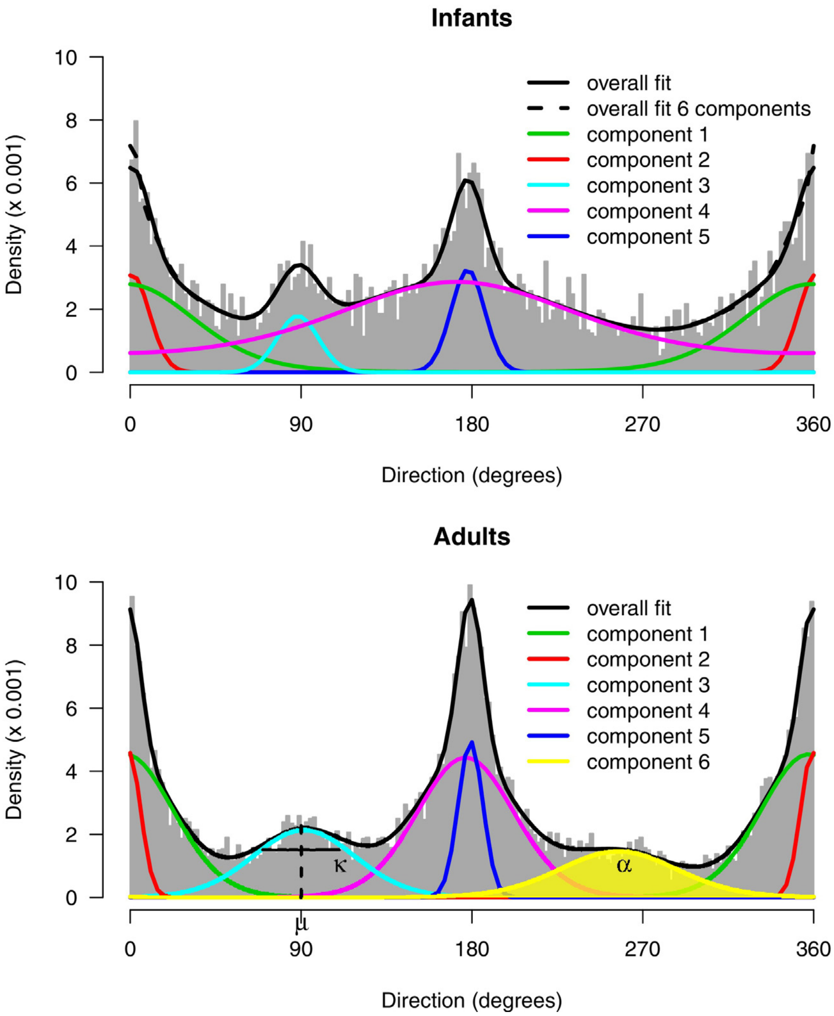

Fig. 5. Fit of the mixture of the Von Mises distribution on the infant (upper panel) and adult (lower panel) data. The components correspond to the components in Fig. 6. In the adult plot, the parameters μ (mean) and κ (variance) are shown for the third (cyan) component. The α (proportion) parameter is shown for the sixth (yellow) component and corresponds to the shaded area of the distribution below the yellow curve. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

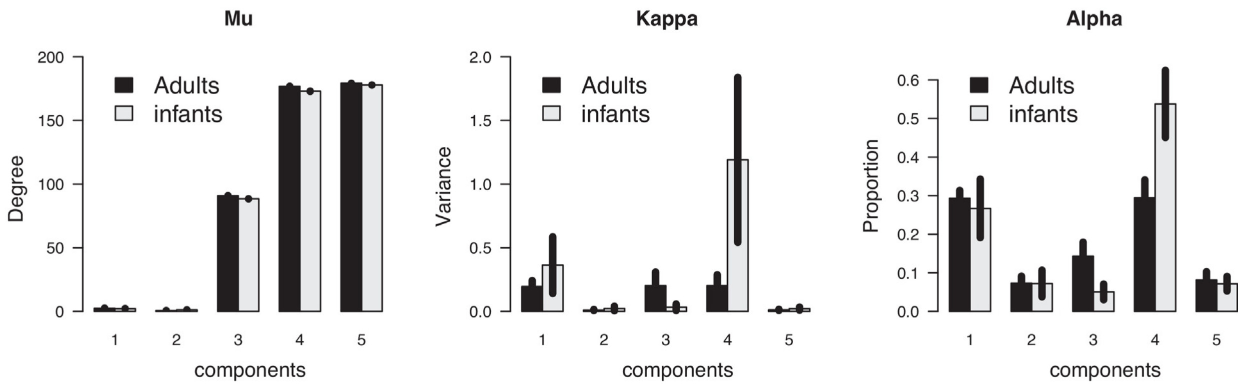

Fig. 6. Bootstrapped means and standard deviations of the μ (mean), κ (variance) and α (proportion) parameters of infants (light bars) and adults (dark bars). Error bars lie two standard deviations around the mean. A visual representation of components 1–5 can be found in Fig. 5.

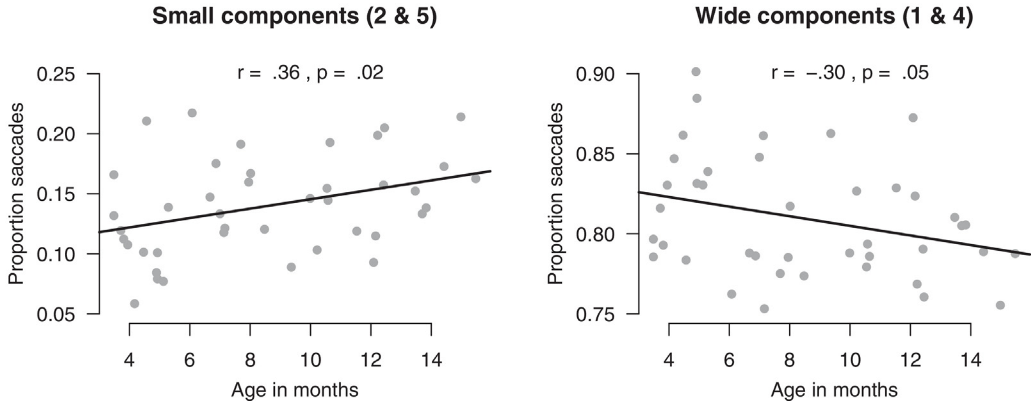

Fig. 7. The correlation between age and proportion of saccades in the small components (left panel) and wide components (right panel). Older infants are more likely to make saccades in the small components than younger infants (left panel) and vice versa are younger infants more likely to make saccades in the wide components than older infants (right panel).

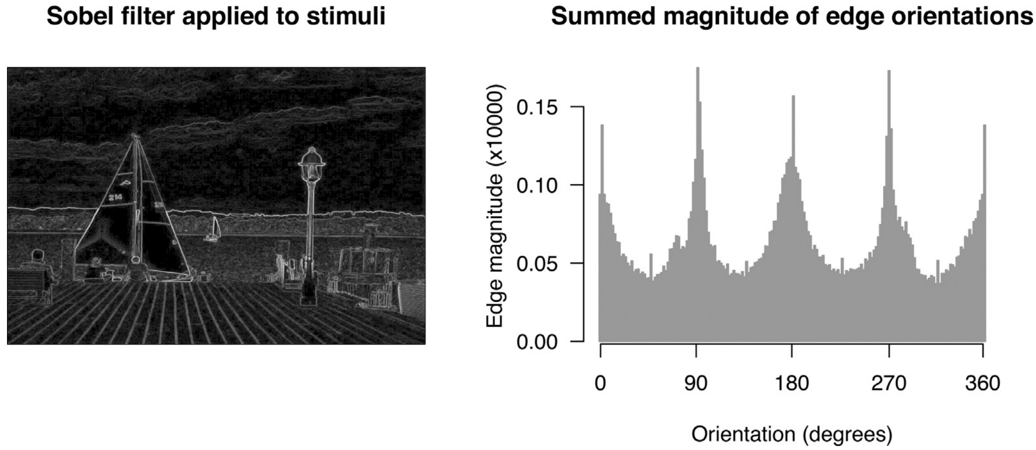

Fig. 8. The left panel shows a Sobel filter applied to stimuli to highlight edges. The right panel shows the histogram of summed magnitudes of edge orientations for these stimuli. The magnitude (white pixel correspond to a high magnitude, black pixels to a low magnitude) of each pixel within a 2° bin is summed. In these stimuli the ratio between horizontal and vertical summed magnitudes is approximately 1 as can be seen from the peaks that have approximately the same heights in both directions.

more saccades to the left. Interpretation of these α parameters should be done carefully, because the adults had another component that is not displayed in the plot.

To compare these findings with the findings of the binning approach the μ and α values were used to classify the proportion of horizontal and vertical saccades in infants and adults. Although the binning approach showed that adults made more horizontal saccades than infants, the Von Mises approach showed the opposite pattern. Ninety-five percent of infant saccades came from components with μ in the horizontal direction, for adults this was only 74% (see the right panel of Fig. 4). In the discussion we will elaborate on this finding. The correlation between the proportion of horizontal saccades and age of infants was not statistically significant when using the Von Mises approach ($r = 0.22$, $t(39) = 1.42$, $p = 0.163$). However, a developmental pattern was observed within the horizontal saccades of the infants. The Von Mises analysis showed that both saccades to the left and right are described by two components, one small and one wide component. When the posterior chances of saccades belonging to these components are averaged over participants and correlated with age, it becomes clear that older infants make more saccades that fall in the small components, whereas younger infants make more saccades that fall within the wide components (see Fig. 7).

3.4. Stimulus properties

The stimuli used in this study were real-world scenes and it is known that these scenes have a predominance of edges in the horizontal and vertical directions (Coppola, Purves, McCoy, & Purves, 1998). To assess the influence of edge orientations on the saccade directions, we applied a Sobel filter to grayscale versions of the stimuli to highlight the edges (see the left panel of Fig. 8). The Sobel filter returns for every pixel a magnitude (how bright that pixel is) and an orientation (in which direction that pixel points). The magnitudes at each orientation were summed for all stimuli separately (see right panel

Fig. 8 for an example). For every stimulus a ratio between horizontal and vertical summed magnitudes was calculated using the same bin sizes as in the binning approach. The mean horizontal/vertical ratio was $M = 1.20$, $SD = .37$, range = .59–1.83. If edge orientations drive the horizontal bias, this ratio would be correlated with the proportion of horizontal saccades. However, the proportion of horizontal saccades classified by the binning approach ($r = -0.22$, $t(26) = -1.13$, $p = 0.268$) and Von Mises approach ($r = -0.16$, $t(26) = -0.81$, $p = 0.427$) in infants did not correlate with ratio of horizontal versus vertical orientations. The same pattern was observed for adults. The proportions of horizontal saccades classified by the binning approach ($r = -0.16$, $t(26) = -0.81$, $p = 0.425$) and Von Mises approach ($r = -0.04$, $t(26) = -0.2$, $p = 0.846$) did not correlate with ratio of horizontal versus vertical orientations. This implies that the horizontal bias is not driven by edge orientations.

4. Discussion

This study shows that infants have the horizontal bias and replicated the horizontal bias in adults. Furthermore, a developmental pattern was found in which older infants make horizontal saccades with more precision than younger infants. That the horizontal bias was found in adults is in line with earlier studies (Foulsham et al., 2008; Gilchrist & Harvey, 2006; Tatler & Vincent, 2008), but that infants also have this bias and that the bias develops are novel findings. Future studies can benefit from these findings by incorporating the horizontal bias in models that describe infant eye movements. Using general biases, such as the horizontal bias, to model behavior has proven to be a fruitful endeavor in the field of action selection (Körding & Wolpert, 2004). Certain motor behaviors are more likely to be selected than others. For instance, moving one finger, increases the likelihood for other fingers on that hand to move as well (Ingram, Körding, Howard, & Wolpert, 2008). Incorporating these behavioral biases improved the ability to model and understand action selection (Körding & Wolpert, 2004). Similarly, incorporating the horizontal bias in eye movement models, can improve our understanding of attention allocation and subsequently cognitive development.

The current study with infants can also shed some light on the origin of horizontal bias. In the introduction, three possible explanations of the origin of the horizontal bias were mentioned. Our findings support the biomechanical and physiological explanations, but make the distribution of objects explanation less likely. The biomechanical explanation is that horizontal saccades require less muscle activity than vertical and oblique saccades (Viviani et al., 1977). The physiological explanation is that the spatial density of rods and cones in the retina is higher along the horizontal direction than the vertical direction (Curcio et al., 1990). Both biomechanical and physiological factors are unlikely to be different for infants and adults. The finding that infants have the horizontal bias does therefore support that biomechanical and physiological factors drive the bias. The explanation that the distribution of objects in the environment drives the bias proposes that, we learn that objects are located along the horizon and therefore develop a horizontal bias. If we do learn that interesting objects are often located along the horizon, we would not expect infants to have the bias. Especially, young infants (<6 months) should not show the bias as they spend most of their time laying on their back looking upwards. That we did find the bias in infants, makes this explanation therefore less likely. Although infants who lay on their back are more restricted in their head movements; movements to the left and right are easier made than back and forth, which could result in more horizontal eye movements due to more experience in horizontal head movements. From an evolutionary point of view, the environment could still play a role in shaping the horizontal bias, because typically information is richer along the horizon. A possible adaption to this environment could be the distribution of rods and cones in the retina.

Two analysis techniques were used in this study: the binning approach and the Von Mises approach. The added value of the Von Mises approach over the binning approach is that the Von Mises approach allowed us to assess variability in eye movement directions and address questions about the source of variability differences between infants and adults. Furthermore, by defining saccade directions in a data-driven manner, no assumptions about saccade directions had to be made upfront. Since the Von Mises approach takes the full distribution into account, it provides a more realistic description of eye movement directions, than pre-defined bins.

The two approaches yielded slightly different findings regarding the extent of the bias. The binning approach showed that adults have a larger horizontal bias than infants, whereas the Von Mises approach showed that infants have a larger horizontal bias than adults. That results are different when binning and continuous approaches are used is not uncommon (MacCallum et al., 2002; Van Der Maas & Straatemeier, 2008) and can be explained by the variance differences in saccade directions between infants and adults. The flat saccade distributions of infants led to the inclusion of relatively few data points in the horizontal bins, whereas the flat distributions led to the inclusion of relatively many data points under the Von Mises approach. Since the difference between the bin size and width of Von Mises distributions is less profound in adults, the two approaches could lead to opposite results.

The Von Mises analysis also found an age-related difference in variance of saccade directions: Older infants were more precise in targeting their saccades along the horizon than younger infants. This is in line with findings of Bronson (1990), who found that very young infants (2–14 weeks) become more accurate in targeting their saccades as they get older. This increased accuracy could be a function of development of the visual system, however it may also be explained by increased control over head and body movements, or a combination of both. The source of this variance may be noise, in a sense that infants are targeting saccades in the horizontal directions and the variance reflects the error. On the other hand, the variance can also reflect a pattern of random scanning behavior. In this study we cannot distinguish these two sources, however we can conclude that infants become less noisy in their saccade directions as they get older.

What could be the function of increased variability in saccade directions in younger infants? From other research areas, it is known that random actions or random inputs to the system can actually foster development. From neural network models it is known that biologically plausible networks form feature analyzing 'cells' that are similar to the cells found in the visual cortex (e.g. on-center-off-surround cells, bar-detectors, etc., Linsker, 1988). These cells emerge based on random input (white noise) to the first layer of the neural network. In modeling hand-eye coordinations, random arm activity helps a model to learn coordinated grabbing behaviors (Bullock, Grossberg, & Guenther, 1993). Such examples show that random input and actions are not necessarily uninformative. Random eye movements may similarly help infants to select different kinds of information from their environments and tune the perceptual system. In particular, early variability in saccade directions can be seen as a form of exploration of the environment that is suitable when little knowledge is present; when the infant has learned more about what to expect, more precisely targeted saccades become more suitable as a form of exploration (cf. Schlesinger, Amso, & Johnson, 2007; Tummeltshammer & Kirkham, 2013). Characterizing the skill or knowledge that is gained by this variability in saccade directions is an interesting challenge for future research.

There are some limitations of this study that should be considered. Images in this study were wider than they were high. This could have resulted in more horizontal than vertical saccades simply due to the image properties. Foulsham, Teszka, and Kingstone (2011) showed that the width/height ratio does influence saccade directions; however, they also found that the horizontal bias remained when stimuli were presented in portrait format. This indicates that the width/height ratio cannot fully explain our findings. Even if the horizontal bias found in this study is completely due to the presentation in landscape format, the result is still relevant as most eye-tracking studies present stimuli on a screen that is wider than high. Another limitation is that only real-world scenes were used as stimuli rather than isotropic images. Therefore, the horizontal bias may not generalize toward other stimuli. In adults the horizontal bias is also present when stimuli are isotropic (i.e. fractals, Foulsham & Kingstone, 2010). We did assess the influence of edge orientations in the stimuli and found no effect on saccade directions. This indicates that stimulus properties do not play an important role in the horizontal bias in infants.

In sum, this study found that infants have a horizontal bias in making saccades during free viewing of real-world scenes. In addition, a developmental pattern was observed in which older infants are more precise in targeting their saccades than younger infants. Future infant eye-tracking studies should consider the horizontal bias when designing experiments and analyzing eye-tracking data. Recognizing that general biases, such as the horizontal bias, exist, will improve our understanding of attention allocation and subsequently our understanding of infant cognitive development.

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