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Spontaneous visual search during the first two years: Improvement with age but no evidence of efficient search

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ABSTRACT

Efficient visual search, wherein reaction times to acquire targets are largely independent of array size, is commonly observed in adults. Evidence for efficient search in infants may imply that selective attention to visual features is similar across development. In the current cross-sectional eye-tracking study, we examined spontaneous visual search at 6, 12, 18, and 24 months. Infants were presented with Random arrays (one target among 7, 13, or 26 pseudorandomly distributed elements) and Circle arrays (one target among 4, 7, or 13 elements arranged in a circle). Contrary to predictions, we did *not* find evidence of efficient search among infants. With increasing array size, time-to-target increased, the proportion of targets fixated (analogous to accuracy) decreased, and the proportion of first looks to the target decreased for both types of array ($ps < .001$). For Random arrays, the proportion of first looks to the target was similar to chance for all ages and array sizes; for Circle arrays, it exceeded chance for some ages and array sizes. The proportion of targets fixated and first looks to target increased with age across display types ($ps < .05$). We also tested adults with the same stimuli under similar conditions; the adults showed evidence of efficient visual search. Possible explanations and implications are discussed.

1. Introduction

Visual search paradigms provide a window into perceptual and attentional development. Work on visual search has distinguished between *efficient* visual search[1], in which the time to find the target is largely independent of the number of distractors, and *inefficient* visual search, in which the time increases steadily with the number of distractors (e.g., Treisman & Gelade, 1980; Wolfe, 1994). Similar patterns of efficient and inefficient search in children and adults suggest that children and adults may process visual stimuli in similar ways (e.g., Lobaugh, Cole, & Rovet, 1998) and even that the "basic perceptual processes underlying visual search are qualitatively invariant across ontogeny" (Gerhardstein & Rovee-Collier, 2002, p. 194). According to this framework, humans, regardless of developmental stage, preattentively detect discrepancies in specific local features (e.g., number of line segments) but must engage in focused attention to detect larger patterns (Julesz, 1981). This idea that a preattentive system automatically and rapidly processes certain types of information whereas a focused attention system constructs basic units into recognizable wholes more effortfully and slowly is consistent with "models in which object recognition is conceptualized as a bottom-up process that begins with the initial

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[1] We use the term efficient search rather than pop-out as the former describes a measurable behavior rather than a subjective experience (Wolfe, 1994) which can not be verified with infants.

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detection of primitive perceptual units" (Rovee-Collier, Hankins, & Bhatt, 1992, p. 445). However, more recent work highlights the contributions of top-down processes to visual search (e.g., Cavallina, Puccio, Capurso, Bremner, & Santangelo, 2018; Wolfe & Horowitz, 2004) and suggests that different factors may affect the deployment of attention at different points in development (Kwon, Setoodehnia, Baek, Luck, & Oakes, 2016).

A number of studies have looked for patterns of efficient and inefficient search in early development, attempting to see whether infants and toddlers have similar selective attention to visual features as older children and adults. There has been some evidence for efficient search in infants and toddlers (e.g., Colombo, Ryther, Frick, & Gifford, 1995; Gerhardstein & Rovee-Collier, 2002; Rovee-Collier, Bhatt, & Chazin, 1996). In an eye-tracking study of spontaneous (unrewarded) visual search, Adler and Orprecio (2006) concluded that based on saccade latencies, 3-month-olds showed evidence of efficient visual search and thus that selective attention to the visual features examined is similar in infants and adults. However, research with older children suggests that accuracy may be even more important than response time for distinguishing between the visual search patterns of children and adults (e.g. Lobaugh et al., 1998). The present study aims to contribute to this growing body of research by using eye-tracking to examine spontaneous visual search among infants at 6, 12, 18 and 24 months (and in a follow-up study with adults) by analyzing multiple measures, including measures of both time-to-target and the proportion of targets fixated (analogous to accuracy) as well as of the proportion of first looks to the target.

1.1. Visual search in adults and infants

In early work on visual search in adults, in which participants were instructed to find the target and search efficiency was assessed by comparing RTs for different array sizes (e.g., Treisman & Gelade, 1980), efficient visual search was thought to occur during *featural* search, in which targets differ from distractors on a single feature (e.g., a yellow triangle among yellow squares); inefficient search was thought to occur during *conjunctive* search, in which targets are defined by the conjunction of two or more features (e.g., a yellow triangle among red triangles and yellow squares). Efficient search was thought to involve preattentive processes in which the visual field is processed in parallel for certain features, whereas inefficient search was thought to involve the subsequent serial application of attention to different locations (Treisman & Gelade, 1980). More recent studies have found that some featural searches can be inefficient and some conjunctive searches efficient (Wolfe & Horowitz, 2004; Wolfe, 1994). In any event, if there is a pattern of efficient visual search for a feature, it implies that attributes in early vision "guide the deployment of attention" (Wolfe & Horowitz, 2004, p. 2).

Thus, visual search can help us understand what features guide the attention of infants and toddlers, show how they segment the world, and shed light on how they come to perceive objects. In addition, autistic children and adults have been found to have enhanced visual search (e.g., Kaldy, Kraper, Carter, & Blaser, 2011; Plaisted, O'Riordan, & Baron-Cohen, 1998), though there have been some mixed results (e.g., Lindor, Rinehart, & Fielding, 2018); one study found that heightened levels of spontaneous visual search in 9-month-olds with and without a familial history of Autism Spectrum Disorder (ASD) predicted more symptoms of ASD later on (Gliga, Bedford, Charman, Johnson, & BASIS Team, 2015). Among infants without a family history of ASD, above-chance proportions of first looks to the target were observed at 9 months and 24 months (but not 15 months). Infants with a family history of ASD exhibited above-chance performance at all three time points. Studies of visual search in typical development, therefore, may help provide a framework for understanding the developmental mechanisms underlying potentially enhanced visual search in ASD.

A number of paradigms have been used to study visual search in infants, who cannot be instructed to search for a target (see Table 1). Some studies have examined whether infants orient to the same features that allow for efficient search in adults. In separate studies using a preferential looking paradigm (Colombo et al., 1995) and a novelty preference paradigm (Quinn & Bhatt, 1998), 3- and 4-month-olds were found to orient more to an array with a discrepant element (a line-crossing) than to an array without such an element. These findings were interpreted as evidence of efficient search among infants. In contrast, Sireteanu et al. (2009) found that 6- and 8-month-old infants did not preferentially look at a display with a discrepant element (such as a circle with a gap amidst complete circles, or vice versa), but rather looked more at displays that only contained repeated elements, whereas 36- and 48-month-olds showed the more adult-like pattern of looking more at displays with discrepant elements.

Efficient search has also been examined using the mobile conjugate-reinforcement paradigm, in which during training the infant's kicking moves a mobile of blocks with stimuli on their sides (e.g., Rovee-Collier et al., 1996, 1992). Even during test when their kicking no longer moves the mobile, infants continue to kick in response to mobiles that are similar to or identical to training mobiles. Among 3-month-olds, the presence of one familiar element among novel elements elicited continued kicking, whereas the presence of one novel element among familiar elements did not, implying that in both cases the discrepant element had attracted attention to the extent of controlling the response (Rovee-Collier et al., 1992).

Responses did not vary with set size (5 or 9 elements) among 6-month-olds (Rovee-Collier et al., 1996), implying efficient search. Somewhat complicating this interpretation, at the largest array size (of 13 elements), only familiar *distractors* (not the familiar *targets* that elicited more kicking in smaller arrays) elicited more kicking, suggesting that the unique element had not been detected.

In a reaction time (RT) paradigm more similar to visual search studies in adults, Gerhardstein and Rovee-Collier (2002) used operant reinforcement to train 12- to 36-month-olds to touch a screen when they saw a target (the featural condition used red or green cartoon dinosaurs; the conjunctive condition included two kinds of dinosaurs as well as the two colors). Similar to visual search findings with adults, RTs in the featural condition did not vary with array size (ranged from 3 to 13 elements), implying efficient search, whereas in the conjunctive condition, RTs increased with array size, implying inefficient search. (Accuracy also increased with array size.) RTs decreased with age.

In an eye-tracking study of visual search in autistic and typically developing 2.5-year-olds (mean ASD age 29.5[4.8] months,

Table 1
Summary of infant/toddler visual search literature discussed in the present article.

Authors	Participants	Stimuli	Reinforcement	Measures included				Results
				RT	Accuracy	Comparison with chance	Comparison of feature +/-or target +/-	
Forced-choice preferential looking								
Colombo et al. (1995)	3 months, 4 months	Arrays with discrepant elements (circles with or without line crossings) paired with homogeneous arrays.	No	N/A	N/A	Yes, chance defined as 50%	Yes	Infants fixated on feature-present array more than on feature-absent array, and at greater than chance levels.
Quinn and Bhatt (1998)	3 to 4 months	Expt. 1: arrays with "+", "L", "T" in varied orientations. Uniform familiarization arrays; test arrays with single discrepant element. Expt. 2.: Arrays with vertical and oblique lines.	No	N/A	N/A	Yes, chance defined as 50%	Yes	Infants preferentially looked at arrays with a novel discrepant element when the element was distinguished by a feature such as a line-crossing.
Sireteanu et al. (2009)	2 to 60 months	Complete or open circles & squares; squares amidst lines of various orientations; low- & high-frequency gratings.	No	N/A	N/A	Yes, chance defined as 50%	In some of the expts	Infants under 12 months preferred repetitive displays to those with a discrepant element. By 36-48 months, children displayed "adult-like" preference for displays with discrepant elements.
Mobile conjugate reinforcement. Kicking moves mobile during baseline, measured during trial								
Rovee-Collier et al. (1996)	6 months	Mobiles w/ varying numbers of blocks (5, 7, 9, 11, 13); "+" and "L" characters.	Yes, kicking moved mobile during familiarization	N/A	N/A	N/A	No	Kicking ratios showed that familiar unique items in novel arrays were detected at all array sizes except the largest (13 items).
Rovee-Collier et al. (1996)	3 months	7-block mobiles with “T”, "L" and "+" characters.	Yes, kicking moved mobile during familiarization	N/A	N/A	N/A	Yes	In delayed recognition and memory reactivation paradigms, infants responded to discrepant elements.
Manual response following training								
Gerhardstein & Rovee-Collier (2002)	12-36 months	Two types of red and green dinosaurs.	Sound/ animation rewarded touching target.	Yes	Yes	No	No	RTs for feature search were flat but RTs for conjunctive search increased with distractor number. RTs decreased with age. Accuracy increased with array size for feature searches.

(continued on next page)

Table 1 (*continued*)

Authors	Participants	Stimuli	Reinforcement	Measures included				Results
				RT	Accuracy	Comparison with chance	Comparison of feature +/-or target +/-	
Eye tracking/electrooculography								
Adler and Gallego (2014)	3 months, adults	Arrays w/" R" & "P" elements; arrays were homogeneous or had feature +/- targets	No	Yes (pooled data)	No	No	Yes	Shorter saccadic RTs for feature-present but not feature-absent arrays in infants and adults. Effects held across set sizes.
Adler and Orprecio (2006)	3 months, adults	"+" targets, "L" distractors	No	Yes (pooled data)	Yes	No	Yes	For target-present arrays, flat latency slopes, said to indicate efficient search. For target-absent arrays, steeper slopes, said to indicate inefficient search.
Amso and Johnson (2006)	3 months	Tilted or moving target rods amidst vertical distractor rods.	No	Yes	% trials w/ targets selected w/in 4 s	Yes	No	Above-chance performance for tilted rods.
Hessels et al. (2016)	10 months	28 white lines in 14 columns/2 rows. Target = tilted line amidst vertical lines.	Cartoon presented in location of target at end of trial.	Yes (pooled data)	Prop trials in which target hit within 4 s	Yes, relative to non-target equidistant from center to target.	No	Targets slanted 30 and 60 (but not 90) degrees were fixated more (target hits as a function of time) vs. chance.
Gliga et al. (2015)	9, 15, 24 months (low or high risk for ASD)	Letter targets; "x" distractors. One array size (8 items), circular.	No	No	% of first looks to the target	Yes	No	First looks to the target at 9 months predicted ASD symptoms at 15 and 24 months. % first looks to the target > chance for all groups except 15 month low risk.
Kaldy et al. (2011)	˜2.5yrs ASD: 29.6(4.8) months Controls: 29.5(2.5) months	Red apple target; blue apple & red bar distractors. Feature trials (5-9 items; target color differs from distractors) and Conjunction trials (5, 9, 13 items; target shares color with distractors).	Example of target "flew in" before trial; target spun at end of trial.	Yes	Fixation on target within 4 s	No	No	On Feature trials, no effect of set size; ASD and control groups were similar. On Conjunction trials, performance decreased with set size, and ASD toddlers had greater accuracy, more time fixated on target, and more inspection of items.
Kwon et al. (2016)	4, 6, 8 months	Study 1: Ellipse/ circular arrays with 1 face and 5 objects that varied in saliency. Study 2: 2 item sets.	No	Yes	First fixation to face/most salient object	Yes	N/A	6- and 8-month-olds looked first and longest at face. 4-month-olds looked first at most perceptually salient item.

mean typically developing age 29.6[2.5]months), Kaldy et al. (2011) emphasized the distinctiveness of the target (it was always a bright red apple, an example of which "flew" onto the screen before each trial; after the trial, the target spun in place). For featural search, accuracy (defined as the proportion of trials on which infants fixated the target within 4 s) did not vary with set size (5 or 9 elements) and was similar for the groups, but accuracy may have been near ceiling due to the long viewing time. RTs were not assessed.[2]

Whereas these studies generally support the notion that preattentive visual processing and efficient visual search are similar in infants and adults, most rely on reinforcement to facilitate target search and few assess both RTs and some measure of accuracy. This leaves open the question of whether infants show *spontaneous* (unrewarded) visual search, which may give us insight into infants' tendency to attend spontaneously to anomalous visual features in the environment. Eye-tracking can be especially useful in studying spontaneous visual search in infants as it can provide precise information about the spatial and temporal characteristics of gaze patterns.

Spontaneous orienting in infants to a featural target has been examined in two recent eye-tracking studies. Using electro-oculography, Adler and Orprecio (2006) examined whether 3-month-old infants and adults oriented to a "+" target in a circular array of "L" distractors. If the first saccade was towards the target, it was counted as a correct response and the latency to begin the saccade was measured; in a target-absent condition, the latency of the first saccade to any item on the screen was measured. RTs were pooled for all infant subjects and for all adult subjects. With increasing set size, RTs in the target-present condition did not differ, whereas RTs in the target-absent condition increased; Adler and Orprecio (2006) concluded that the former was evidence for efficient search. Accuracies were reported to be similar for array sizes of 3, 5, and 8 in the target-present condition, though specific accuracies were not provided. In a more recent eye-tracking study with 3-month-olds and adults that used arrays containing "R" and/or "P" elements, Adler and Gallego (2014) concluded that the slopes for target-present arrays were consistent with efficient search whereas those for target-absent arrays showed inefficient search, similar to the asymmetry found in adults. RTs were pooled for infants and for adults and measures of accuracy were not reported.

As part of a larger study on the development of perceptual completion (perception of the unity of an occluded object), Amso and Johnson (2006) used displays with one tilted rod amidst vertical rods to examine visual search in 3-month-olds. Amso and Johnson argued that for both perceivers and nonperceivers of perceptual completion, accuracy (defined as the proportion of usable trials in which a saccade was begun toward the target within 4 s) was above chance; perceivers were more accurate but slower than non-perceivers. However, the study's comparison with chance did not take into account the number of distractors, and speed-accuracy tradeoffs might have affected the comparison of perceivers and nonperceivers (i.e., perceivers might have taken longer to find targets overall because some of the greater number of targets they found were fixated close to the end of the available viewing time).

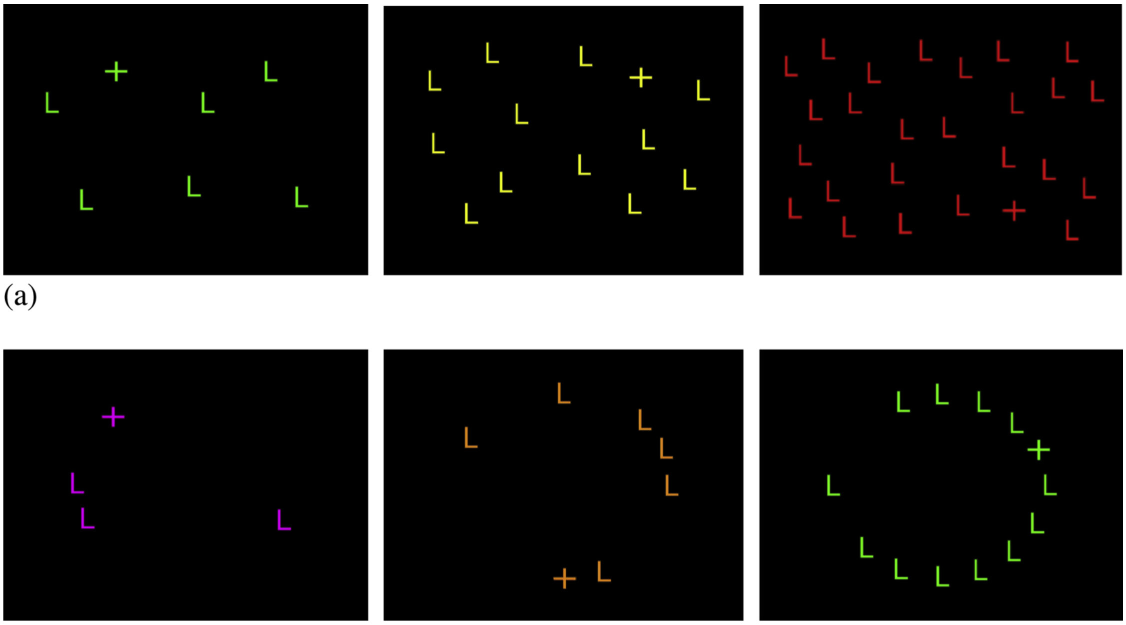
1.2. The present study

In the present cross-sectional study, we used eye-tracking to examine the development of spontaneous visual search in infants and toddlers at 6, 12, 18, and 24 months. To establish a more complete understanding of spontaneous visual search in infants and toddlers, and to be able to compare our results to previous studies which reported different measures of visual search, we used several measures: time-to-target, the proportion of targets fixated, and the proportion of first looks to the target.

Noting that eye movements and attention are closely linked (e.g., Hoffman & Subramaniam, 1995; Williams, Reingold, Moscovitch, & Behrmann, 1997), Adler and Orprecio (2006) used latency to begin a saccade towards the target as a measure. Because infant saccades are often hypometric (i.e., fall short of their apparent goal), Adler and Orprecio counted saccades that went more than 50% toward the target as correct in their target-present condition. While latency to begin an eye movement is a reasonable and commonly used measure, it has not been directly associated with manual RT, a commonly used measure of visual search efficiency (Wolfe, 1998). Indeed, latency to *begin* a saccade may be less directly comparable to manual RT than are other eye-tracking measures. A comparison of eye movements and manual RTs in response to visual search opportunities revealed that adults' initial saccades did not typically go directly to the target (Zelinsky, Rao, Hayhoe, & Ballard, 1997; Zelinsky, 2008). Instead, a series of saccades progressively approximated the location of the target. Manual indication that the target had been located co-occurred with eye fixation on or very near the target. Correspondence between manual RT and latency to fixate a target was also observed in a recent study with adults (Beck, Hollingworth, & Luck, 2012). This finding suggests that the timing of target detection may be more directly related to commonly used measures of search efficiency than is latency to begin the first saccade. By examining how long it took infants to look at the target within the available time for each array (2 s), we sought to examine the "drawing power" of targets with features that had previously been found to guide efficient search (e.g., Adler & Orprecio, 2006; Quinn & Bhatt, 1998; but see Wolfe & DiMase, 2003).

To permit comparison of performance at different array sizes, we also recorded the proportion of targets fixated, defined as the proportion of usable trials in which targets were fixated within the 2 s stimulus viewing time. This is somewhat analogous to accuracy, measured in other studies of visual search in both children (Adler & Orprecio, 2006; Amso & Johnson, 2006; Gerhardstein & Rovee-Collier, 2002; Kaldy et al., 2011) and adults (e.g., Treisman & Gelade, 1980). (Because the infants cannot be instructed to look for the targets and were not rewarded in our study for doing so, we reasoned that proportion of targets fixated is a more precise term than accuracy for the behavior assessed in this study.)

[2] In Kaldy et al.'s (2011) conjunctive condition, set size did affect accuracy, and the autistic toddlers found the targets more frequently than the typically developing ones.



(a) (b)

Fig. 1. Examples of stimuli used for (a) Random arrays and (b) Circle arrays.

Finally, we used the proportion of first looks to the target for each array size as a measure that was comparable to an estimate of chance. Based on earlier studies, we predicted that at each age there would be evidence of efficient search: that infants would look at the target at above-chance levels (determined by comparing the proportion of first looks to the target for each array size with an estimate of chance performance) and that proportion of targets fixated and time-to-target would remain constant with increasing array sizes. In addition, we predicted that performance on these measures would improve with age.

Similar to a number of studies of visual search in infants and adults (e.g., Adler & Orprecio, 2006; Quinn & Bhatt, 1998; Rovee-Collier et al., 1996), we used "+" targets and "L" distractors; see Fig. 1 (below). To examine visual search abilities across our wide range of ages, we used two kinds of arrays. In Circle arrays, distractors and targets were arranged in a circle, with an unobstructed path between center and target. In Random arrays, distractors were distributed pseudorandomly around the screen and might be placed between center and target; set sizes were larger than in Circle arrays. The Circle arrays let us see whether efficient search occurred in smaller arrays with an unobstructed path to the target; the Random arrays let us see whether such findings also held true in larger and more cluttered arrays. Because it was anticipated that the Random arrays would be more difficult than the Circle arrays, the Random arrays were always presented first, when the infants were fresher. These conditions were analyzed separately.

2. Experiment 1: infants and toddlers

2.1. Method

2.1.1. Participants

Infants were recruited from the Greater Los Angeles area with a letter sent to the parents of newborns, asking them to express interest using a stamped postcard. The final sample included 15 6-month-olds (8 male), mean = 5.98 months (*SD* = .43 months); 16 12-month-olds (8 male), mean = 11.77 months, *SD* = .49 months; 16 18-month-olds (8 male), mean = 17.62 months, *SD* = 1.44 months; and 16 24-month-olds (8 male), mean = 24 months, *SD* = .44 months. Data were excluded from 23 infants (2 6-month-olds; 7 12-month-olds; 7 18-month-olds; 7 24-month-olds) due to eye-tracking difficulties and fussiness (inaccurate calibrations, shaky gaze points, or frequent looks away from screen), from 18 infants (2 6-month-olds, 2 12-month-olds, 14 18-month-olds) due to experimenter error (incorrect screen resolution or too many infants of a particular gender), and from 3 infants (3 12-month-olds) because both blocks were excluded (insufficient central fixations; see below). Informed consent from participating families was obtained prior to any experimental procedures under protocols approved by the University of California, Los Angeles, Institutional Review Board.

2.1.2. Stimuli

Each stimulus consisted of a "+" target among "L" distractors. In the Random condition, 7, 13, or 26 elements were distributed pseudorandomly around the screen. In the Circle condition, 4, 7, or 13 elements were distributed randomly around a circle. In both conditions, all targets were equidistant from the center, placed around an imaginary circle (radius 9.5 cm; 8.4° of visual angle) divided into 16 segments. Each target was randomly placed on this imaginary circle, with the following constraints: For each Circle or Random block, equal numbers of targets were placed on the left and right sides of the screen; at the midline, 10% and 13% of targets were at the top and bottom of the screen, respectively.

The height and width of each element was 2.1 cm (1.9°). For each stimulus display, target and distractors were in the same lighter color against a black background. For each condition (Random or Circle), there were five stimuli each of a different color (green, orange, purple, red, or yellow) for each array size, for a total of 15 Random and 15 Circle stimuli. Color was varied to maintain infant attention; to avoid potential confounds, each array size included one stimulus in each of the five colors. Each display was accompanied by Bach cello music.

Between displays, infants' gaze was attracted to the center of the screen with a variety of animated cartoons accompanied by sound effects (attention-getters). Each attention-getter was approximately 6.2 cm square (6.0°).

2.1.3. Apparatus and procedure

Infants were seated in a darkened room on their parents' laps approximately 60 cm from the 27 x 34 cm screen. Eye movements were recorded with a Tobii 1750 eye tracker and fixations were defined using a dispersion model, grouping samples within a 30-pixel radius for at least 100 ms. Cameras beneath the monitor recorded reflections from an infrared light at a frequency of 50 Hz to assess the distance between the cornea and pupil of both eyes, with an approximate accuracy of .5-1° of visual angle according to manufacturer's estimates. Stimuli were displayed with ClearView software (Tobii Technology AB; http://www.tobii.com/). The "normal" ClearView validity filter averaging across both eyes was used. A 5-point calibration was administered prior to the assessment.

For each stimulus array, two Areas of Interest (AOIs) were defined, each 4.9 cm (4.4°) square, one centered on the target and one placed at the center of the screen. For the centrally located attention-getters, the central AOI was enlarged slightly.

Following calibration, infants viewed the Random and Circle blocks of stimuli. For each trial, an attention-getter was presented in the center of the screen. As soon as the experimenter had judged that the infant had oriented to the monitor, the attention-getter was replaced by the stimulus which remained on the screen for 2 s, followed by the next attention-getter.

All 15 Random condition stimuli were presented once before the 15 Circle condition stimuli were each presented once, for a total of 30 trials for each infant. Each block was presented in a pseudorandom order, which constrained how many times the same array size could appear sequentially.

2.1.4. Design and analyses

The experiment had a 4 × 3 mixed design, with age (6, 12, 18, 24 months) as a between-subjects factor and array size (7, 13, 26 in the Random condition; 4, 7, 13 in the Circle condition) as a within-subjects factor.

For all measures, only data from trials for which there was an adequate central fixation were used. An adequate central fixation was defined as (a) a fixation on the attention-getter that ended within 1000 ms before the onset of the stimulus, and after which the infant did not fixate on another area prior to the stimulus onset or (b) a fixation on the center of the screen during the stimulus onset. Data from blocks in which fewer than half of the trials (i.e., fewer than 8 trials) had adequate central fixations were excluded.

Measures included the proportion of targets fixated (for each array size, the proportion of trials in which there was at least one fixation on the target within the ˜2 s the array was on the screen); time-to-target (for trials in which there was a fixation on the target, the time from the stimulus onset to the onset of the first fixation on the target); and the proportion of first looks to the target (for each infant, for each array size, the proportion of trials in which the first fixation after disengaging from the center was to the target).

2.2. Results

2.2.1. Analysis approach

Because time-to-target data were limited by accurate responses, mixed models (which accommodate missing data; Seltman, 2012) were used to analyze response time data; for consistency, mixed models were also used to analyze the other measures. Mixed effects commands from two statistical packages, SPSS and Stata, were used where appropriate (SPSS was the default; Stata is better at handling skewed data and also was able to show standard errors when the mixed command was used on a single factor, as was done with the adult data).

Because response time and accuracy in visual search experiments (analogous to our proportion of targets fixated) are generally regarded as linear functions of the number of elements in the search arrays, array size was analyzed as a continuous variable to convert the non-linear sets of array sizes for each condition (Random: 7, 13, 26 elements; Circle arrays: 4, 7, 13 elements) into linear data. For the proportion of first looks to the target, it is less clear whether array size should be continuous or categorical; results seem more likely to be related to a measure of chance (1/arraysize).

To determine whether array size should be analyzed as continuous or categorical, each measure was analyzed both ways and the Akaike's Information Criterion (AIC) was compared for each method. These information criteria measure goodness-of-fit of a statistical model by looking at the size of the residuals in relation to the number of parameters in the model (Burnham & Anderson, 2004; Dziak, Coffman, Lanza, & Runzi, 2012); smaller residuals in conjunction with fewer parameters indicate a better fit, such that lower numbers for the AIC are better. The AIC confirmed that models with array size as continuous better fit the data for most of the analyses (the exceptions were two infant/toddler analyses for Circle arrays – the proportion of targets fixated and the proportion of first looks to the target). For consistency, array size was treated as continuous for all analyses.

In addition, for the proportion of first looks to the target, results for each array size were compared with a rough measure of chance based on the proportion of targets to the total number of elements on the screen. For example, if one target and three distractors were on the screen, the probability of first looking at the target by chance would be .25. For the corresponding array sizes, the probabilities are shown in parentheses: 4 (.25); 7 (.143); 13 (.08); 26 (.04).

In the comparisons with chance and post-hoc pairwise comparisons, a False Discovery Rate (FDR; Benjamini & Hochberg, 1995) procedure was used to correct for multiple comparisons while maintaining more power than Familywise Error Rate control methods. In the FDR procedure, *p*-values in an analysis are first listed from smallest to largest, then multiplied by the number of *p*-values and divided by their numerical rank; a final step ensures that the resulting *q*-values increase monotonically (Yekutieli & Benjamini, 1999). For all analyses, we used a *q* level of .05. (The *q*-level is the expected proportion of false discoveries and is somewhat analogous to an alpha level.) When comparing different ages within each array size, to minimize multiple comparisons, we compared adjacent ages only.

2.2.2. Amount of usable data

As noted above, only trials with adequate central fixations were used, and data from a Random or Circle block were only included if there were 8 or more adequate central fixations for that block. In what follows, the number of participants for each age group with enough adequate central fixations for that condition is given, followed by the mean number of usable trials; SDs are in parentheses.

For the Random arrays, for the 6-month-olds, there were 15 usable blocks (i.e., 15 participants exhibited at least 8 adequate central fixations on the Random arrays and were included in analyses) with a mean of 14.47(.83) usable trials; for the 12-month-olds, 16 usable blocks with a mean of 14.63(.81) usable trials; for the 18-month-olds, 16 usable blocks with a mean of 14.88(.34) usable trials; and for the 24-month-olds, 16 usable blocks with a mean of 14.69(1.25) usable trials.

For the Circle arrays, for the 6-month-olds, there were 15 usable blocks, with a mean of 14.6(.63) usable trials; for the 12-month-olds, 14 usable blocks with a mean of 14.86(.36) usable trials; for the 18-month-olds, 16 usable blocks with a mean of 13.88(1.6) usable trials; and for the 24-month-olds, 14 usable blocks with a mean of 13.9(1.33) usable trials.

2.2.3. Time-to-target

Mixed models analyses showed that time-to-target increased with increasing array size for both Random arrays, $F(1, 98.589) = 11.196$, $p < .01$ and Circle arrays, $F(1, 104.905) = 14.566$, $p < .001$[3] ; see Fig. 2. For the Random arrays, with increasing array size, overall time-to-target increased an average of 12.19 ms/element; for Circle arrays, it increased an average of 25.14 ms/element. For the Random arrays, time-to-target decreased with age, $F(3, 54.888) = 3.588$, $p < .05$; age did not affect time-to-target for the Circle arrays ($p > .05$). There was no interaction between age and array size for either Random or Circle arrays ($p > .05$).

2.2.4. Proportion of targets fixated

As noted above, for each array type and array size, the proportion of targets fixated was defined as the proportion of usable trials (i.e., those with an adequate central fixation as defined above) in which the target was fixated within 2 s, divided by the total number of usable trials for that array size. The proportion of targets fixated decreased with increasing array size for both Random arrays, $F(1, 124) = 64.127$, $p < .001$, and Circle arrays, $F(1, 116) = 118.346$, $p < .001$; see Fig. 3.

The proportion of targets fixated increased with age for both Random arrays, $F(3, 177.036) = 10.832$, $p < .001$, and Circle arrays, $F(3, 58) = 7.143$, $p < .001$. Array size interacted with age for the proportion of targets fixated for the Random arrays, $F(3, 124) = 4.367$, $p < .01$ but not for Circle arrays ($p > .05$).

In post-hoc analyses, slopes for proportion of targets fixated for the Random arrays differed from zero for all ages except for the 6-month-olds. For the 12-month-olds, the slope was −.013% per element, $t(1, 124) = -4.171$, $p < .001$; for the 18-month-olds, −.021% per element, $t(1,124) = -6.820$, $p < .001$; for the 24-month-olds, −.011% per element, $t(1, 124) = -3.489$, $p < .01$. Comparing the slopes for the proportion of targets fixated for adjacent ages, the slope for the 18-month-olds was more negative than the slope for the 24-month-olds, $t(1, 124) = 2.238$, $p < .05$).

Fo the Random arrays, we also compared the proportion of targets fixated for adjacent ages within each array size. For both the 7-element arrays and the 13-element arrays, 18-month-olds had a greater proportion of targets fixated than 12-month-olds ($qs < .05$); for the 26-element arrays 24-month-olds had a greater proportion of targets fixated than 18-month-olds ($q < .01$). There were no other significant differences between adjacent ages ($q > .05$).

2.2.5. Proportion of first looks to target

The proportion of trials on which the first look was to the target decreased with increasing array size for Random arrays, $F(1, 124) = 10.256$, $p < .01$. The proportion of first looks increased with age for Random arrays, $F(3, 62) = 7.504$, $p < .001$. There was no interaction between array size and age for Random arrays ($p > .05$) or Circle arrays ($p > .05$). For Circle arrays, the proportion of first looks to the target decreased with increasing array size, $z = -8.24$, $p < .001$, $\beta = -.0299$, $SE = .0036$, and increased with age, df(3), $\chi^2 = 9.09$, $p < .05$.

In post-hoc one-sample *t*-tests, the proportion of first looks to the target for each array size at each age was compared with an estimate of chance performance computed as described above, and FDRs were applied; see Fig. 4. For the Random arrays, no age group performed significantly different from chance on any array size ($q > .05$). For the Circle arrays, performance on the 4-element arrays was greater than chance for the 12-month-olds ($q < .05$) and 24-month-olds ($q < .05$), as was performance on the 7-element

[3] In a mixed models analysis, SPSS uses a Satterthwaite approximation to estimate the denominator of the degrees of freedom.

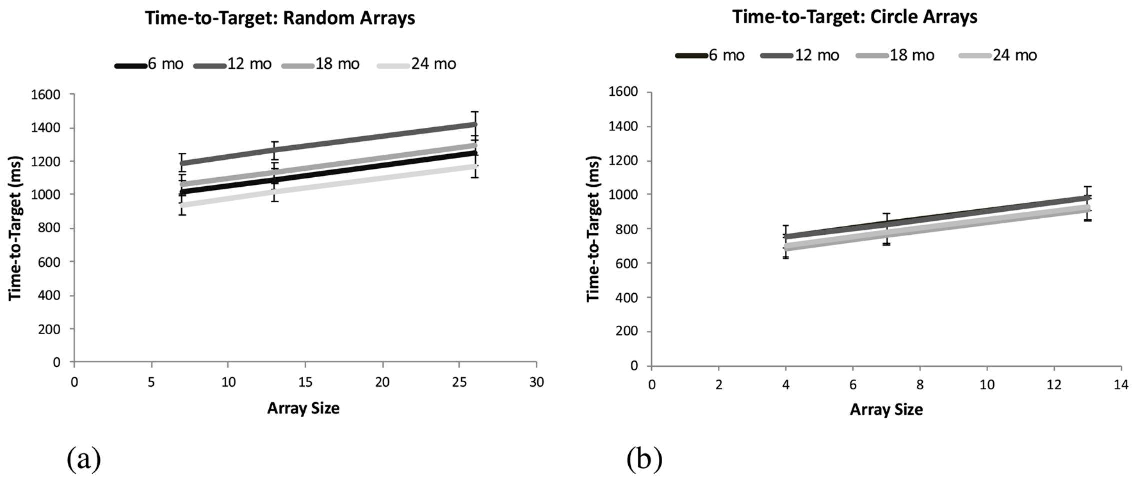


Fig. 2. Time-to-target for (a) Random arrays and (b) Circle arrays. Error bars represent standard errors. In Fig. 2b, the lines for 6- and 12-month-olds are superimposed, as are the lines for 18- and 24-month-olds.

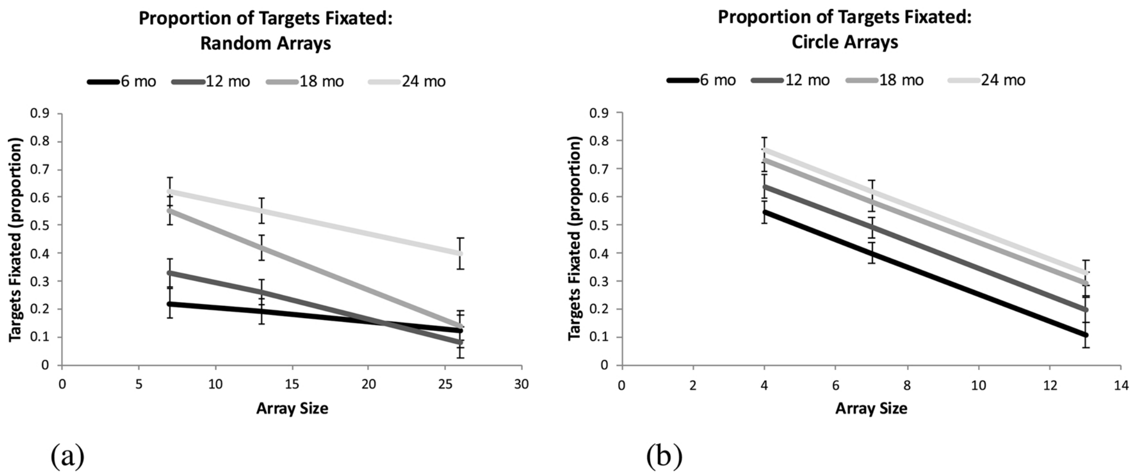


Fig. 3. Proportion of targets fixated for each array size for (a) Random and (b) Circle arrays. Error bars represent standard errors.

arrays by the 18-month-olds ($q < .05$); for the other age group/array size combinations, the proportion of first looks to the target was not significantly different from chance ($q > .05$).

2.2.6. Gender effects: infants and toddlers

Because the primary focus of this paper was the relation of array size to the three measures at different ages, possible gender effects were collapsed over array size and were analyzed separately. For the infants and toddlers, there were no significant gender effects ($p > .05$) for either array type for any of the three measures (time-to-target, proportion of targets fixated, and proportion of first looks to the target).

2.3. Discussion of infant and toddler results

We found little evidence of efficient spontaneous visual search among infants and toddlers. Time-to-target increased with array size in response to both random and circular arrays; the average increase in time-to-target of 12.19 ms per item for Random arrays and 25.14 ms per item for Circle arrays exceeds the oft-recommended cut-off for efficient search of 10 ms per item mentioned by Wolfe and Horowitz (2004), though they point out that there is no clear cut-off. The proportion of targets fixated within 2 s and the proportion of first looks to the target decreased with increasing array size for both Random and Circle arrays. Turning to the effects of age, time-to-target decreased with age for Random but not for Circle arrays. The proportion of targets fixated and the proportion of first looks to the target increased with age for both types of array.

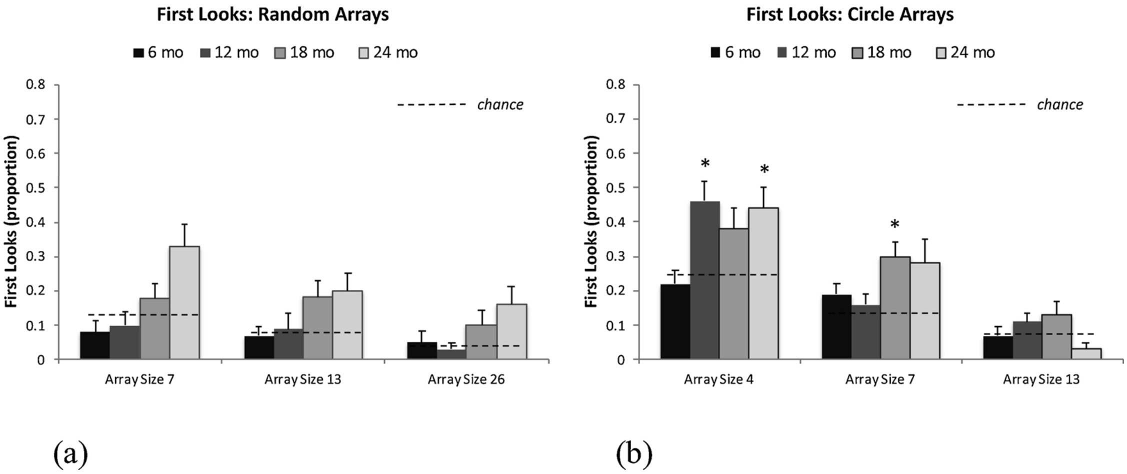


Fig. 4. Mean proportions of of first looks to the target for each array size for infants at each age in (a) Random arrays and (b) Circle arrays. Dotted lines represent an estimate of chance performance, in which the proportion of targets (as opposed to all elements on the screen) was computed for each array size; proportions are shown in parentheses: 4 (.25); 7 (.143); 13 (.08); 26 (.04). Asterisks indicate age/array size values that were significantly greater than chance after an FDR correction ($q < .05$).

Crucially, for most ages and array sizes, the proportion of first looks to the target did not exceed chance. Although no age group performed significantly above chance on any array size for the Random arrays, 12 and 24 month olds performed better than chance on the smallest (4-element) Circle arrays while 18 month olds performed better than chance on the intermediate (7-element) Circle arrays.

Therefore, there was evidence of improvement in spontaneous visual search with age between 6 and 24 months, although this pattern was not linear and did not generally lead to efficient visual search even among the 24-month olds in this study. These results will be discussed further in the General Discussion.

3. Experiment 2: adults

3.1. Introduction

To put the data from infants and toddlers in perspective, we also tested adult participants using the same stimuli and a comparable procedure (e.g., no explicit instructions to search for the target).

3.2. Method

3.2.1. Participants

Sixteen University of California, Los Angeles undergraduate students, 8 male and 8 female, participated for course credit; the average age of the adults was 21.62 years. Data from one additional male participant and from three additional female participants were excluded due to experimenter error and a lack of participants of the opposite gender, respectively.

3.2.2. Stimuli and apparatus

Stimuli and apparatus were the same as those used for Experiment 1.

3.2.3. Procedure

Participants were seated approximately 60 cm from the 27 x 34 cm screen. After calibration, participants were instructed to “Please pay attention to the screen." After the task, they were asked “What did you think the purpose of the experiment was?” and “What did you do during the experiment?”

3.2.4. Design and analyses

Similar to experiment 1, experiment 2 used repeated measures (array size: 7, 13, 26 in the Random condition; 4, 7, 13 in the Circle condition). The measures (time to target, proportion of targets fixated within 2 s, and proportion of first looks to the target) were the same as for Experiment 1.

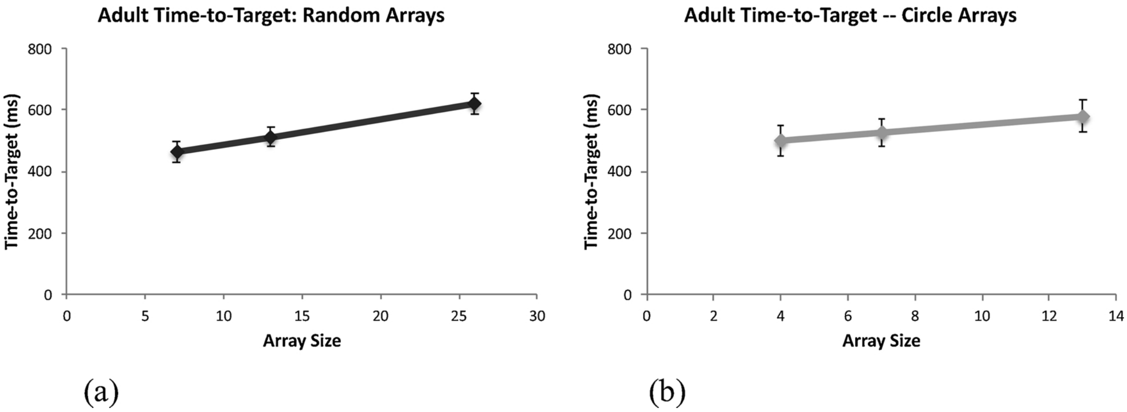


Fig. 5. Adult time-to-target for (a) Random arrays and (b) Circle arrays. Error bars represent standard errors.

3.3. Results

3.3.1. Analysis approach

For consistency with Experiment 1, mixed models were used to analyze the three measures. Because the statistical package used for the infant data, SPSS, does not compute standard errors for one-way mixed models analyses, another package, Stata, was used for the adult data; it also does multi-level mixed effects analysis but uses different statistics. As in Experiment 1, FDRs were computed for pairwise comparisons and comparison with measures of chance.

3.3.2. Debriefing results

When asked what they did during the experiment, nine participants said they looked for the plus sign (which they sometimes called a cross or "x"); two said they looked for the item that was different. Seven did not mention looking for the plus sign or items that were different. When asked about the purpose of the experiment, four said it was to look for the plus sign; four said it was to look to the item that was different.

3.3.3. Amount of useable data

For the adults, based on the criterion that a block was to be used only if it had 8 or more trials with adequate central fixations, there were 16 blocks of usable data for the Random arrays, with a mean of 15 (0) usable trials and 16 blocks for the Circle arrays, with a mean of 14.94(.25) usable trials.

3.3.4. Time-to-target

Mixed models analyses showed that for Random arrays, time-to-target increased with increasing array size ($z = 5.1$, $p < .001$, $\beta = 8.26$, $SE = 1.62$, constant = 11,449.5); see Fig. 5a. Time-to-target was significantly different between each pair of array sizes ($q < .001$). For Circle arrays, time-to-target was not significantly different for different array sizes ($z = 1.43$, $p = .154$, $\beta = 8.79$, $SE = 6.16$, constant = 22,266.17); see Fig. 5b.

3.3.5. Proportion of targets fixated

Array size had no effect on the proportion of targets fixated for the Random arrays ($z = .42$, $p = .67$, $\beta = .0008613$, $SE = .002$,

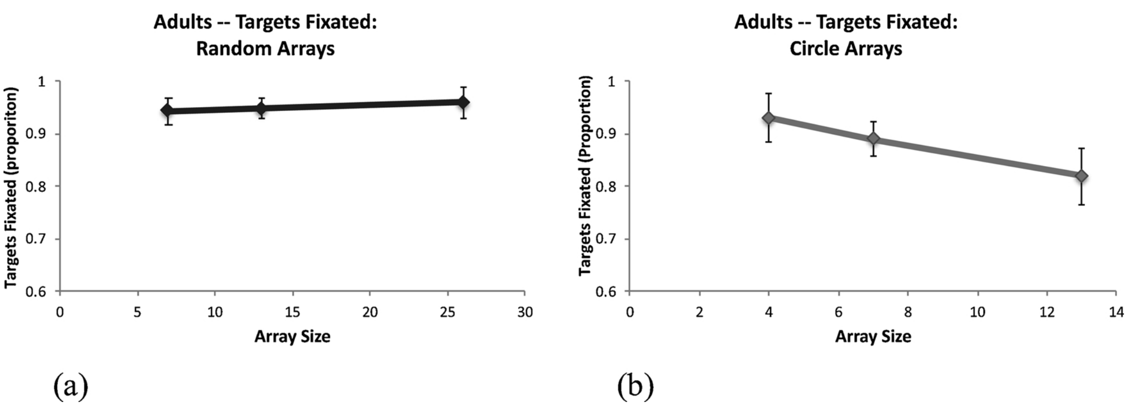


Fig. 6. Adults – proportion of targets fixated for (a) Random arrays and (b) Circle arrays. Error bars represent standard errors.

constant = .00169) or for the Circle arrays, ($z = -1.38$, $p = .168$, $\beta = -.0117496$, $SE = .008516$, constant = 1.28e-22); see Fig. 6.

3.3.6. Proportion of first looks to the target

For the Random arrays, the proportion of first looks to the target decreased with increasing array size, $z = -2.85$, $p = .004$, $\beta = -.0093584$, $SE = .00328$, constant = .0397494. Proportions of first looks to the target at each array size were significantly different from proportions at the other array sizes, $z = -2.85$, $q < .01$. For the Circle arrays, the proportion of first looks to the target was not affected by array size ($z = -1.46$, $p = 0.1440$, $\beta = -.0122024$, $SE = .008352$, constant = .0276916).

As described above for the infant data, post-hoc one-sample *t*-tests were used to compare the proportion of first looks to the target with an estimate of chance performance. Adult performance exceeded chance for each array size for both Random arrays ($q = .001$) and Circle arrays ($q = .001$); see Fig. 7.

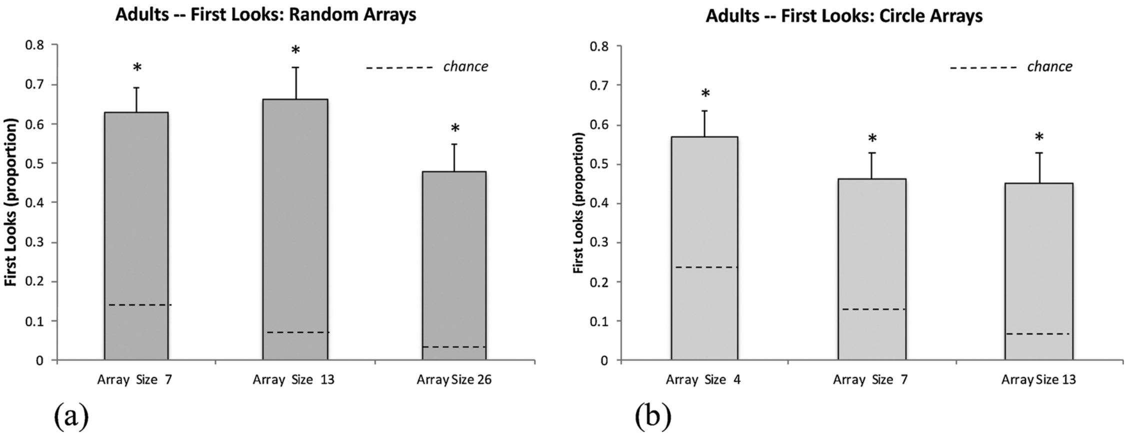


Fig. 7. In adults, the proportion of first looks to the target in (a) Random arrays and (b) Circle arrays. Error bars represent standard errors. Estimates of chance performance are also included, in which the proportion of targets (as opposed to all elements on the screen) was computed for each array size; proportions are shown in parentheses: 4 (.25); 7 (.143); 13 (.08); 26 (.04). Asterisks indicate array size values that were significantly greater than chance after an FDR correction (q < .05).

3.3.7. Gender differences: adults

For time-to-target, for Random arrays, females (M = 472.3 ms, $SE = 36.2$) were faster than males ($M = 592.7$, $SE = 36.2$); $z = -2.36$, $p = .019$, $\beta = -120.4361$, $SE = 51.14$, constant = 5678.722; no gender differences were observed for Circle arrays ($p > .05$). For the proportion of targets fixated, the genders were not significantly different for Random arrays ($p > .05$) or Circle arrays ($p > .05$). For the proportion of first looks to the target, for Random arrays, females ($M = .6916$, $SE = .071$) had a higher proportion of first looks than males ($M = .4895$, $SE = .071$), $z = 2.01$, $p = .044$, $\beta = .2021$, $SE = .1$, constant = .02678; for Circle arrays, the difference was not significant ($p > .05$).

3.4. Discussion of adult results

The adult findings contrasted with the findings for infants and toddlers in that adults showed better performance on all three measures. Whereas time-to-target for the Random arrays increased with increasing array size, the increases of 8.25 ms/element are more consistent with efficient than inefficient search (Wolfe & Horowitz, 2004). For the Circle arrays, increases in times-to-target with array size were not statistically significant, consistent with efficient search. Perhaps because the proportion of targets fixated within 2 s was very high, array size had no effect on the proportion of targets fixated for Random or Circle arrays. Whereas the proportion of first looks to the target decreased with increasing array size for Random arrays (but not for Circle arrays), it exceeded chance for all array sizes for both Random and Circle arrays.

The high proportion of targets fixated, and the above-chance proportion of first looks to the target for both Random and Circle arrays, support the view that adult performance reflects efficient search, or at least that the plus signs strongly draw attention.

One caveat: Though the instructions to the adult participants were simply to look at the screen, a majority of the participants said that they looked for the plus signs or for the element that was different. Thus, though their results reflect efficient visual search, they may not always reflect spontaneous (unrewarded and non-deliberate) visual search, and in that regard, may not be completely parallel to the infant/toddler results. (That said, the infants and toddlers, especially the older ones, may also have looked for the plus sign.)

4. General discussion

Contrary to our first prediction and in contrast to the findings of previous studies, we found little evidence of spontaneous efficient search with our stimuli in infants/toddlers between 6 months and 24 months. For both types of array, with increasing array size, time-to-target increased, whereas the proportion of targets fixated and the proportion of first looks to the target decreased. In addition, the proportion of first looks to the target rarely exceeded chance.

Our second prediction, that performance would improve with age in infants and toddlers, was borne out. With increasing age, time-to-target decreased for the Random arrays, and the proportion of targets fixated and first looks to the target increased for both types of array. Thus, the targets appeared to draw more attention with development. The adult findings fit this picture of improved performance with development because compared with the infants and toddlers, they had lower times-to-target and lower additional time per element, higher levels of targets fixated, and higher proportions of first looks to targets; the proportion of first looks to targets only consistently exceeded chance for adults. These findings will now be discussed in more detail.

4.1. Discussion of specific findings

4.1.1. Time-to-target

At first glance, the relatively modest overall increase of 12.19 ms/element that we found in infants and toddlers for the Random arrays might seem to be equivocal for determining efficient vs. inefficient search, whereas the larger increase of 25.14 ms/element for the Circle arrays might indicate inefficient search.[4] However, the relatively low proportion of targets fixated and especially the chance-level proportion of first looks to the target argue against efficient search for either type of array among infants and toddlers. The adult findings, with increases of 8.5 ms/element for the Random arrays and no significant increases per element for the Circle arrays, support this view by providing a contrasting pattern of performance.

4.1.2. Proportion of targets fixated

In the infants and toddlers, for both Random and Circle arrays, the overall decrease in the proportion of targets fixated with increasing array size argues against efficient search. The increase in the proportion of targets fixated with increasing age attest to a general improvement with development.

Looking at the interaction between age and the proportion of targets fixated for the Random arrays, the proportion of targets fixated declined more steeply with increasing array size as age increased from 6 months to 18 months. Coupled with the finding of a greater proportion of targets fixated at 18 than at 12 months for the 7- and 13-element arrays and at a greater proportion at 24 than at 18 months for the 26-element arrays, one interpretation is that infants get better at smaller and medium-sized arrays before they get better at larger arrays. By adulthood, the proportion of targets fixated was high for both types of arrays and for all array sizes.

4.1.3. Proportion of first looks to the target

The comparison of the proportion of first looks to the target to an estimate of chance provides further evidence against the possibility of efficient search under the tested conditions for the infants and toddlers. For Random arrays, the proportion of first looks to the target was not significantly different from chance for any age or array size. For the Circle arrays, the proportion of first looks to the target was not greater than chance for the youngest infants (6 months); for the older infants, it was only greater than chance for one small or medium array size per age group: for the 12- and 24-month-olds, for the 4-element arrays; for the 18-month-olds, for the 7-element arrays. In contrast, for the adults, the proportion of first looks to the target greatly exceeded chance for both Random and Circle arrays and for all array sizes.

Considering the three measures together, the general picture is that with increasing age, infants and toddlers move from random performance to more of a focus on targets, with improvements occuring on smaller arrays before larger arrays.

4.2. Relation to earlier studies and limitations

Whereas our finding of little evidence for efficient search in the first 24 months fits with Sireteanu, Rettenbach, and Wagner (2009) conclusion that adult-like spontaneous orienting to a display with a discrepant item only develops by 36 months, our findings contrast with those of a number of other studies mentioned above. Table 1 above summarizes key features of studies discussed in this paper that include participants under 36 months old.

The lack of evidence for efficient search observed here contrasts with Gerhardstein and Rovee-Collier (2002) finding that in 12- to 36-month-olds RTs in featural searches did not increase nor did accuracy decrease with increasing array size. Whereas the different results may stem from differences in the stimuli used, we believe that a key factor was that Gerhardstein and Rovee-Collier trained the toddlers to respond to the target, and hence they were looking for it. Our results also contrast with findings from the mobile conjugate reinforcement paradigm (e.g, Rovee-Collier et al., 1992), in which patterns of generalization indicated that infants focused on a single contrasting element in a display with little effect of array size (Rovee-Collier et al., 1996), and with the findings of Kaldy et al. (2011). Our findings also contrast with those of Hessels, Hooge, and Kemner (2016)), which concluded that 10-month-olds engaged in visual search (for a tilted line amidst vertical lines) when a popular cartoon was presented at the target location at the end of each trial. In all of these studies, looking at the target was rewarded or encouraged in some way.

We conclude that whereas a discrepant element may increasingly attract attention as infants get older, it may not lead to efficient search unless the infant is looking for it. It is unclear whether the improvement with age in our study reflects the development of

[4] Both slopes are larger than the increase of 5.2 ms per element found by Adler and Orprecio (2006) for 3-month-olds on circular arrays; as discussed below, a number of differences between the two studies may have contributed to the different results.

spontaneous efficient search for those particular features and stimuli, infants actively searching for the target, or both; a condition in which infants were rewarded for looking at targets might clarify this. As noted above, many of our adult participants, though given no specific instructions, thought that the task was to look for the plus sign or for the item that was different, so their performance may not have been completely spontaneous.

Because we did not find evidence of spontaneous efficient search in infants, our results also contrast with those of Gliga et al. (2015) and Adler and Orprecio (2006). There are a number of possible reasons for the contrast with Adler and Oprecio. Though the general arrangement of our Circle arrays was similar to their arrays, the elements in our arrays were smaller ($< 2°$ square as opposed to 4° square), and our arrays subtended a larger area than their arrays (with a radius of 8.4° as opposed to 5°). Our arrays were in a variety of colors, whereas theirs were red; this might have caused our infants to be interested in the color of each array rather than in the target. Our engaging attention-getters, designed to ensure an adequate central fixation, might have distracted attention from the stimulus arrays. Finally, our measure of time-to-target was different from their measure of latency to begin a saccade.

It is worth noting, however, that line intersections—though long thought to guide efficient search—may not guide efficient search when other aspects of the stimulus elements, such as overall size, radial symmetry, and number of line endings, are controlled for (Wolfe & DiMase, 2003). Therefore, it may be that for our stimuli (and for those similar to them) some other aspects (e.g., line endings) control the development of efficient search by adulthood.

Comparing our study to others in the table, we used measures of time-to-target, individual accuracy, and a comparison with chance performance, but we had no target-absent condition. Future research examining visual search in infancy should include rewarded and spontaneous search conditions, different types of distinctive features (such as color and orientation), and present and absent targets. Another limitation of our study was that because Random arrays were always presented before Circle arrays, we cannot tell whether differences in performance on Random and Circle arrays for infants and adults were due to array type or array order. Future studies should counterbalance the order of different array types. Finally, it's also important to take into account how top-down and bottom-up factors in visual search change during infancy, childhood, and adulthood (Cavallina et al., 2018; Kwon et al., 2016; Sireteanu et al., 2009).

4.3. Conclusion

To conclude, we found little evidence of spontaneous efficient visual search in infants and toddlers (despite evidence of efficient visual search in adults viewing the same stimuli), but we did find that infants/toddlers improved with age on several measures. These findings contrast with previous research and suggest that spontaneous attention to at least some visual features may develop with age.

Author note

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