

An in-depth look at saccadic search in infancy

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Two questions were posed in the present study: (1) Do infants search for discrepant items in the absence of instructions? We outline where previous research has been inconclusive in answering this question. (2) In what manner do infants search, and what are the fixation and saccade characteristics in saccadic search? A thorough characterization of saccadic search in infancy is of great importance as a reference for future eye-movement studies in infancy. We presented 10-month-old infants with 24 visual search displays in two separate sessions within two weeks. We report that infant saccadic search performance at 10 months is above what may be expected by our model of chance, and is dependent on the specific target. Infant fixation and saccade characteristics show similarities to adult fixation and saccade characteristics in saccadic search. All findings were highly consistent across two separate sessions on the group level. An examination of the reliability of saccadic search revealed that test–retest reliability for oculomotor characteristics was high, particularly for fixation duration. We suggest that future research into saccadic search in infancy adopt the presented model of chance as a baseline against which to compare search performance. Researchers investigating both the typical and atypical

development of visual search may benefit from the presented results.

Introduction

For humans and primates, it is vital to adequately process their visual surroundings. One method that has been prevalent in studying (aspects of) processing of a visual scene in humans and primates is studying behavior in a visual search task (e.g., Motter & Belky, 1998a; Williams, 1967). The basics of a visual search task are straightforward; subjects are required to search for a target stimulus in a visual scene, which may or may not be present (Wolfe, 1998). The subject then commonly responds whether the target is present or not. The dependent variables are often accuracy and reaction time of target detection. The target is defined by the presence or absence of a feature or some unique combination of features, and is located somewhere between nontarget stimuli. Although there are many variants of the visual search task, the overarching concept is that by varying aspects of both the target and nontarget, one might investigate different aspects of visual processing (Wolfe, 1998). Indeed, visual

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search tasks have been used extensively to study and model attentional processes (Treisman & Gelade, 1980; Wolfe, 1994) and oculomotor control (Hooge & Erkelens, 1996; McPeck, Skavenski, & Nakayama, 2000; Motter & Belky, 1998b). As a visual search task can be used to study different aspects of visual processing, it may be an ideal candidate to study the development of vision from infancy to adulthood. Indeed, recent years have seen an increase in developmental studies using a visual search paradigm to study the early development of vision. We first briefly introduce an example of how research on visual search in infancy may inform developmental models of vision, after which we introduce our scope on infant eye-movement behavior in search.

Previous research into the development of processes underlying visual search, particularly in infancy, has focused on establishing whether findings reported in the adult literature are present in infancy as well. One example is visual pop-out: when search for a target is relatively unaffected by the amount of nontargets, it is often denoted as visual pop-out, preattentive search, or efficient search (Duncan & Humphreys, 1989; Rosenstiel, 1998). A specific example is searching for a feature-present target among feature-absent nontargets; for instance, a Q among O's (the added line of the Q being the feature; Wolfe, 1998). As the feature “pops out,” search time is relatively unaffected by the amount of feature-absent nontargets. However, searching for a feature-absent target among feature-present nontargets (O among Q's) is typically inefficient: The absence of a feature does not “pop out.” This is referred to as a search asymmetry—the situation where target A among nontargets B is detected faster than target B among nontargets A. Early research in infancy first investigated whether infants detected this feature-present stimulus among feature-absent stimuli at all. Colombo, Ryther, Frick, and Gifford (1995); and Quinn and Bhatt (1998) reported that infants aged 3 to 4 months preferentially looked at feature-present among feature-absent stimuli (Q among O's), after being familiarized with just feature-absent stimuli (only O's), but not vice versa (O among Q's). Colombo et al. (1995); and Quinn and Bhatt (1998) claimed that visual pop-out was present in infancy, based on this asymmetry in preferentially looking at feature-present but not feature-absent stimuli. However, Adler and Orprecio (2006) argued that this could not be concluded on the basis of preferential looking times, which are typically on the order of several seconds, while visual pop-out or efficient search occurs on the order of several hundreds of milliseconds. They argued that knowledge of the eye movements was needed in order to draw this conclusion. In their study, Adler and Orprecio (2006) measured saccade latencies of 3-month-old infants to a target and report that saccade

latency was unaffected by the number of nontargets. When search for a target is unaffected by the number of nontargets, it may be noted as visual pop-out or efficient (Rosenstiel, 1998). Adler and Orprecio (2006) consequently conclude that visual pop-out is present in infancy. Adler and Gallego (2014) extend this by reporting that infants exhibit efficient search for feature-present but not for feature-absent visual search trials. In conclusion, there is evidence that infants exhibit visual pop-out and search asymmetries, and these findings may consequently inform developmental models of visual search (e.g., by extrapolating brain-based models to infants; Li, 1999), or more general models of visual attention (e.g., Johnson, 1990).

In the present study we take an in-depth look at eye-movement behavior itself—specifically in a highly relevant visual task, namely search. In the present study we are concerned with saccadic search in infancy, and how saccadic search behavior in infancy can be characterized. Saccadic search is topic in a subset of the visual search literature, and is concerned with target localization after multiple saccades (Caspi, Beutter, & Eckstein, 2004; Hooge, Over, van Wezel, & Frens, 2005; Motter & Belky, 1998a, 1998b; Scinto, Pillalamarri, & Karsh, 1986; Vlaskamp & Hooge, 2006; Vlaskamp, Over, & Hooge, 2005; Wu & Kowler, 2013). Saccadic search may occur, for example, when instructions are given to find a target, but the target cannot be located at first glance. Here, search is an active exploration of the visual scene as opposed to mere visual pop-out (i.e., locating the target at first glance). The investigation of eye-movement behavior in saccadic search in infancy is particularly relevant for multiple reasons. First, by investigating eye-movements in the context of search, one can draw conclusions about performance (i.e., how well do infants localize the target?). For infants, this is particularly interesting due to the absence of instructions: Do infants actually search for a discrepant item in the absence of instructions? If they do, this allows for an investigation of the development of oculomotor control in search. Second, a characterization of eye-movement behavior in search in infancy may allow us to compare infant saccadic search to primate and adult saccadic search in the future. This comparison may, for instance, shed light on whether, and how, search strategies are learned or innate, and how they develop. Moreover, a thorough characterization may serve as a reference for distinguishing typical from atypical development of visual search behavior, as has previously been observed in autism spectrum disorder (ASD; e.g., Gliga et al., 2015; Kaldy, Kraper, Carter, & Blaser, 2011; see also the suggestions made in Hessels, Hooge, Snijders, & Kemner, 2014). For a recent review on visual search in ASD, see Kaldy, Giserman, Carter, and Blaser (2013).

Investigating saccadic search in infancy is, however, not as straightforward as in adults. While adults can be given instructions to find a target, infants cannot (or will not follow instructions when given so). One approach adopted by Kaldy et al. (2011) in older children (toddlers of around 2.5 years old) is to indicate the special status of the target by familiarizing children with it before search trials commenced. Another approach is to present infants with stimuli that are typically used to study search behavior in adults, and determine whether infants spontaneously search for a discrepant item. As no instructions are given, we deem it more appropriate to refer to visual search *stimuli* instead of a visual search *task* when studying search in infancy. One major assumption here is that, when infants fixate the target, infants have identified it as being a discrepant item. Indeed, for toddlers there is sound evidence that the target was indeed perceived to be special in the absence of instructions (Kaldy et al., 2011). In recent years, two studies have used visual search stimuli in infancy that may have elicited saccadic search, while eye movements were simultaneously recorded. Amso and Johnson (2006) presented 3-month-old infants with search displays containing vertical lines and one titled line (the target). In addition, they presented search displays containing vertical lines and one moving line (the target) as a visual pop-out control condition. They report that infants fixated the static target in about half the trials compared to nearly 90% of the moving targets. The average time to target hit for the static target was around 1400–1500 ms, compared to roughly 1100 ms for the moving target. Frank, Amso, and Johnson (2014) employed the same visual search displays for 3-, 6-, and 9-month-old infants, and report that the proportion of target hits—defined as fixation of the target location, measured with an eye tracker—in the static trials increases from roughly 25% to 40% from 3 to 9 months. For the trials containing moving targets, the proportion of target hits increases from roughly 55% to 100%. Moreover, time to target hit for the moving trials decreased from roughly 1800 ms to below 1000 ms, whereas time to target hit for the static trials did not decrease as a function of age. These two studies clearly demonstrate that target localization is slower for static targets compared to moving targets. Moreover, Amso and Johnson (2006) conclude that target localization is above what may be expected by chance.

While Amso and Johnson (2006) and Frank et al. (2014) conclude that infants indeed search for a target, even in the absence of instructions, there are two questions that need to be further addressed. First, given that there were eight possible target locations, Amso and Johnson (2006) expected infants to locate the target by chance in 12.5% of the cases. This model might be valid when there are eight possible options, and one

must be chosen. However, infants were given a maximum of 4 s to locate the target. It may very well be that multiple possible target-locations were selected in that 4-s period. Moreover, it may also be that no target-locations were selected at all. It may therefore not be the case that one, and only one, of eight possible locations is fixated. We consequently deem the model of 12.5% chance unfit for this experiment, and propose a different model of chance. The model we propose is derived from the definition of saccadic search: target localization that generally occurs after multiple saccades. Saccadic search then consists of two parts: explorative behavior—fixations on different parts of the display—and orienting to the target—in other words, fixating the target. During the first part (explorative behavior), any number of nontargets in the display may be fixated. If the target has no special status over the nontargets, one would not expect that the target is fixated with higher probability than nontargets in the same time span. However, given that there is a general bias to fixate in the center of the screen, the probability of each nontarget being fixated is not necessarily equal, and consequently it is impossible to determine the probability of fixating any particular element in a display up front. However, by computing the search time and probability of fixating nontargets at equal distance from the center of the screen as the target, we obtain a chance level. If, for example, a nontarget at the same distance from the center as the target is localized as often in the same time span as the target, target localization is not above chance. If, on the other hand, the target is consistently localized faster and more often than nontargets at equal distance from the center of the screen, target localization is above chance.

The second question that remains from Amso and Johnson (2006) and Frank et al. (2014) is whether time to target localization (as determined by the time from trial onset to target fixation) depends on the dissimilarity between targets and nontargets. When a target cannot be localized at first glance and a saccade (or multiple) is required, there are multiple aspects that may determine search performance. Increasing the number of nontarget stimuli to a search display should decrease search performance (see, e.g., Rosenstiel, 1998). Previous work on visual search in toddlers has used this approach effectively to conclude that toddlers with ASD are more effective in visual search than typically developing controls (Kaldy et al., 2011). Moreover, if dissimilarity between target and nontargets decreases, search performance should decrease also (Duncan & Humphreys, 1989). In the previous experiments, one would therefore expect search performance to differ for the three different targets (30°, 60°, and 90°). While this is not essential to conclude that infants search, it may be expected on the basis of

the adult visual search literature. These two remaining questions are addressed in the first question of the present study, and its components:

Q1: Do infants search for a discrepant item in the absence of instructions?

Q1.1 (Necessary): Is target localization above what may be expected by our model of chance?

Q1.2 (Additional): Is time to target localization dependent on target and nontarget dissimilarity?

In the present study, we aim to answer this question with an experiment in a group of 10-month-old infants. Given that Amso and Johnson (2006) and Frank et al. (2014) concluded above-chance target localization for infants between 3 and 9 months old, we hypothesize that infants at 10 months should also search for a discrepant item in the absence of instructions.

The second question addressed in the present study concerns the characterization of saccadic search in infancy. Previous infant studies in which saccadic search may have taken place have until now not reported eye-movement measures other than saccadic reaction time, and it therefore remains unknown exactly *how* infants search. A thorough description of infant oculomotor characteristics may serve as a reference for future eye-movement studies with infants. In addition, a characterization of infant saccadic search may be of importance to research on atypical development such as in ASD, where visual search superiority is often reported (e.g., Kaldy et al., 2013; O’Riordan, Plaisted, Driver, & Baron-Cohen, 2001). We determine and describe oculomotor characteristics of infant saccadic behavior in visual search displays. First, fixation duration is often used as an estimate for the average visual processing time at the location fixated (Hooge & Erkelens, 1996). The processing time may subsequently be seen as an estimate for the difficulty of the visual stimulus. As in adult visual search, we expect the initial fixation duration—or the latency to initiate the first saccade—to be longer than subsequent fixation durations (Hooge & Erkelens, 1996; Zingale & Kowler, 1987). Second, we describe infant saccadic directional and amplitude changes during search as has previously been done in adults (Hooge et al., 2005).

Q2: In what manner do infants search? What are the fixation and saccade characteristics of infant saccadic search?

Given the recent emphasis on replication of psychological research (e.g., Open Science Collaboration, 2015) we presented the group of 10-month-old infants with the same visual search stimuli twice within 2 weeks to ascertain that the observed saccadic search behavior was reliable at the group level.

Method

Participants

Seventy-seven infants were invited into the lab center for a day of multiple studies (see e.g., Hessels, Andersson, Hooge, Nyström, & Kemner, 2015), recruited through the local municipality. Of the 77 infants invited, sufficient data (at least half the trials, mean 21.7 trials) was recorded for 55 (25 male, 30 female) infants in the first session of the visual search study. Forty (18 male, 22 female) out of the 55 that provided enough data for the first session completed the visual search study on their second visit. They all provided data for at least one-third of the trials (mean 19.6 trials) on their second visit. Mean age during the first session was 302 days ($SD = 11.8$ days); mean age during the second session was 307 days ($SD = 11.4$ days). Infants were only invited to participate if the parents indicated that the infants were not born preterm (i.e., before 37 weeks of pregnancy), and indicated that the infants had no impaired hearing or vision or developmental disorders. Parents gave written informed consent on the day of the first session, and the study was approved by the ethics committee of the local University Medical Centre (Protocol ID 14-221) and conducted in accordance with the Declaration of Helsinki. Parents received a 10 € compensation for each testing day, with another 5 € travel compensation if required.

Apparatus and stimuli

Stimulus presentation was handled by MATLAB R2013a and the PsychToolbox (version 3.0.11; Brainard, 1997) running on a MacBook Pro with OS X 10.9 (Apple, Cupertino, CA). Stimuli were presented on an external 23-in. screen belonging to the Tobii eye tracker (Tobii, Stockholm, Sweden) at a resolution of 1920×1080 pixels and a refresh rate of 60 Hz. The Tobii TX300 eye tracker running at 300 Hz was used for tracking infants’ eye movements. Median accuracy in session 1 was 0.89° and 1.03° in session 2. Standard deviation for accuracy values is noninformative as infants may not attend the validation stimulus and consequently achieve very large values for accuracy (see Hessels et al., 2015, for an elaborate discussion). Median precision during detected fixations (see Data reduction section) in session 1 was 0.61° RMS ($SD = 0.36^\circ$), and 0.62° RMS ($SD = 0.36^\circ$) in session 2. Further measures on data quality from the present experiment have been reported on extensively in Hessels et al. (2015). The Tobii SDK was used for communication between MATLAB and the eye tracker.

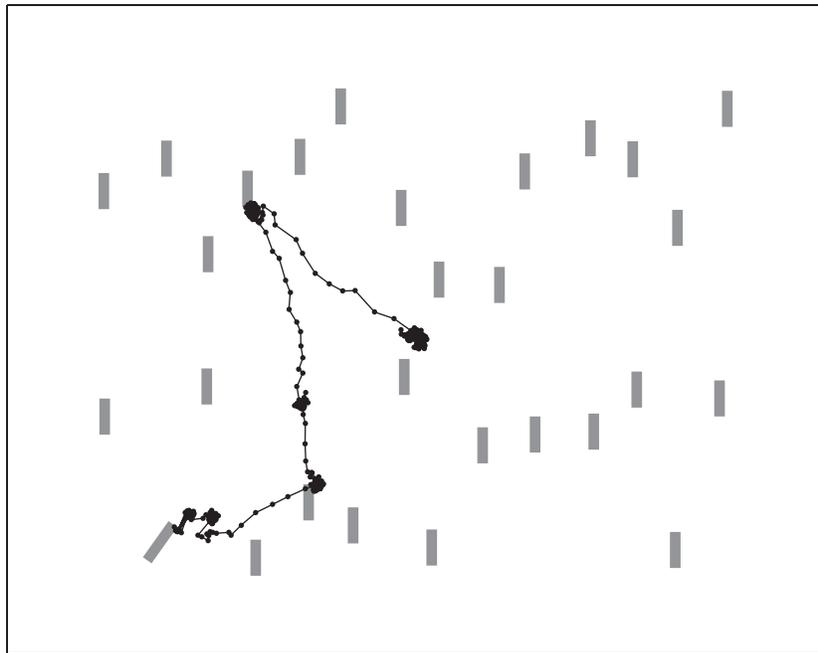


Figure 1. Example visual search display with gaze overlaid in black. Gaze starts in the center and ends at the target location. The display is schematic; size and color differed in the experiment (see Apparatus and stimuli section).

The experiment consisted of 24 visual search displays (based on Amso & Johnson, 2006). Each visual search display consisted of 28 white lines ($3.3^\circ \times 0.9^\circ$) as target candidates on a black background (see Figure 1 for a schematic version of a typical search display). The lines were arranged in a grid of 14 columns by 2 rows, and subsequently jittered between -1.6° and 1.6° in horizontal and between -6.3° and 6.3° vertical direction. All lines except the target line were aligned vertically. The target line was tilted 30° , 60° , or 90° clockwise, and could appear in one of eight fixed locations. Each combination of target line angle and location was presented once, resulting in 24 trials. Preceding the visual search experiment was a five-point calibration sequence. Each calibration consisted of a colored spiral (red, green, yellow, purple, or blue) on a black background. The spiral changed in size between 4.0° and 5.4° at 0.8 Hz following a sinusoidal wave. In addition, the spiral rotated at 0.8 Hz. Following a key press of the operator, the spiral shrank in size to 0.5° over a period of 0.5 s. The spiral then remained on screen for 0.2 s. At the start of this period the point was calibrated. Following the first and every additional fifth visual search display a validation stimulus identical to the calibration spiral was presented to determine accuracy.

Procedure

Positioning

The infants and parents were welcomed into the eye-tracking room and familiarized with the experimental

setup. Thereafter, the infants were strapped in a baby seat, and the parent was seated on a height-adjustable chair. The baby seat was subsequently placed on the parent lap, with the infant placed parallel to the screen of the eye tracker. Positioning the infant in a baby seat was done as this would give the most stable positioning through the recording and limit the infants' movements. If, however, the parent indicated that the baby seat would probably result in a restless or upset infant, the infant was seated without a baby seat in the parents lap or in a high chair. The decision for either the parents lap or the high chair was up to the judgment of the operator, i.e., which of the two would work best for the particular infant. After positioning the parent and infant, the position of the eye tracker was adjusted so that the eyes of the infant were at 65 cm from the eye tracker and at the same height as the center of the screen.

Calibration and experiment

After positioning, a five-point calibration sequence was started. Calibration stimuli were serially presented in the four corners and center of the screen. The order of points was random each time the calibration was run. The infant was monitored with a webcam. The operator judged from this video whether the infant looked in the direction of the calibration stimulus and pressed the spacebar to calibrate the current point. After the calibration sequence the calibration output was examined. Calibration points without data, or with

data that were inconsistent and characterized by dispersed gaze points around the calibration point, were recalibrated by the operator. Each recalibration was noted down as an additional calibration run. After calibration was deemed successful, or when the infant started losing attention, the experiment was initiated. A colorful static picture was presented centrally before each visual search trial to attract or maintain the infants' attention. The operator initiated the trial by pressing the spacebar when the infant was judged to look at the screen. The visual search trial remained on screen until either 4 s had passed, or the infant fixated the target within a range of 1.4° for a minimum duration of 100 ms. This was very conservative, and only allowed precise target fixations to end the trial. Note that the definition for target hit is different in the offline analysis (see Data reduction section). After the trial ended, a short video clip of a popular cartoon was presented at the target location in an attempt to stimulate spontaneous visual search. If, during the experiment, the infant was not attending to the screen, the operator could present sounds or videos with sound in the center of the screen to attract the infants' attention. The entire experiment, including calibration and positioning, lasted approximately 10 to 15 min.

Data reduction

Raw position signals from the left and right eye were first combined into an average position signal. If gaze position was only available from one eye, that signal was used. First, cubic spline interpolation was performed for periods of data loss with a duration of less than 100 ms (Amso & Johnson, 2006). Hereafter, a fixation detection algorithm specifically designed for use in infant data was applied. The algorithm operates as an adaptive dispersion algorithm, with which fixation detection can be achieved across large variations in noise levels, both local and between participants or trials. The algorithm, Identification by 2-Means Clustering (I2MC; Hessels, Niehorster, Kemner, & Hooge, 2016), is based on a procedure called k-means clustering (where $k = 2$), which is used to determine whether one or two fixation clusters are present in a small moving window (200 ms in this case). When the window contains a saccade, the algorithm detects two clusters in 2D space (fixations) that are clearly separated in time (i.e., one cluster follows the next in time). When the window contains no saccade, the algorithm is still forced to detect two clusters in 2D space, although they are not clearly separated in time. The clustering method combined with a moving window ensures a noise-robust detection of fixations, both locally and across participants. Finally, fixations shorter than 40 ms were excluded, and successive

fixations separated less than 0.7° in location and less than 30 ms in time were merged.

In infant research, the amount of data available per infant may vary widely due to, e.g., inattention by some infants, differences in eye-tracking stability (Hessels et al., 2015). As we were firstly interested in determining saccadic search behavior of 10-month-old infants in general, trials from all infants were pooled following fixation detection in order to produce better estimates for group search performance measures (see, e.g., Adler & Gallego, 2014; Adler & Orprecio, 2006). Hereafter, time to target hit, number of fixations to target hit, and proportion of trials in which the target was hit were calculated. Target hit was defined as gaze entering an area of 4.7° from the center of the target.

In order to determine a baseline against which search performance for the target could be compared, we ran a computation for comparison nontargets. In each visual search trial, the target could appear at one of eight possible locations: two possible locations in each quadrant of the screen. In each of the three quadrants not containing the target, a nontarget was selected as a comparison nontarget. For each quadrant, the nontarget with the distance to the center that most closely matched the distance of the target to the center was selected. For each of the three comparison nontargets in a visual search trial, the time it took the infant to fixate that element was determined. If the number of times a target was hit in the 4-s span of a trial did not exceed the number of times a comparison nontarget was hit in the same time span, we conclude that target localization is not above chance.

Although there were three comparison nontargets available for each visual search trial, there was no difference in the number of times these targets were hit in a 4-s timespan: The empirical cumulative proportion of object hit as a function of time overlapped for the three nontargets. Therefore, the most conservative comparison nontarget was chosen as the reference: The comparison nontarget in the opposite quadrant from the target in the 90° target trials was chosen. In addition, comparison nontargets were averaged for the analyses of proportion of target-directed saccades and target capture at next saccade (see Saccadic search performance section).

Results

Saccadic search performance

Figure 1 depicts an example trial of one infant. As can be seen, gaze starts in the center of the display and after some time, following fixation of two nontargets, the target is located in the bottom left corner. As can be seen

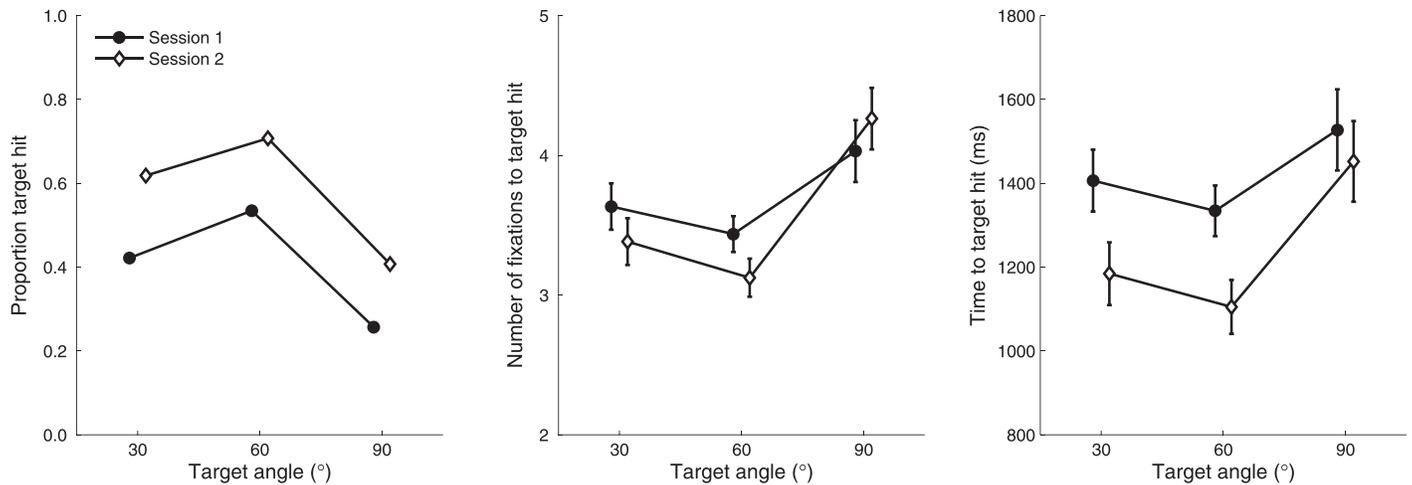


Figure 2. Proportion target hit (left), number of fixations to target hit (middle), and time to target hit (right) as a function of target angle for both sessions. Error bars (middle and right panel) depict standard error of the mean. The data between the two sessions are shifted horizontally, as to prevent overlapping error bars.

from the left panel in Figure 2, proportion of trials with a target hit was lowest for the 90° target, followed by the 30°, and finally the 60° target. In addition, mean number of fixations to target hit (middle panel Figure 2) was highest for the 90° target, followed by the 30°, and finally the 60° target. Finally, mean time to target hit was longest for the 90° target, again followed by the 30° target, and the 60° target. This relative pattern was identical across session 1 and 2, although targets were hit faster and more often in session 2. As standard statistical tests cannot combine both proportion of target hit and time to target hit as a single measure of performance, we performed bootstrap analyses on cumulative frequencies of target hit as a function of time (see, e.g., Hooge &

Camps, 2013). To determine the proportion of objects that were hit after each 500 ms increment, and corresponding 95% confidence intervals, 1,000 samples of equal size were drawn with replacement from the distribution of time to first hit. The nontarget in the opposite quadrant in the 90°-target trial served as the chance level (see Data reduction section).

The cumulative proportion of target and comparison nontarget hit as a function of time are depicted in Figure 3. As can be seen from the left panel in Figure 3, 60° targets were detected most often in the 4-s timeframe, followed by the 30° target in session 1. The cumulative proportion of 90° target hit almost overlaps with the cumulative proportion of the comparison

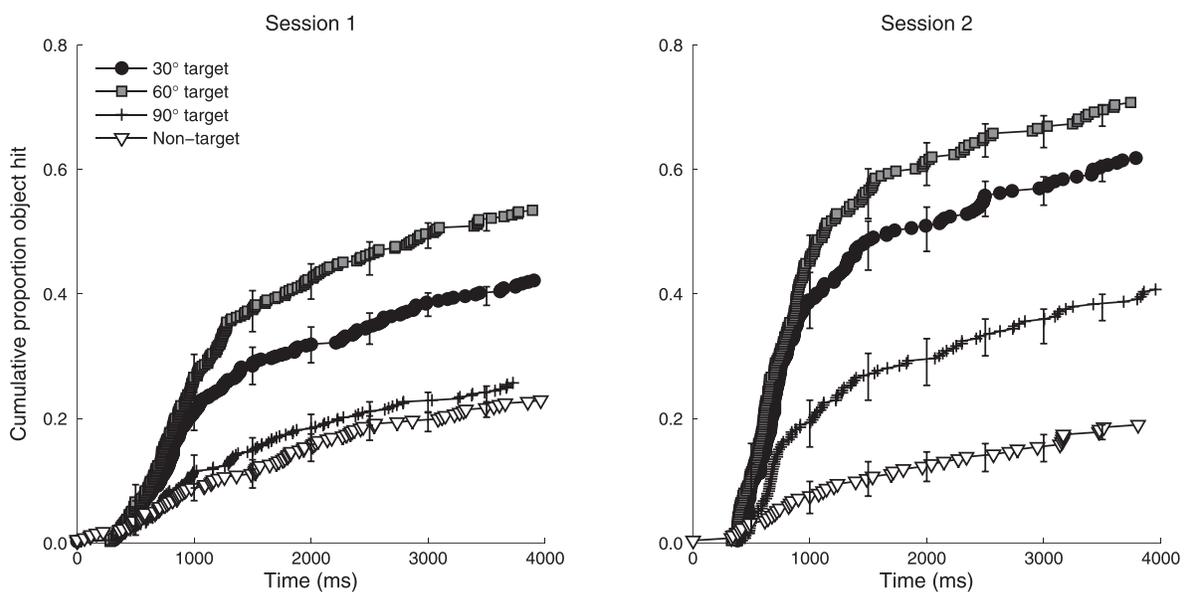


Figure 3. Cumulative proportion of 30°, 60°, and 90° targets hit and comparison nontarget hit as a function of time for session 1 (left) and session 2 (right). Error bars represent 95% confidence intervals acquired using bootstrapping procedures in MATLAB.

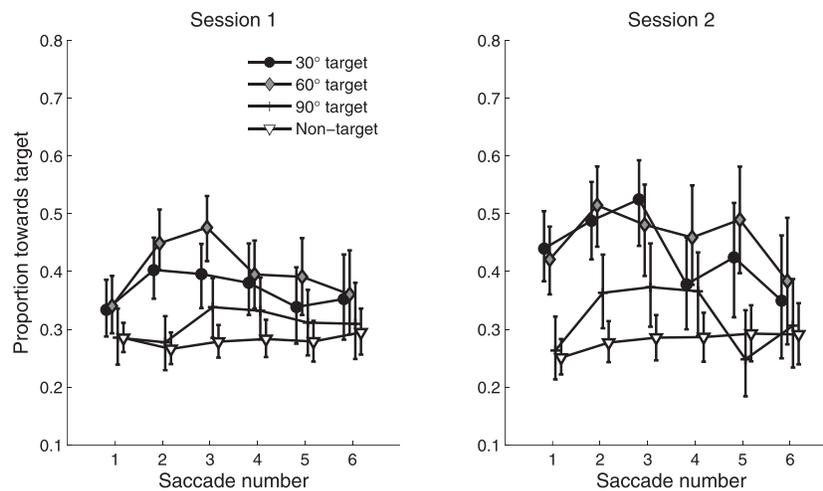


Figure 4. Proportion 30° target, 60° target, 90° target, and comparison nontarget directed saccades as a function of saccade number for session 1 (left) and session 2 (right). Error bars represent 95% confidence intervals acquired using bootstrapping procedures in MATLAB. The data between the (non)target(s) are shifted horizontally, as to prevent overlapping error bars.

nontarget hit. This suggests that the 90° target was not actively searched for or distinguished from nontargets above chance—as determined by the time to fixate a comparison nontarget at the opposite location. For session 2, 60° targets were again detected most often in the 4-s timeframe, followed by the 30° target. This time, the cumulative proportion of 90° target hit did not overlap with the cumulative proportion of comparison nontarget hit. This suggests that in session 2, the 90° target was, in fact, more often fixated than a comparison nontarget.

We reasoned that if infants search actively for the target, saccades towards the target might initially be low in proportion if the target is not yet locatable from the periphery. Subsequently, the proportion of saccades towards the target might increase after gaze is brought closer towards the target. We calculated the proportion of target-directed saccades as a function of saccade number to investigate this. Target-directed saccades were defined as saccades with an unsigned angle of less than 45° between the line through the saccade start and endpoint, and the line through the saccade start point and the target. Figure 4 depicts the proportion of target-directed saccades for the 30°, 60°, 90°-target, and the mean of the comparison nontargets. As can be seen from the left panel in Figure 4, the proportion of target-directed saccades in session 1 increases after the first saccade for the 30° and 60° target, and after the second saccade for the 90° target, compared to the comparison nontarget. As visible from the right panel in Figure 4, the proportion of target-directed saccades increases for the 30°, 60°, and 90° after the first saccade in session 2, compared to the comparison nontarget. Unlike the data from session 1, the proportion of target-directed saccades are already much higher for the 30° and 60° target at the first saccade compared to the comparison

nontarget. These findings suggest that infants actively search for a target beyond the first shift of gaze.

While search performance depended on the angle of the target (i.e., 30°, 60°, or 90°), 90° targets were less often fixated than the other two targets. If target to nontarget similarity decreases linearly with increasing target angle, a linear decrease of time to target hit as a function of target angle would similarly be expected. As this was not the case in both sessions, we examined target differences in more detail. Conspicuity areas—the area around the fixation point within which information about the target can be extracted (Engel, 1971, 1977)—were calculated for all three targets according to Motter and Belky (1998a). Figure 5 depicts the probability that the target would be hit on a next saccade as a function of target eccentricity at the current fixation. If the 90° target was qualitatively different in terms of target fixation (e.g., because it was more salient), one might expect saccades from further eccentricities than for the 30° and 60° target. As can be seen from Figure 5, there is a general decrease of target capture on the next saccade as a function of target eccentricity, for all targets and the mean comparison nontarget—i.e., there is no qualitatively different pattern for the 90° target. In addition, the 60° target was more often fixated, followed by the 30° target, the 90° target, and finally the comparison nontarget. The pattern was similar for session 1 and 2.

Characterization of infant saccadic search behavior

In order to characterize infant saccadic search behavior, we examined two aspects: fixation durations and saccade characteristics. As in adult research, we

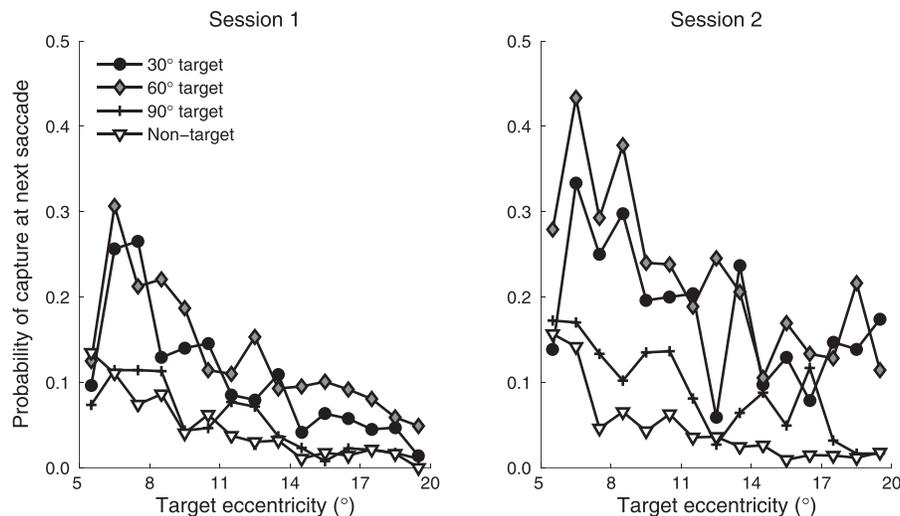


Figure 5. Probability that the next saccade was on target (or comparison nontarget) as a function of the distance between fixation and target for session 1 (left panel) and session 2 (right panel).

expected the first fixation duration—which is the latency to initiate the first saccade—to be longer than subsequent fixation durations (Hooge & Erkelens, 1996; Zingale & Kowler, 1987). As can be seen from Figure 6, median fixation duration for the first fixation (i.e., the latency to first saccade) was consequently longer than subsequent fixation durations for session 1 and session 2. As fixation durations are not normally distributed (confirmed by separate Kolmogorov–Smirnov tests for first fixation duration and subsequent fixations separately for each session), Wilcoxon rank-sum tests were carried out to assess statistical significance. In session 1, first fixation duration ($N = 573$, median = 360.01 ms) was significantly longer than

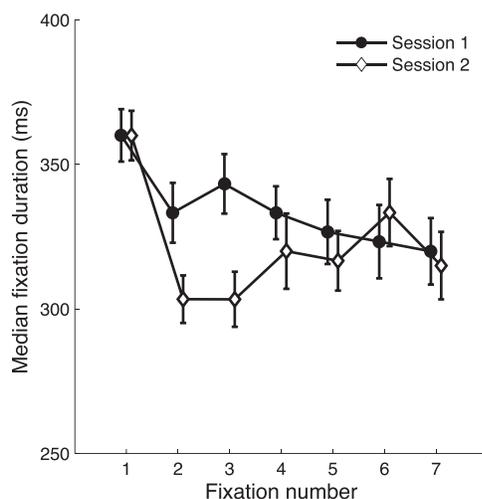


Figure 6. Median fixation duration as a function of fixation number for session 1 and session 2. Error bars depict standard error of the mean. The data between the two sessions are shifted horizontally, as to prevent overlapping error bars.

duration of subsequent fixations ($N = 3525$, median = 333.24 ms, $W = 1235801$, $p < 0.05$).

In session 2, first fixation duration ($N = 354$, median = 359.95) was also significantly longer than duration of subsequent fixations ($N = 2077$, median = 313.32, $W = 496479.5$, $p < 0.05$).

To investigate saccade characteristics, the differences in amplitude and direction from one saccade to the subsequent saccade were plotted in a two-dimensional histogram. Each bin in Figure 7 contains those saccades that changed in direction and amplitude compared to the previous saccade as given by the bin edges. For example, if two saccades are made in the same direction, one saccade is added to the bin with the corresponding amplitude change in the left column (no direction change). As visible from Figure 7, there are two peaks in the distribution. Saccades generally went in the same direction with equal amplitude as previous saccades or saccades went in the opposite direction with equal amplitude. The latter are saccades to the previously fixated location. This pattern was observed both in session 1 and in session 2.

Discussion

Two questions were posed in the present study. First, we questioned whether infants search for a discrepant item in the absence of instructions. Two components of this question were whether target localization is above what may be expected by chance and whether target localization is dependent on the target to nontarget dissimilarity. Second, we questioned in what manner infants search and we describe fixation and saccade characteristics of infant saccadic search. We charac-

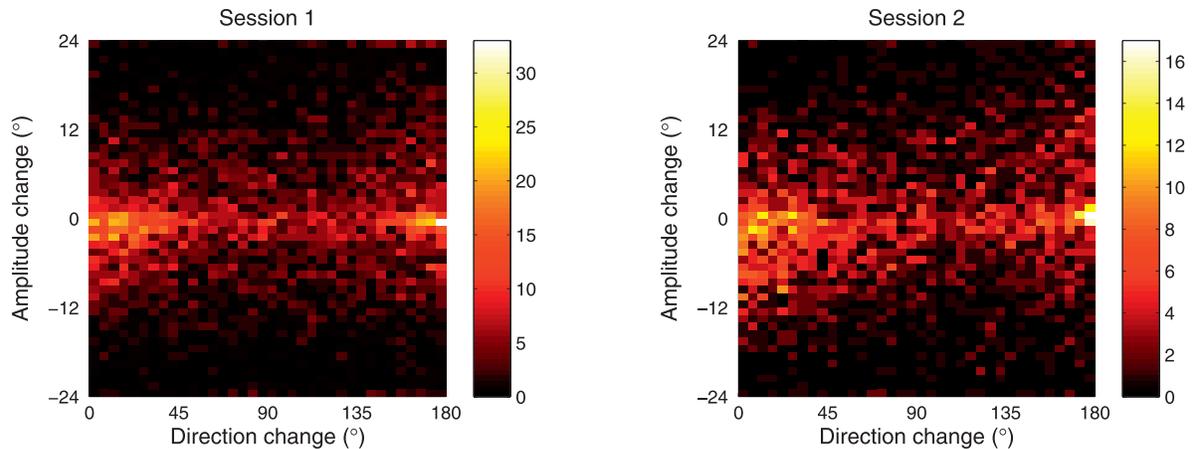


Figure 7. Two-dimensional histograms for the change in amplitude and direction from one saccade to the next for session 1 (left) and session 2 (right). Color indicates frequency of occurrence.

terized infant saccadic search behavior in visual search displays, and describe how it may relate to adult and primate saccadic search behavior. We presented 10-month-old infants with 24 visual search stimuli and collected eye-movement data in two separate sessions to ascertain the reliability of the findings. All presented findings were consistent across both sessions, unless specifically stated otherwise.

Do infants search for a discrepant item in the absence of instructions?

We first report that, depending on the session and target, targets were hit in 30% to 70% of the trials. Infants took on average 1100–1500 ms to locate the target (approximately three to four fixations). Moreover, we noted that saccadic search performance was dependent on the target: Saccadic search performance was best for the 60° target, followed by the 30° target, and finally the 90° target. While we initially expected search performance to increase from 30° to 60° to 90° targets, the 90° targets were least likely to be fixated. We return to this point momentarily, but conclude that saccadic search performance is at least target-dependent. Another indication that infants indeed specifically search for the target, was demonstrated by the 30° and 60° target more readily being fixated than comparison nontargets at equidistant locations from the trial start point (center of the screen). The 90° target was only more readily fixated than comparison nontargets in the second session, not in the first session. We conclude that target fixation in visual search stimuli in infancy is above what can be expected based on our model of chance: in this case the fixation of a nontarget bearing no featural differences to the other nontargets. Moreover, the proportion of fixations on a nontarget was higher—22.9% in session 1 and 19.0% in session

2—than what previous studies expected theoretically (i.e., 12.5% by Amso & Johnson, 2006). To sum, we observe multisaccadic target localization initiated without instruction, and performance that is target-dependent, both suggesting that infants search for discrepant items in the absence of instruction.

To substantiate these findings, we examined when infants directed their gaze to the target. If infants search for the target by looking around until a discrepant item appeared in the periphery, we might expect that the proportion of target-directed saccades increased after the first saccade. If, on the other hand, no active search is taking place, the proportion of target-directed saccades should not change as a function of saccade number. The first is precisely what we observe in the present study. The proportion of target-directed saccades increases after the first saccade, up until around the third or fourth saccade. We suggest that this provides further evidence that infants search for discrepant items in the absence of instruction.

As explained previously, we expected search performance to decrease as a function of target–nontarget similarity, yet we observed a different pattern (but consistent across two separate sessions). If the angle between the vertical nontargets and the target is what specifies target–nontarget similarity we would expect performance to be best for the 90° target, followed by the 60° and 30° target, respectively. The result was that we could not compute linear slopes of visual search performance (i.e., in terms of time to, or number of fixations to, target hit) as a function of target angle. As this was the case, we further investigated how targets were fixated. Specifically, we investigated whether there was a qualitatively different pattern of target fixation as a function of target eccentricity. For example, we might observe that 90° targets were mainly fixated from larger eccentricities compared to the 30° and 60° targets. However, we found that the 90° target was generally

fixated less often than the 30° and 60° targets, irrespective of target eccentricity. We therefore suggest that the 90° target may either constitute a less conspicuous target than the 30° and 60° targets, or infants do not consider the 90° line to be a target. This may be due to the 90° target being horizontal, and not slanted as the 30° and 60° target are. If infants categorize slanted objects from horizontal and vertical objects, as has been suggested by earlier research (Quinn & Bhatt, 1998; Treisman & Gormican, 1988), subjective target–nontarget similarity for the 90° target is expected to be higher than for slanted objects. Future research into infant visual search performance should benefit from using a smaller range of target angle (i.e., excluding the horizontal target) in order to calculate search slopes as function of target–nontarget similarity, or adopt different set sizes to calculate search slopes.

In what manner do infants search?

In an attempt to provide a thorough overview of infant saccadic search behavior, we describe fixation and saccadic characteristics when infants scan a visual search display. We report that there is a bias for saccades to continue in the direction of the previous saccades with equal amplitude, or to go in the opposite direction with equal amplitude (i.e., saccades to previously fixated locations). How can these characteristics be interpreted? Previous research on adults and primates has reported on saccade characteristics in visual search as well, and several speculative connections may be made. Hooge et al. (2005), for example, report that for adults during uniform search (i.e., a task comparable to our present task), as well as during search in pictures and free viewing of pictures, there is also a bimodal distribution of change in saccade direction and amplitude. Saccades generally continued along the current trajectory with the same amplitude or return to the previous fixated location. It appeared as if all elements were systematically investigated, and recently visited locations were sometimes visited again. Infant saccade characteristics are similar to adult saccade characteristics in this regard, although there we observed more variation in saccadic direction and amplitude change in infants. In monkey research, on the other hand, Motter and Belky (1998b) report that saccades in a visual search task have a slight bias to return to the previous fixation location, but otherwise appear directionally random with respect to the previous saccade direction. Future research may focus on determining to what extent human and monkey saccade characteristics are age- and stimulus-dependent. Such investigations may inform us whether search strategies for typical real-

world search tasks are uniquely human or not, and what role experience plays herein.

In addition to describing infants' saccade characteristics when scanning a visual search display, we examined infants' fixation durations during saccadic search. We expected that the first fixation duration—the latency to initiate a saccade—would be longer than subsequent fixation durations based on adult research (Hooge & Erkelens, 1996; Zingale & Kowler, 1987). We observe this pattern in infants as well. The initial saccade latency is associated with the planning of a sequence of saccades and increases with the number of elements in the task (Zingale & Kowler, 1987). Further research may investigate whether increasing set size in changes the saccade latency across infancy as well, indicating when planning of saccade sequences matures. Concluding, there are several notable similarities as well as differences in fixation and saccade characteristics in visual search displays between human infants, adults and primates.

On the reliability of infant oculomotor characteristics and saccadic search behavior

As most infants in the present study participated twice in the same experiment within 2 weeks, we had the possibility of assessing test–retest reliability for oculomotor characteristics during saccadic search and saccadic search performance. While practically all group results described previously were similar across both sessions, we wondered how stable individual oculomotor characteristics during saccadic search and saccadic search performance are. In order to determine test–retest reliability, Pearson's product–moment correlation and intraclass correlation (McGraw & Wong, 1996; Weir, 2005) were calculated for fixation duration, saccade latency, and time to target hit. Figure 8 depicts test–retest reliability for oculomotor characteristics during saccadic search: median saccade latency (shown left) and median fixation duration (shown right). Fixation duration showed high test–retest reliability ($r = 0.71$, $p < 0.05$; $ICC(A,1) = 0.66$, $p < 0.05$), while saccade latency was slightly less reliable ($r = 0.47$, $p < 0.05$; $ICC(A,1) = 0.46$, $p < 0.05$).

Fixation duration has previously been shown to be reliable during infant free-viewing (Wass & Smith, 2014), and we extend this finding here to visual search stimuli. Test–retest reliability for saccadic search performance (as determined by time to target hit) was lower for the 60° target than oculomotor characteristics ($r = 0.47$, $p < 0.05$; $ICC(A,1) = 0.35$, $p < 0.05$). Test–retest reliability for the 30° and 90° target was, on the other hand, not reliable at all (both not significantly different from zero). While enough data was available

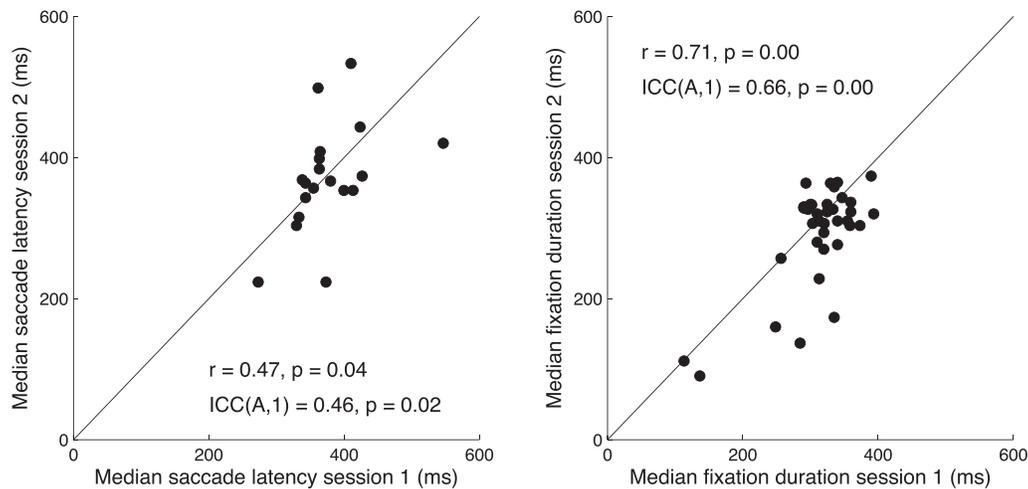


Figure 8. Test–retest reliability for median saccade latency and median fixation duration. Pearson’s product–moment correlation and intraclass correlation are given in text.

for group comparisons, it is likely there have been too few trials to estimate reliable individual means for saccadic search performance. This is particularly relevant for future studies where individual differences in saccadic search behavior are important, for example in early recognition of ASD (e.g., Gliga et al., 2015). More trials may need to be presented in order to obtain reliable individual estimates of saccadic search performance. Future research should address test–retest reliability for saccadic search performance on more data.

Conclusions, limitations, and future research

The main findings of the present study are as follows. Infants search for discrepant items in the absence of instruction, and saccadic search performance is dependent on target and nontarget dissimilarity. Infant saccadic behavior in visual search displays is characterized by saccades following the current trajectory with equal amplitude, and saccades returning to previously fixated locations. These findings were highly consistent across two separate sessions. As saccadic search appears to be above chance in 10-month-old infants, visual search displays are indeed suitable for investigating the development of saccadic search in infancy (Amso & Johnson, 2006; Frank et al., 2014; Schlesinger, Amso, & Johnson, 2007). However, as the empirical chance level was higher than what previous studies theoretically expected, we suggest that future studies always report a proper baseline condition when participants cannot be instructed to perform a visual search task.

While the present study is the first comprehensive description of infant saccadic search behavior, there are several limitations to the study. First, we only measured at one time point (10 months). However, in doing so we have provided a reference point for future research investigating the development of saccadic search performance across the first year after birth. Researchers investigating both the typical and atypical development of visual search may benefit from these results, particularly when investigating the development of saccadic search behavior in ASD. Second, we observed that 90° targets were not more readily detected compared to 30° and 60° targets. In hindsight, using the 90° target prevented us from calculating search slopes as a function of target–nontarget similarity. Future research should benefit from using a smaller range of target angles (e.g., 0° to 45°), or adopting differences in set size to allow search slopes to be calculated.

Keywords: visual search, saccadic search, infancy, eye tracking, test-retest

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