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Infants' center bias in free viewing of real-world scenes

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ABSTRACT

This study examines how salience and a center bias drive infants' first fixation while looking at complex scenes. Adults are known to have a strong center bias, their first point of gaze is nearly always in the center of the scene. The center bias is likely to be a strategic bias, as looking towards the center minimizes the distance to other parts of the scene and important objects are often located at the center. In an experimental design varying salience regions of scenes and start positions we examined infants' (N = 48, Age = 5–20-month-olds) first fixation after scene onset. The pre-registered hypothesis that infants also have a center bias while looking at real-world scenes was confirmed. The strength of the center bias is correlated with the saliency distribution such that the bias is weaker when the strongest salience is peripheral rather central. In the absence of clear salient regions there still was a strong center bias. These results suggests there is a competition between stimulus-driven factors and a center bias in steering attention from a young age onwards.

1. Introduction

How do infants explore their complex visual world? The available information is overwhelming, whereas attentional resources are limited. Necessarily, infants must select certain information to process, while ignoring other information. Infants have several attentional mechanisms that help them to explore their surroundings efficiently. For instance, innate biases enable infants to focus on biologically important features, such as faces (Fantz & Nevis, 1967; Valenza, Simion, Cassia, & Umiltà, 1996). Furthermore, infants use statistical regularities to identify meaningful visual features (Fiser & Aslin, 2001; Kirkham, Slemmer, & Johnson, 2002) and orient towards nor too simple, nor too complex visual information (Kidd, Piantadosi, & Aslin, 2012; Piantadosi, Kidd, & Aslin, 2014). Also, infants prefer novel (Spelke, Breinlinger, Macomber, & Jacobson, 1992; Fantz, 1963) and surprising (Téglás et al., 2011) information.

Most of our knowledge about infant cognitive development comes from looking behavior studies (Aslin, 2007, 2012), such as the studies revealing the characteristics of infant visual attention mentioned above. These studies often use artificial and simple stimuli, which allow to carefully control experimental conditions to reveal the mechanisms underlying infant visual attention. In contrast, viewing real-world scenes[1] is studied in adults because different attentional processes are involved when objects appear in context and the scenes are more complex (Henderson, 2003). For similar reasons, this study examines infants' attention over complex real-world scenes.

1.1. Infant visual attention

Infant visual attention is theorized to transition from exogenous driven towards more endogenous driven (Johnson, 1990; Johnson, 2002). That is, younger infants are mainly influenced by exogenous features in the environment such as salience and novelty (Spelke et al., 1992; Fantz, 1963). As infants grow older they also gain more endogenous control and become able to shift their attention voluntarily and intentionally (Colombo, 2001). In parallel infants develop more complex object knowledge with age (Cohen, Chaput, & Cashon, 2002; Johnson, Slemmer, & Amso, 2004). This makes it possible for older infants to shift their attention based on prior knowledge or expectations. During infancy, visual attention increasingly becomes an interplay between both exogenous and endogenous factors.

This interplay between exogenous to endogenous factors also lies at

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[1] In this literature on free-viewing real-world scenes are understood as pictures of real-world scenes either naturalistic or human-made seen on computer screens or otherwise seen in a lab-setting.

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the core of adult visual attention. To what extent and under which circumstances human visual attention is driven by exogenous or endogenous factors is one of the main research questions in the scene viewing literature (Henderson, 2017; Malcolm, Groen, & Baker, 2016). In the scene viewing literature this debate can be summarized as the salience versus objects debate. There is a correlation between low-level salience and where people look (Borji, Sihite, & Itti, 2013), but this correlation is often explained as the result of our attention towards meaningful objects that happen to be also salient based on low-level features (Einhäuser, Spain, & Perona, 2008; Stoll, Thrun, Nuthmann, & Einhäuser, 2015; Nuthmann & Henderson, 2010). The question to what extent adult visual attention is under exogenous or endogenous control relates closely to the developmental question of how and when a transition towards more endogenous control of visual attention in infants occurs. Scene viewing is the paradigm of choice to study visual attention and its genesis and development by studying infants in particular.

1.2. The center bias

A well-known and agreed-upon finding in the adult scene viewing literature is the existence of general tendencies in viewing behavior (Tatler & Vincent, 2009; Tatler & Vincent, 2008). Most prominently the horizontal bias (Tatler & Vincent, 2008; Foulsham, Kingstone, & Underwood, 2008) and the center bias (Tatler, 2007; Clarke & Tatler, 2014). These biases influence how adults distribute their attention across a scene. Notably, these biases are a confounding factor in examining other factors that drive attention. Recent studies into infant visual attention using complex and/or video stimuli all find that low-level salience does influence where infants look (e.g., Franchak, Heeger, Hasson, & Adolph, 2016; Amso, Haas, & Markant, 2014; Althaus & Mareschal, 2012; Frank, Amso, & Johnson, 2014). However, these studies do not explicitly mention or report these general biases. It is possible that the salience effects reported in these studies are actually the result of a center bias in infants and the center of the scenes being salient. As such it is important to understand the existence of these biases in infants. In a recent paper it was shown that infants, similar to adults, have a horizontal bias (Van Renswoude, Johnson, Raijmakers, & Visser, 2016), the focus of this paper is on the center bias in infants.

The center bias is the tendency to attend more to central than to peripheral regions of scenes (Tatler, 2007; Clarke & Tatler, 2014). The term center bias must be understood in the context of looking at a computer screen and cannot be easily generalized to the real (off-screen) world, although there is some evidence for the center bias from head-mounted eye-tracking paradigms (Ioannidou, Hermens, & Hodgson, 2016). Despite this limit to computer screens, understanding the center bias is still of great importance to understand infants' scene perception. To interpret infants looking behavior we need to know a baseline for their looking at the center, which is currently unknown. Also, infant research broadly depends on infants looking at screens, and hence knowing the basic tendencies that infants have in a such a situation is potentially relevant to many infant research paradigms. This led us to formulate three research questions: (1) Do infants have the center bias? (2) What is the interplay between the center bias and scene salience in infants' visual attention? (3) Does the center bias of infants develop with age?.

Several explanations have been giving for the center bias in adults. Importantly, the center bias in adults is not an artifact of the position of the fixation cross before the start of trials (Tatler, Baddeley, & Gilchrist, 2005). When the fixation cross is set away from the center, the first eye-movement is almost always made towards the center (Foulsham et al., 2008; Tatler, 2007). This rules out the most simple explanations, but three other common explanations remain; the center bias is a (1) physiological bias, (2) salience bias or (3) strategic bias. These three explanations are not mutually exclusive and are likely to all influence to bias to some extent.

The center bias can be a physiological bias caused by orbital reserve. This is the tendency to re-center the eyes in the orbits. During scene viewing re-centering would results in a bias toward the center of the scene when people are seated facing the center of the screen, which is usually the case. This explanation is in line with the findings of the center bias in a mobile eye-tracking study (Ioannidou et al., 2016).

Another common explanation is that the center of scenes is often salient, which draws the attention towards the center. The center of scenes are indeed often salient and this is believed to be a result of photographers making compositions with objects in the center, known as photographer bias (Tseng, Carmi, Cameron, Munoz, & Itti, 2009).

Thirdly, the center bias is also often explained as a strategic bias for two reasons. First, because of the photographer bias, the center is the region of the scene that is most likely to contain useful information. It is therefore helpful to shift attention always towards the center as it is likely to contain important information to understand the scene. Note that this is a different explanation than the salience explanation above as this does not require the center to be actually salient, simply the learned expectation that the center is salient is enough. Second, looking towards the center minimizes the distance to other parts of the scene and maximizes the total amount of information, or gist, that can be extracted from the scene (Najemnik & Geisler, 2005; Tatler, 2007). Both reasons highlight that having a center bias is helpful to efficiently process complex real-world scenes.

1.3. Do infants have the center bias?

The explanations of the center bias described above can be used to derive predictions of what we could expect in infants. The physiological and salience explanations of the center bias in adults would also predict a center bias in infants, given what is known about infant visual development. If the bias is physiological, infants are expected to have the bias since the physiology is similar in infants and adults. When salience causes the bias it would also be expected that infants have the bias, as infant attention is known to be driven primarily by exogenous factors such as salience. Finally, however, given the explanation that the center bias results from a learned expectation, we would expect the bias to be stronger for older infants than for younger infants. The few papers on infant scene perception known to us do not explicitly report the center bias (e.g., Mahdi, Su, Schlesinger, and Qin, 2017; Helo, Rämä, Pannasch, and Meary, 2016), but the tendency to fixate the center does seem apparent in their data and this is also what we observe in the scene viewing data of infants collected in our own lab. Taken together this led us to hypothesize that infants have or acquire the center bias within their first year.

1.4. The center bias and salience?

Given what is known about infant visual development it is very likely that salience plays an important role in infant visual attention. Hence, to study infant central bias we need to control for salience. To this end, we explicitly selected scenes with different salience distributions to experimentally investigate the influence salience has on the center bias. All in all, salience is considered an important factor in infant attention and hence also scene viewing and this led us to hypothesize that the strength of the center bias in infants does depend on saliency of the center versus the out-of-center areas.

1.5. The center bias and age of infants?

Following the physiology and salience explanation of the center bias we would not expect any developmental effect. Given the strategy hypothesis, however, we would expect the center bias to develop with age. Since young infants do not have much experience looking at screens (Rideout, Vandewater, & Wartella, 2003), it is unlikely that they have already learned this bias. Older infants have more experience looking at

screens and are thus more likely to have learned that looking at the center is an efficient strategy. We therefore did hypothesize that the center bias does develop with the age of infants, although the timeline is quite unclear. We included infants between 5 and 20 months old. The lower age is chosen because we wanted to make sure that the perceptual system of the child is well-enough developed. Contrast sensitivity, for example, still has a rapid development during the first three months of life (Atkinson, Braddick, & Moar, 1977). The upper bound has also practical reasons, children beyond 20 months are more difficult to test with an eye-tracker, for which they have to sit still. Moreover, given the amount of experience infants have with screens, 16 months of development should already show some learning effects if such are present.

1.6. Current study

To answer these questions we propose to test infants in a free-viewing experiment where they see pictures of real-world scenes. To test the first hypothesis, "Do infants have the center bias?", we varied the initial position of a fixation before the appearance of the stimulus, using a gaze contingent setup (Wang et al., 2012) such that eye movements to both the center and periphery of scenes could be made. The crucial measure was whether the first fixation after scene onset would be in the center or in the periphery of the scene. To test the second hypothesis, scenes with central, uniform and peripheral salience distributions were included to be able to quantify the role of salience. To test the third hypothesis that the center bias develops with age we included a wide age range of infants (5–20-month-olds) such that the variation in screen experience is sufficiently large (Rideout et al., 2003).

2. Method

2.1. Pre-registration

There is a recent focus on reproducible research (Open Science Collaboration, 2015) in psychology as many studies could not be replicated. Unfortunately, infant studies also suffer from questionable research practices (Peterson, 2016), but initiatives such as the Many Babies Collaboration (Frank et al., 2017) are undertaken to promote open and reproducible results. To contribute to the open science movement, we pre-registered the study on the Open Science Framework (Spies, 2013). The three hypotheses, the confirmatory analyses that we use to test the hypotheses, a power analysis that indicated 50 infants yield enough power, the study design and more information can be found at the pre-registration website[2].

2.2. Participants

Sixty-four infants were recruited via the University of Amsterdam's baby database and 22 students participated for course credit. Sixteen infants and six adults had to be excluded for various reasons: inability to calibrate point of gaze (1 infant and 1 adult), problems with data recording (2 infants and 4 adults) and problems with the presentation software that caused the experiment to terminate too early (13 infants and 1 adult). Unfortunately these issues did not occur during pilot testing and since we pre-registered the experiment we decided to keep testing and stick with our pre-registered plan. The data of the remaining 48 infants (Mean age = 12.16 months, SD = 3.10, range = 5.46–20.53) and 16 adults (Mean age = 20.79 years, SD = 2.17, range = 18–24) were used in the analyses.

[2] https://osf.io/fg6sd/register/565fb3678c5e4a66b5582f67.

2.3. Stimuli

2.3.1. Salience algorithm

The algorithm of Itti and Koch (2000) was used to define salience as this is a sensible choice to use in infants. In a recent paper (Mahdi et al., 2017) in which several saliency algorithms are compared in predicting infant fixations, the Itti and Koch algorithm is among the best on several measures. Moreover the algorithm is biologically plausible, which makes sense to use in infants as it mimics the visual system and selects what stands out as salient. Here we used the python implementation from https://github.com/akisato-/pySaliencyMap.

2.3.2. Stimuli selection

To select scenes from the LabelMe database (Russell, Torralba, Murphy, & Freeman, 2008) with different salience distributions (biased to the center, to the periphery or uniformly distributed), the following procedure was used: (1) Folders from the LabelMe database with real-world scenes and high resolution images ($> 1280 \times 1024$ pixels) were selected. (2) Salience maps of all images in these folders were made using the (Itti & Koch, 2000) algorithm as described above (see Fig. 1 B, C & D for examples). (3) Correlations between these salience maps and a center biased salience map (Fig. 1A) were calculated using a simple correlation measure (Le Meur & Baccino, 2013). The prototype center bias map is a bi-variate normal distribution with means 0 and standard deviations.2 ranging from -1 to 1. That is, a two-dimensional matrix of numbers representing a multivariate normal distribution of values with higher numbers in the center of the matrix and lower numbers towards the periphery of the matrix to represent the center bias. In order to correlate this prototype map to a salience map, the prototype map is scaled such that each number in the center biased map corresponds to a pixel in the salience map. The reported correlations are the correlations between the center biased map and the salience maps on a pixel by pixel level. This resulted in the distribution of correlations shown in Fig. 1E. As expected, most images correlated positively (*Mean* $r = .13$) with the center biased salience map. (4) We selected the 20 scenes with the strongest negative correlation (r's $< -.3$), a random sample of 20 scenes with positive correlations (r's $> .3$ & $< .4$, to match the magnitude of the negative correlations) and the 10 images with correlations closest to zero. (5) From these 50 images we manually selected a final sample of 10 scenes in each condition by excluding indoor scenes and similar scenes, also we included 3 white noise scenes as pure uniformly distributed scenes. Fig. 1 F, G & H show examples of how the scenes were presented, overlaid with a circular aperture to avoid any biases due to the presentation format (Foulsham, Teszka, & Kingstone, 2011). To avoid additional biases due to sharp edges of the aperture, the edges were blurred using the *raisedCos* function in Psychopy (Peirce, 2007).

2.4. Design, apparatus & procedure

Thirty real-world images were presented to participants while an eye tracker recorded their eye movements. Prior to every image a colored dot appeared on the screen for a maximum of 2500 ms. The dot would expand and contract, and was accompanied by a beeping sound that was to attract the participants' attention towards the dot. This dot acted as a starting location and was located equally far from the scene center as from the scene boundary. Only after participants looked at the dot for at least 100 ms within 1.25° of visual angle, the scene appeared on the screen for 2500 ms. If participants failed to fixate the dot for at least 100 ms, the scene would not be displayed and a new trial would start. The experiment ended if participants saw all 30 scenes, or after a maximum of 60 trials.

The experiment was programmed in Python (Python Software Foundation, https://www.python.org/), and Pygaze (Dalmaijer, Mathôt, & Van der Stigchel, 2014) was used to interact with the EyeLink 1000 eye tracker and run the experiment using Psychopy (Peirce, 2007) as back-end. The remote EyeLink 1000 eye tracker (SR Research

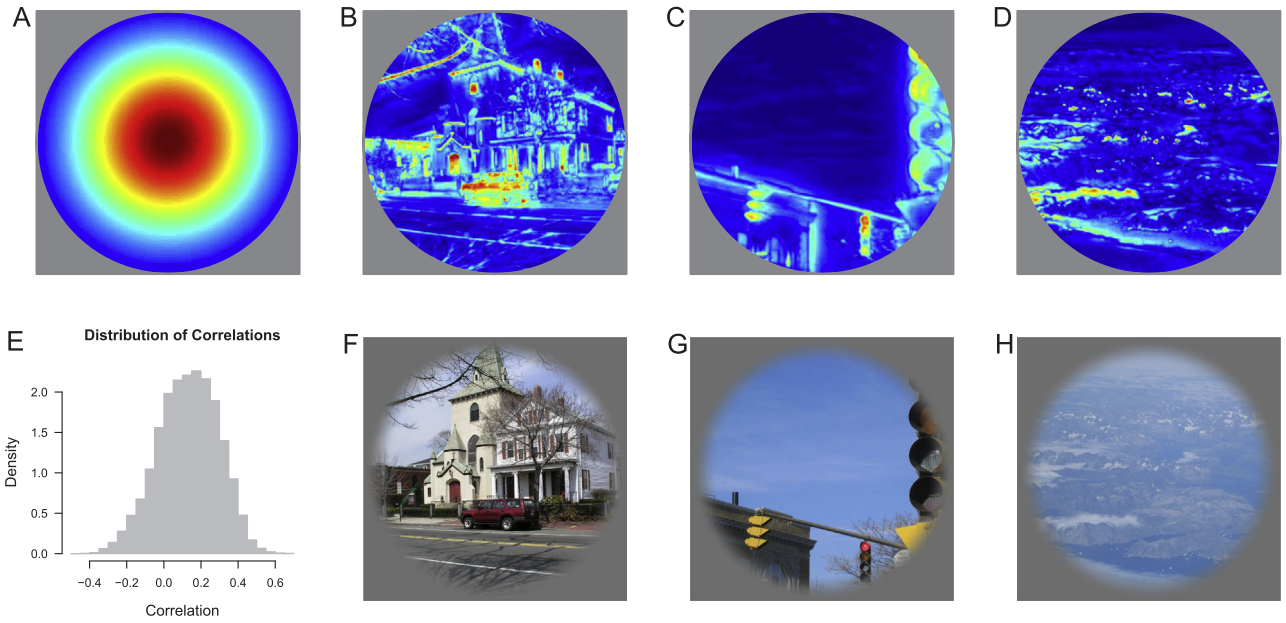

Fig. 1. Panel A shows a prototype center biased salience map and panels B, C & D show salience maps of three scenes used in the center, periphery and uniform conditions in this study. Panel E shows the distribution of the correlations between the prototype center biased salience map and over 6000 salience map from scenes of the LabelMe (Russell et al., 2008) database. There is an overall positive correlation which indicates that real-world scenes have salience distributions that are biased towards the center. Panels F, G & H show examples of how the scenes in the center, periphery and uniform condition were in the presented during the experiment, overlaid with a circular aperture to avoid any biases due to format (Foulsham et al., 2011).

Ltd., Ontario, Canada) recorded participants' eye movements at 500 Hz, and only one eye was digitized. In order to record eye movements, a target sticker was placed on the participants' foreheads. This ensured that head positions were tracked when participants moved their heads during the experiment.

Before the start of the experiment all parents and/or caregivers of the infants gave their informed consent. The experiment was carried out in accordance with the Code of Ethics of the World Medical Association and approved by the ethical commission of the University of Amsterdam. Participants were seated in a darkened room with dimmed lights in order to avoid them attending to anything other than the stimuli. Both adults and infants were seated at a distance of 55 cm from a 17-inch-screen, with a subtended visual angle of approximately 27° × 34°. Infants were seated in a baby car seat or on their parent's lap. Parents were instructed not to interact with their child. Prior to stimulus presentation, a five-point calibration and validation method calibrated the point of gaze until it fell within 1° of the target's center. To calibrate point of gaze, green, expanding, and contracting dots were presented on a grey screen. When the dots failed to attract the infants attention, we started a calibration procedure in which the green dots were replaced by the children's book character Miffy. We used the Miffy-calibration in 8 infants (5.46 to 13.19-month-olds, M = 9.04, SD = 3.08). After successful calibration, the experiment began.

2.5. Data analyses

2.5.1. Data Pre-processing

Raw sample to sample data were classified into fixations and saccades, using the R-package (R Core Team, 2017) Gazepath (van Renswoude et al., 2017). Gazepath uses an algorithm to classify eye tracking data into fixations and saccades, while accounting for individual differences and data-quality. Especially in studies where data of different populations is compared (such as infants and adults in this study), this is very useful as the same method can be applied to participants in all populations. This rules out the possibility that population differences occur because of differences in noise-levels.

2.5.2. Confirmatory hypothesis testing

The (binary) dependent variable is the location of the first fixation: inside the center of images (1) or outside the center of images (0). Every first fixation after scene onset that fell within 6.4° of visual angle from the center of the scene (the start position) is classified as being inside the center of the scene. Fixations outside this circle are classified as being outside the center of the scene. The independent variables are the salience distribution of scenes (biased to the center, biased to the side, or evenly distributed) and the infants' age (5.46- to 20.53-month-olds). A General linear mixed model (GLMM) is fitted to this data and we report the beta coefficients of the intercept, age and salience distribution. When the intercept beta coefficient deviates from zero we conclude infants have a center bias. The other two coefficients indicate whether this bias depends on age and salience respectively.

2.5.3. Exploratory analyses

To replicate previous findings of the center bias in our stimulus set we included adults in the study as well. We fit a similar GLMM to the combined data of infants and adults with a group (Infants vs Adults), instead of age variable. This analysis allows us to test for differences in center bias between infants and adults. Furthermore we conduct follow-up analyses after removing outliers and using the distance to the center as dependent variable.

3. Results

The Results section starts with the description of the data followed by the confirmatory analyses in which the pre-registered hypotheses are tested. Afterwards several exploratory follow-up analyses are conducted to verify the robustness of the results. In these exploratory analyses the center bias replicates in adults, it is shown that the results are similar when outliers are removed and verified that using the continuous distance from the center as measure of the center bias instead of the location of the first fixation being inside or outside the center provided similar results.

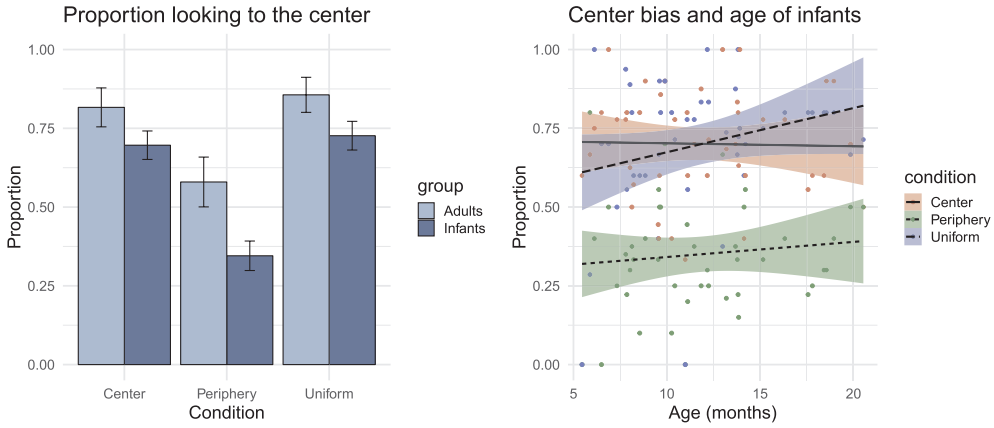

Fig. 2. The left panel shows the proportions of looking to the center for infants and adults in all three conditions. The right panel shows the relationship between looking to the center and age of infants.

3.1. Descriptives

For infants, 85% of the trials were available for data analyses. On average only 5 trials were missing distributed evenly across conditions. Ten infants provided data on all 30 trials and there was no significant correlation between the number of trials on which data was available and age. For adults only 5 trials in total were missing leaving 99% of the data available for analyses. There were 1213 first fixations in infants (mean duration = 509.39 ms, SD = 317.3 ms, range = 100–2102 ms), and 475 first fixations in adults (mean duration = 367.17 ms, SD = 387.87 ms, range = 100–2302) available for analysis. The left panel of Fig. 2 shows the proportions of looking to the center for infants and adults in the three conditions. The right panel shows the relationship between age and looking to center for the three conditions.

3.2. Confirmatory analyses

The GLMM analysis of the infant data with salience condition and age as predictors and participant and image as random effects confirmed the first hypothesis: first fixation locations were more likely to fall in the center, than in the periphery of scenes ($\beta = 0.85$, SE (β) = 0.175, $z = 4.855$, $p < .001$). The second hypothesis was also confirmed, there was an effect of scene content. Scenes with salience distributions biased towards the periphery of scenes were less likely to elicit central fixations than scenes with salience distributions biased towards the center ($\beta = -1.532$, SE(β) = 0.244, $z = -6.289$, $p < .001$). The third hypothesis was not confirmed, there was no significant effect of age within the group of infants ($\beta = -0.012$, SE (β) = 0.029, $z = -0.406$, $p = 0.685$).

To validate that our stimulus set could replicate the center bias in adults, we tested 16 adults with the same procedure as we tested the infants with. The adults also showed an overall center bias ($\beta = 1.582$, SE(β) = 0.272, $z = 5.819$, $p < .001$), replicating the center bias in adults (Foulsham et al., 2008; Tatler, 2007; Tseng et al., 2009). Adults showed a similar effect of scene content as infants ($\beta = -1.221$, SE (β) = 0.334, $z = -3.652$, $p < .001$), the bias was weaker for scenes in the periphery condition than in the center condition.

3.3. Exploratory analyses

An exploratory GLMM analysis combining the infant and adult data was conducted to compare the magnitude of the center bias effect between infants and adults. Salience condition and group (infant or adult) were the predictors and participant and image were included as random effects. This analysis showed that the center bias is weaker for infants than for adults ($\beta = -0.699$, SE(β) = 0.247, $z = -2.831$, $p = 0.005$). The distributions of first fixations are displayed in Fig. 3 for infants (top row) and adults (middle row) in the center (left column), periphery (middle column) and uniform (right column) conditions. These plots confirm a center bias for both infants and adults when the center is salient or salience is uniformly distributed across scenes. The periphery condition shows a bi-modal pattern for both infants and adults. Most fixations fall around the bottom of the scene, which is also the most salient part of the scenes in this condition (bottom middle panel). The second mode of adults' fixations fall in the center, whereas the second mode of infants' fixations fall at the top of the scene. The bias towards the periphery of infants' fixations could be explained by the salience distribution that is also biased towards the periphery. In adults, however, the fixations in the center cannot be explained by the salience distribution, as the center is not salient. Something similar seems to occur in the uniform condition; both infants and adults show a center bias, but this bias cannot be explained by the uniform salience distribution.

3.3.1. Outlier removal

The experimental manipulation we used in this study led to saccade latency distributions that were bi-modal for the saccades following the fixations on the start locations. Fig. 4 shows these distribution of fixation duration for both adults and infants. These shorter latencies are the result of an already planned saccade during the time the screen showed the dot on the starting location. Although the actual scene is on the screen when these saccades take place, they are targeted at the dot that is no longer on screen, but executed anyway. This is confirmed by the fact that basically all fixations following the shorter latencies are re-fixations on the starting location. This effect is common in scene onset delay paradigms (Henderson & Smith, 2009; Henderson & Pierce, 2008) and is taken into account in saccade generating models (Nuthmann, Smith, Engbert, & Henderson, 2010; Trukenbrod & Engbert, 2014; Tatler, Brockmole, & Carpenter, 2017). However, we did not anticipate this and this caused several outliers in our data. Since the re-fixations that follow these shorter latencies are not under control of the stimuli, it makes sense to remove them from the analyses. To do so we used a threshold of 175 ms., this threshold is able to separate both the infant and adults latencies as can be seen by the red vertical bars in Fig. 4. Moreover, 175 ms. is considered to be the shortest amount of time in which a saccade can be planned and executed (Rayner, Slowiaczek, Clifton, & Bertera, 1983).

The analyses without the outliers show basically the exact same results as the original analyses. The bottom panels of Fig. 4 show the same plots as Fig. 2, but with the outliers removed. The overall pattern of results is the same, there is a main effect of the center bias and an effect of condition, but not of age. The only notable difference is that the center bias effect is even stronger after removing the outliers. This makes sense as the outliers are fixations following saccades targeted at

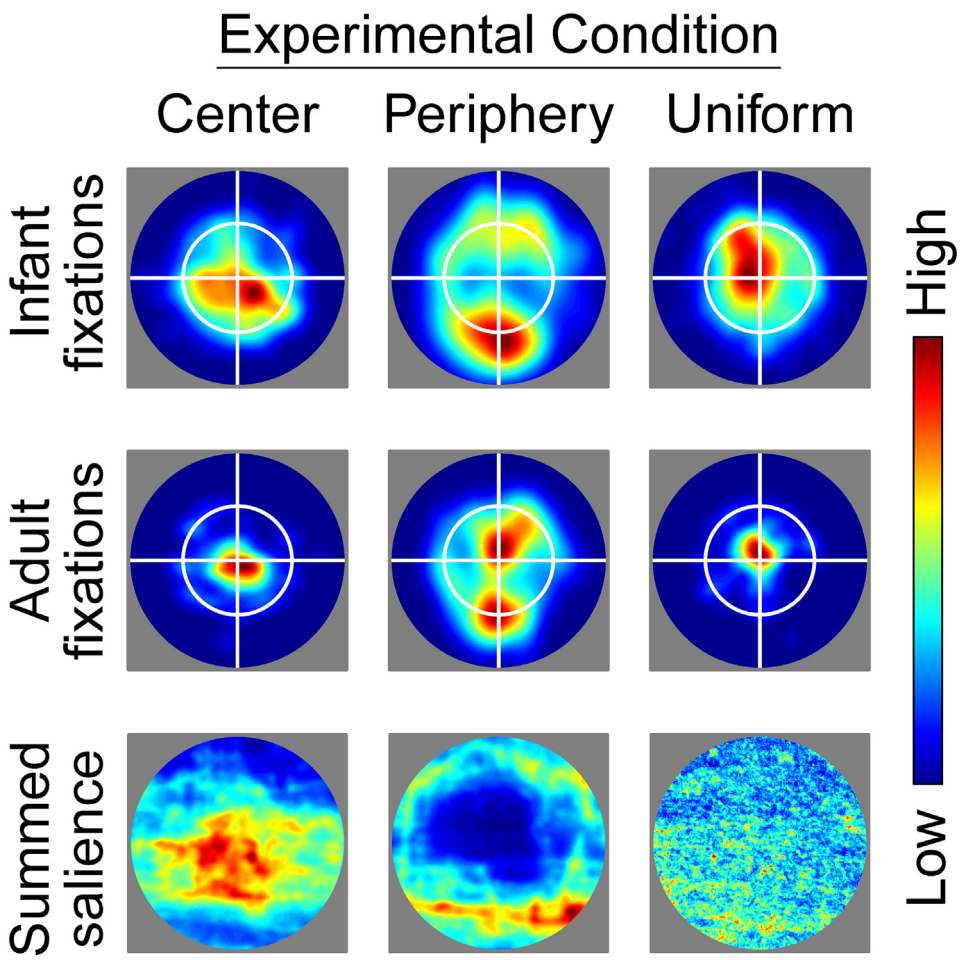

Fig. 3. The top and middle row shows heat maps of the fixations of infants and adults within the center, periphery and uniform salience conditions. Blue colored regions received none or very few fixations, whereas red regions are frequently fixated. The bottom row shows the combined salience distribution of the scenes within each condition. Here, blue colored regions are not salient, whereas red colored regions are most salient.

the starting location dot. Some of these fixations will fall on the side of the center while others will fall on the side of the periphery. We would not expect any systematic deviations within the outlier locations and thus the outliers are just introducing noise. After this noise is removed the effect becomes more clear. If the outcome variable had been distance from the center the effect of the outliers would have been more severe, because in that case all outliers would be biased away from the center. With the outliers removed it also makes sense to check if an analysis with distance as continuous outcome variable yields similar results as the initial analysis.

3.3.2. Distance analyses

An analysis on the distance from the center was conducted to validate that the results would be the same if a continuous measure was used, see Fig. 5. A linear mixed model for the infant data with distance to the center as outcome variable and salience condition and age as predictor variables showed there was an effect of scene content. We report the coefficients with *t*-values above 2 or below −2 as significant predictors. Scenes with salience distributions biased towards the periphery of scenes received more fixations away from the center than scenes with salience distributions biased towards the center (β = 2.224, SE(β) = 0.627, t = 3.546). Similar to the initial analysis there was no significant effect of age within the group of infants (β = −0.014, SE (β) = 0.035, t = −0.41).

A linear mixed model for the infant and adult data combined showed a main effect for infants, infant fixations fall further away from the center than adult fixations (β = 1.568, SE(β) = 0.262, t = 5.979). There is also a main effect of scene content, scenes with salience distributions biased towards the periphery of scenes had fixations further away from the center than scenes with salience distributions biased towards the center (β = 2.133, SE(β) = 0.437, t = 4.884). Overall the results of the distance analyses were very similar to the results of the initial analyses.

3.3.3. Distance and saccade latency

Recently it was shown that the center bias is weakened when participants hold their gaze on the location of the fixation cross after scene onset (Rothkegel, Trukenbrod, Schütt, Wichmann, & Engbert, 2017). In this study a fixation cross would appear away from the center on a gray screen and after a fixation on the cross a scene would appear. However the fixation cross would remain on the screen for 0–1000 ms. depending on the condition. Participants were instructed to only start to explore the scene after the fixation cross disappeared. The results showed that the tendency to fixate the center was weaker when participants held their gaze at the position of the fixation cross. Importantly, the same pattern was observed between the saccade latencies and distance from the center when there was no overlap between the fixation cross and scene onset. This implies that the saccade latencies can be a confound in this study as adults' shorter latencies may explain why they show a stronger bias than infants.

To test if saccade latencies influenced the center bias in this study we fitted a linear mixed model with random intercepts for participants and images, distance from the center as outcome variable and saccade latency (scaled with mean 0 and sd 1), condition, group and there

Fig. 4. Top panels show the fixation durations on the starting locations. The distributions are bi-modal for both infants and adults. This is caused by the fact that the shorter latencies were the result of already programmed saccades towards the starting locations dot that was no longer on screen. After removing these outliers (left of the red bars in the top panels) the overall results do not change as can be seen from in the bottom panels were the exact same plots are shown as in 2, but with the outliers removed.

interactions as predictor variables. The raw data with simple linear effects is displayed in Fig. 6. In line with earlier analyses, there were main effects of scene content and group. Scenes with salience distributions biased towards the periphery of scenes received more fixations away from the center than scenes with salience distributions biased towards the center ($\beta = 2.397$, SE(β) = 0.634, $t = 3.783$). Infants had fixations that fell further away from the center than adults ($\beta = 1.71$, SE(β) = 0.455, $t = 3.761$). In contrast to the findings of Rothkegel et al. (2017) there was no main effect of latency ($\beta = -0.131$, SE(β) = 0.564, $t = -0.233$) and none of the interactions between latencies and either group, condition or both reached significance. This implicates that the latencies are unlikely to be a confounding factor in this study as there was no overall effect and latencies did not have different effects for infants and adults. Looking at Fig. 6 it is clear there is no latency effect on the center bias in adults, for infants in the center and uniform condition it seems there might be an effect, but do note that this effect is not significant.

4. Discussion

In this study we examined the center bias in infants experimentally by manipulating the start position of fixation and salience distribution of scenes. The confirmatory analyses showed support for the hypothesis that infants have the center bias when viewing complex real-world scenes. Furthermore, we confirmed the second hypothesis that the center bias is stronger for scenes that are salient in the center than for scenes that are salient in the periphery. The third hypothesis, that the center bias is larger in older than younger infants, was not supported by the data. However, the exploratory analyses did show a developmental effect; infants have a weaker center bias than adults. Also, the center

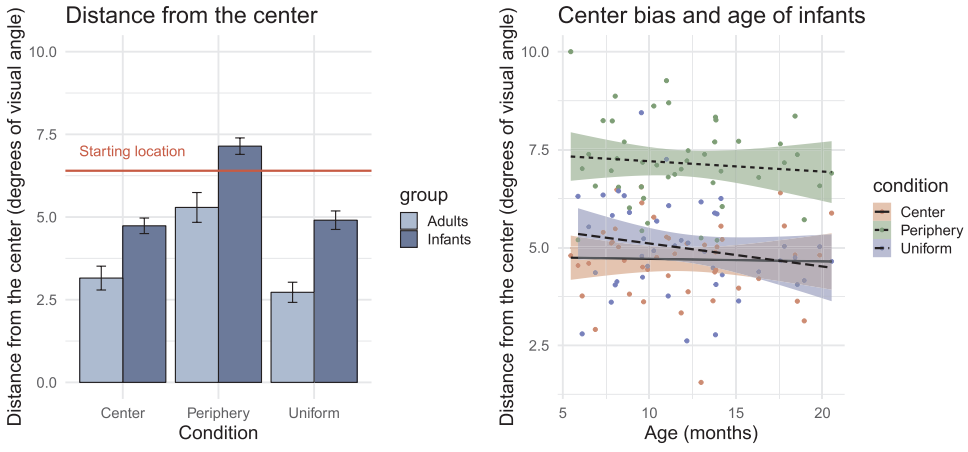

Fig. 5. The left panel shows the distance from the center of the first fixation measured in degrees of visual angle. The red line is the distance of the start location. Error bars lie ±2 standard errors around the mean. The right panel shows the relationship between the age of infants and the distance from the center for the center, periphery and uniform condition.

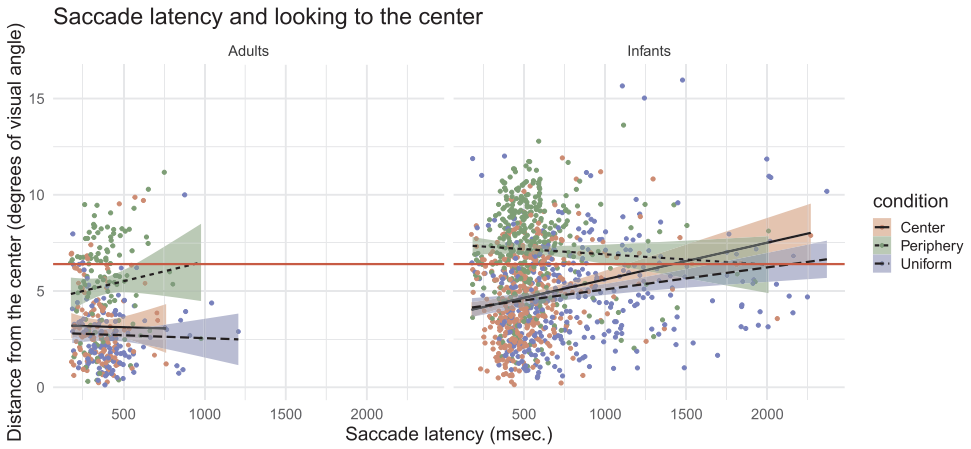

Fig. 6. The relationship between the saccade latencies and of the distance from the center is shown for adults (left panel) and infants (right panel) for the center, periphery and uniform conditions. The red line corresponds to the starting location.

bias in adults (Foulsham et al., 2008; Tatler, 2007; Tseng et al., 2009) was replicated with the stimuli used in this study. In addition, several exploratory follow-up analyses confirmed the robustness of the effect after removing outliers and using the distance to the center of the screen as dependent variable.

In the introduction three common explanations for the center bias were discussed: physiology, salience and strategy. These explanations are often difficult to disentangle, but the experimental setup used in this study and the fact that both infants and adults participated makes it possible to assess how likely these different explanations are given the results reported in this study. The experimental setup in this study was specifically used to test the first instance of the center bias. That is, by varying the start position it is known that the first saccade is nearly always directed at the center (Tatler, 2007; Foulsham et al., 2008), here we explicitly manipulated salience and tested both infants and adults looking for the limits of this effect. This experimental design allows us to some extent to disentangle these three explanations that might cause the center bias.

Orbital reserve explains the bias as the tendency to re-center the eyes in the orbits. This explanation would predict a center bias in both infants and adults regardless of the salience distribution of the scene. Although we did find an overall center bias there also is a strong effect of salience condition in both infants and adults which indicates that the physiological explanation is unlikely to be the only explanation of the center bias.

The salience explanation of the center bias predicts that both infants and adults would shift their attention towards the salient parts of the scene. In infants this was the case to a large extent, which is in line with the literature on infant development that highlight the importance of exogenous factors such as salience as driver of infant attention (Johnson, 1990; Johnson, 2002). In adults, however, there also were effects of salience albeit more mixed. The results showed a population of first saccades to the center and a populations of first saccades towards the periphery when the periphery was most salient. Moreover, in the absence of salient regions, when salience is distributed uniformly, both infants and adults fixate the center, whereas a more uniform distribution of fixations would be predicted if salience is the main or only force driving the center bias. This implies that salience cannot fully explain the center bias in both infants and adults.

The efficient viewing strategy explanation of the center bias would predict that adults fixate the center regardless of the salience distribution of scenes. For infants we would expect a developmental pattern that shows that the center bias increases as older infants have learned that the center bias is often the most informative region and it is efficient to fixate the center as it minimizes the distance to other parts of the scene. The results of this study are not completely in line with the strategy explanations, as we did not observe a developmental pattern *within* infants and did find an effect of salience in adults. However, there is a developmental difference as adults have a stronger center bias than infants. This does imply that the center bias does have a developmental component which is in line with the idea that the center bias may be acquired over time. Moreover, although there was an effect of salience in adults, the first fixations of adults when the periphery is most salient show a bi-modal distribution, which does not directly reflect the salience distribution. This bi-modality suggests a competitive dynamical process (Tatler et al., 2017). This pattern of results is consistent with a cognitive process that is best described as a competition between exogenous factors steering attention and an endogenous center bias seeking to optimize information uptake. Consistent with a shift from exogenous to endogenous control of eye-movements, the results further suggest that salience has a relatively larger impact in this competition in infants than it does in adults.

This study sets a first step towards understanding infants' gaze patterns over real-world scenes. Only a few other studies address real-world scene perception in infants (e.g., Mahdi et al., 2017; Helo et al., 2016) and this is a serious gap in both the scene viewing and developmental literature. We know from the many adult studies into scene perception that top-down factors are important in predicting where adults look. Adults are likely to look at meaningful objects in scenes (Einhäuser et al., 2008; Stoll et al., 2015) and focus their attention towards regions that are likely to contain useful information (Henderson, 2017; Torralba, Oliva, Castelhano, & Henderson, 2006). Moreover, individual differences in scene viewing are linked to personality traits (Risko, Anderson, Lanthier, & Kingstone, 2012) and cognitive abilities (Hayes & Henderson, 2017). Scene viewing is a paradigm that can be applied to both infants and adults, making it possible to study the development of individual differences from a preverbal age onwards. In addition, studying scene viewing in infants can provide interesting insights into the mechanism underlying scene perception in adults. Especially, the ongoing debate to what extent bottom-up salience or to top-down knowledge influences scene viewing is closely related to the developmental shift from exogenous (bottom-up) towards more endogenous (top-down) visual attention.

Understanding what drives attention allocation over complex scenes, is best done with an integrative approach in which all factors that are known to play a role are part of a single model. For instance, a model that uses salience, general biases and individual differences such as age or knowledge as a function of fixation locations and durations. Examples of models that predict fixation locations are the SceneWalk model (Engbert, Trukenbrod, Barthelmé, & Wichmann, 2015) and the

saccadic model of eye movements (Le Meur & Liu, 2015). These models generate scan paths based on salience, task demands and general biases that can be compared to actual scan paths. Developing such a model for infant attention allocation would provide further insights into the transition from exogenous towards endogenous factors steering attention as it allows to test hypotheses by manipulating model settings. For instance, to test the role of salience, scan paths with a varying importance of salience settings could be generated and compared to actual infant scan paths to assess its role. This study shows that the center bias is an important factor to account for in such models.

A possible limitation of this study that is worth discussing concerns our manipulation of the salience distribution of scenes. We did not expect to find such strong effects of the salience distribution as we did (see the pre-registered document). Salience effects reported in the literature are often relatively small, but here we found a strong effect between the center and periphery conditions. This may be explained by the manipulation in the salience condition that was quite extreme, especially for periphery condition. This extreme manipulation may have led to the large effects of salience we found is this study. It would be interesting to replicate this study with a more subtle manipulation to keep closer to scenes people often encounter and get a better understanding of the generalization of the effects reported here.

Recently, there is a strong focus in psychology on replicable and transparent science (Spies, 2013; Open Science Collaboration, 2015). Especially in infant studies researchers often encounter obstacles, such as data loss due to uninterested infants or noisy data that is difficult to interpret. A recent field study in which someone went undercover in three baby labs, showed that questionable research practices (Simmons, Nelson, & Simonsohn, 2011) were common in these baby labs (Peterson, 2016). Here, we aimed to avoid these practices by pre-registering our hypotheses and analyses at the OSF (Spies, 2013). Using these best practices, we found that infant attention to real-world scenes is driven by two competing factors, the center bias and scene content. Scenes with salient centers elicit a center bias, whereas scenes with salient peripheral regions do not or to a lesser extent. Scene content cannot fully explain the bias, as scenes with uniformly distributed salience also elicit the bias. The center bias cannot be simply explained by human physiology or scene salience, but is more likely to be a cognitive strategy used to efficiently explore the environment.

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