Search asymmetry and eye movements in infants and adults

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Abstract Search asymmetry is characterized by the detection of a feature-present target amidst feature-absent distractors being efficient and unaffected by the number of distractors, whereas detection of a feature-absent target amidst feature-present distractors is typically inefficient and affected by the number of distractors. Although studies have attempted to investigate this phenomenon with infants (e.g., Adler, Inslicht, Rovee-Collier, & Gerhardstein in *Infant Behavioral Development, 21,* 253–272, 1998; Colombo, Mitchell, Coldren, & Atwater in *Journal of Experimental Psychology: Learning, Memory and Cognition, 19*, 98–109, 1990), due to methodological limitations, their findings have been unable to definitively establish the development of visual search mechanisms in infants. The present study assessed eye movements as a means to examine an asymmetry in responding to feature-present versus feature-absent targets in 3-month-olds, relative to adults. Saccade latencies to localize a target (or a distractor, as in the homogeneous conditions) were measured as infants and adults randomly viewed feature-present (R among Ps), feature-absent (P among Rs), and homogeneous (either all Rs or all Ps) arrays at set sizes of 1, 3, 5, and 8. Results indicated that neither infants' nor adults' saccade latencies to localize the target in the feature-present arrays were affected by increasing set sizes, suggesting that localization of the target was efficient. In contrast, saccade latencies to localize the target in the feature-absent arrays increased with increasing set sizes for both infants and adults, suggesting an inefficient localization. These findings indicate that infants exhibit an asymmetry consistent with that found with adults, providing support for

functional bottom-up selective attention mechanisms in early infancy.

To avoid becoming overwhelmed by the overabundance of available information and to ensure behavioral and cognitive efficiency, we rely on the ability to selectively attend to particular information, while ignoring other, simultaneously available information (Driver, 2001; James, 1890; Posner & Petersen, 1990; Theeuwes, 1994; Yantis, 1993). Mechanisms of selective attention, therefore, provide the means by which to allocate limited processing resources to items deemed to be task relevant, while at the same time inhibiting information that is considered irrelevant. For developing infants, being able to selectively filter the large amount of novel information impinging on them would seem to be particularly crucial, since their processing resources are likely more limited than those of adults (Rose, Feldman & Jankowski, 2004). Thus, the developmental state of mechanisms that guide and control the selective allocation of attention is particularly important, since it may be a limiting factor in infants' learning about their world and in their construction of a knowledge base (e.g., Adler, Inslicht, Rovee-Collier & Gerhardstein, 1998; Bahrick, Walker & Neisser, 1981; Cohen, 1972; Colombo, Mitchell, Coldren & Atwater, 1990). To better understand the development of selective attention mechanisms, there has been recent research interest in the development of visual search (Adler, 2005; Adler et al., 1998; Adler & Orprecio, 2006; Colombo, Ryther, Frick & Gifford, 1995; Gerhardstein, Kraebel, Gillis & Lassiter, 2002; Gerhardstein & Rovee-Collier, 2002), an attentional phenomenon that has received considerable investigation with adults.

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Processing phases and visual search

Early models of visual information processing proposed that there exist two distinct phases. In the initial or *preattentive* stage, processing was hypothesized to decompose visual stimulation into their basic perceptual features that are registered, in parallel, on distinct feature maps (e.g., Julesz, 1984; Neisser, 1966; Treisman & Gelade, 1980). When a stimulus is defined by the presence of a unique perceptual feature, attentional resources are automatically and selectively guided to this stimulus, producing the phenomenon of *pop out* (Julesz, 1984; Treisman & Gelade, 1980; Treisman & Gormican, 1988). Consequently, search is considered to be *efficient*, defined by the accuracy and the speed required to find a feature-present target being relatively unaffected by the number of distractors in the visual array (Treisman & Gelade, 1980). When the target is not defined by a unique perceptual feature, a subsequent stage of attentional processing is initiated in which a selective allocation of resources is engaged. As a result, search is considered to be *inefficient*, which is defined by the accuracy and speed of detecting the target increasing with increasing number of distractors in the display (Treisman & Gelade, 1980).

Although the preattentive/attentive models (e.g., Julesz, 1984; Neisser, 1966; Treisman & Gelade, 1980) described above at one time dominated explanations of visual search phenomena, due to numerous findings that did not fit neatly into this dichotomy, they no longer are capable of accounting for the full range of visual search effects. That is, search has been shown to not fall neatly into two categories of searches, efficient and inefficient, but instead seem to be categorized by a continuum from efficient to inefficient (Wolfe, 1998). Wolfe (1998) and others (Cave, 1999; Di Lollo, Kawahara, Zuvic & Visser, 2001; Theeuwes, Kramer & Atchley, 1999) have pointed out that all search tasks require at least some allocation of attentional resources. As a result, even tasks classically thought to engender "preattentive" search can be inefficient (e.g., Joseph, Chun & Nakayama, 1997), and searches that typically would be "serial" can be efficient (He & Nakayama, 1995; Nakayama & Silverman, 1986). Consequently, more recent models of visual search have posited that a single mechanism is responsible for the continuum of search types. These models have different flavors, from Wolfe's Guided Search model (Wolfe, 1994, 2007) to Attentional Engagement Theory (Duncan & Humphreys, 1992) to signal detection approaches (Carrasco, McLean, Katz & Frieder, 1998; Palmer, Fencsik, Flusberg, Horowitz & Wolfe, 2011; Vincent, 2011); for extensive recent reviews of these models see Eckstein (2011) and Chan and Hayward (2013).

On some level, each of the more recent approaches consists of a process based on the uniqueness of target stimulus properties, relative to distractor properties, which is integral for the determination of the level of search efficiency. These

processes assess—typically, in a bottom-up fashion—the local feature contrast or saliency of stimulus properties (Wolfe & Horowitz, 2004), the biasing of object representations that contain target properties based on the level of target–distractor similarity (Duncan & Humphreys, 1992), or the signal-to-noise ratio of stimulus target properties relative to distractor properties (Carrasco et al., 1998; Palmer et al., 2011). More specifically, according to Wolfe's Guided Search model (1994), for example, targets that have a unique feature, relative to distractors, produce strong bottom-up saliency signals regardless of the number of distractors, which can then guide efficient searches. Targets that do not consist of a unique feature (e.g., feature-absent targets or conjunction targets) produce weaker saliency signals that weaken with more distractors, thereby relying on top-down activation of target features and resulting in inefficient searches.

Search asymmetry and infants

A visual search phenomenon that had classically epitomized the preattentive (parallel)–attentive (serial) dichotomy of functioning but has more recently been explained by a single parallel mechanism model is search asymmetry (for reviews, see Nakayama & Martini, 2011; Wolfe, 2001). Search asymmetry occurs when detection of a target that contains a unique perceptual feature that is absent among distractors (e.g., search for a Q among Os) is efficient, producing a relatively flat reaction time (RT) by set size function, whereas the reverse search where the target is defined by the absence of a feature that is present among distractors (e.g., search for an O among Qs) is inefficient, producing an increasing RT by set size function (Treisman & Gelade, 1980). Recent models of visual search can account for asymmetries with a single mechanism that examines the relation of target properties relative to distractor properties (Carrasco et al., 1998; Vincent, 2011; Wolfe, 1994). According to Guided Search (Wolfe, 1994), for example, the feature-present target that has a unique feature, relative to the feature-absent distractors, produces a strong bottom-up saliency signal resulting in an efficient search, whereas a feature-absent target that shares its features with the feature-present distractors produces a weak bottom-up saliency signal resulting in an inefficient search. As a consequence, performance to feature-present versus feature-absent targets is asymmetric.

Although search asymmetry has been extensively studied in adults (Nagy & Cone, 1996; Royden, Wolfe & Klempen, 2001; Treisman & Souther, 1985; Vincent, 2011), only a few studies have attempted to assess search asymmetry in infants, with each having limitations that hinder what they can inform about visual search behavior in early infancy. A study by Colombo et al. (1995; see also Coldren & Haaf, 2000), for example, attempted to assess search asymmetry in 3- to

4-month-old infants, using a preferential-looking paradigm. In their feature-present condition, the visual displays depicted a homogeneous display composed of Os and a feature-present display composed of a target Q among distractor Os. In their feature-absent condition, the visual displays depicted a homogeneous display composed of Qs and a feature-absent display composed of a target O among distractor Qs. Results revealed that 3- and 4-month-old infants in the feature-present condition showed significantly greater looking toward the feature-present display than to the homogeneous display, whereas no particular preference between the visual displays was demonstrated in the feature-absent condition. This result is consistent with the pattern of asymmetric search behavior exhibited by adults. Colombo et al. concluded that these young infants exhibit search asymmetry similar to that of adults and took this as evidence that the same attentional mechanisms are likely functioning in infants as they are in adults.

A subsequent study also attempted to investigate search asymmetries in 3-month-old infants but used the mobile conjugate reinforcement paradigm instead of preferential-looking (Adler et al., 1998). In this study, infants were trained to kick to move a seven-block mobile displaying either all Rs or all Ps; as they learn this task, their kick rate increases. Infants were then tested 1 day after training with one of two mobiles: a mobile consisting of a single R block amidst six P distractor blocks (feature-present mobile) or a single P block amidst six R distractor blocks (feature-absent mobile). If infants exhibit recognition at test, their kick rates remain significantly higher, relative to their prelearning level, whereas if they discriminate at test, their kick rates return to and are not significantly different than their prelearning levels. Results indicated that only infants in the feature-present condition (trained with the Ps mobile and tested with R among Ps mobile) exhibited discrimination, suggesting that the infants exhibited discrimination on the basis of detecting the R among the Ps. Infants in the feature-absent condition (trained with Rs and tested with P among Rs mobile), in contrast, did not seem to detect the target (P), resulting in their exhibiting recognition of the distractor Rs. This pattern of results suggests that attention in the feature-absent condition was predominantly governed by the distractors, which were familiar, and not the target. Overall, these findings suggest that the feature-present R popped out from Ps, but not vice versa, providing additional support for the presence of pop-out and search asymmetries in early infancy.

A more recent study, however, argues against early development of adultlike visual search behavior, including search asymmetries (Sireteanu, Rettenbach & Wagner, 2009). Instead, the study suggests that adultlike visual search behavior is not evident until the beginning of the second year of life. This study by Sireteanu et al., like many of those before, used a preferential-looking paradigm to assess asymmetries in infants' correct fixations to arrays in which a discrepant target

(e.g., circle with a gap) was on either the left or the right within a set of distractors (e.g., complete circles) and to arrays with the reverse combination. Their findings indicated that infants younger than 12 months of age did not prefer to fixate the location (right or left) of either discrepant target but, instead, preferred to fixate the repetitive stimuli of distractors. Not until children were between 3 and 4 years of age did they show a preference pattern that was consistent with the asymmetric search pattern shown by adults. Sireteanu et al. concluded that not until after the first year of life do the attentional mechanisms, like the ones responsible for visual search behavior and search asymmetries, become functional, and then not until after 2 years of age do they become adultlike.

Timing and methodological issues

Although the developmental studies described above have attempted to provide a foundation for understanding selective attention and visual search in infants, a number of issues clouds their capacity to fully illuminate the development of visual search and the underlying attentional mechanisms. One major issue is that the paradigms used with infants lack sufficient sensitivity in their time scales to assess the phenomena of visual search (see also Adler, 2005). Pop-out, for example, is a phenomenon that is typically exhibited by adults within hundreds of milliseconds after the presentation of the stimuli (e.g., Treisman & Gelade, 1980). In contrast, in the preferential-looking, novelty-preference, and mobile-conjugate reinforcement paradigms that have been used to assess infant's visual search and pop-out behavior, the time scales have been on the order of seconds and even minutes. As a consequence, infants' performance cannot be unequivocally determined to be the product of any type of search mechanisms because there was more than sufficient time for other cognitive processes, such as memory, to play a role in determining their behavior (also see Adler, 2005; Adler & Orprecio, 2006).

Additionally, previous infant search studies have used measures that seem to have no connection or similarity to the measures used to assess search in adults. For instance, RT to detect a target in a visual search array versus percentage of fixations to a general direction in an array (i.e., left or right, but not specifically localized to the target) differ so greatly, direct comparison between adults' and infants' visual search behavior are neither possible nor experimentally valid to make. Furthermore, a critical methodological manipulation and theoretical diagnostic used in adult visual search studies is the presentation of different numbers of distractors and the effect that the different set sizes has on search performance. In none of the infant studies using the looking and mobile paradigms has set size been used as a variable for assessing the development of visual search. As a result, any conclusion or speculation

regarding the nature of the development of infants' attentional and visual search mechanisms, relative to adults, are at best inaccurate and likely fraught with errors. To properly assess visual search phenomena in infants, therefore, a timing scale and methodology that is comparable to those used in adult research had to be devised and used to provide more accurate findings as to the nature of visual search and attention in early development.

In order to eliminate timing and methodological differences as issues in the assessment of infants' visual search and selective attention mechanisms, Adler and Orprecio (2006) conducted a visual search and pop-out study that used comparable methodologies and measures in 3-month-old infants and adults. This equivalency was accomplished by measuring the latency of eye movements, a measure that has been used successfully with adults (Findlay, 1997; Keech & Resca, 2010; Zelinsky, 2008). Eye movement latencies have the advantage of occurring on the order of milliseconds even in young infants (e.g., Canfield, Smith, Brezsnyak & Snow, 1997) and have been consistently shown to be tightly linked to attentional mechanisms (Adler, Bala & Krauzlis, 2002; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher & Blaser, 1995; Sheliga, Riggio & Rizzolatti, 1994; Smith, Rorden & Jackson, 2004; Van der Stigchel & Theeuwes, 2007). Thus, assessing the latency of infants' eye movements in a visual search paradigm has the potential to provide meaningful and comparable data for assessing visual search through development and, more importantly, informing about the development of selective attention mechanisms from infancy to adulthood.

In the Adler and Orprecio (2006) study, two conditions were administered: a target-present condition in which a target (+) was presented among arrays of different number of distractors (Ls) and a target-absent condition in which arrays of different numbers of only distractors (Ls) were displayed. Results demonstrated, consistent with previous adult research, that 3-month-old infants and adults exhibited an efficient "search" as indicated by the latencies of the eye movements to localize the target in the target-present condition remaining relatively unchanged despite increasing set size. Latencies to any one of the distractors in the target-absent condition increased linearly as set size increased, suggesting an inefficient search to find the target. The results of this study, therefore, provide evidence that infants as young as 3 months of age can exhibit "popout" on a millisecond scale similar to adults that is unaffected by the array's set size, suggesting that an attentional mechanism is functioning in early infancy that is similar to that used by adults.

Considering that infants were not instructed prior to the presentation of the arrays, the Adler and Orprecio (2006) study does not constitute a clear "search" task, in that the infants did not know for what they searched. Consequently, performance in that study was likely not based on top-down

attentional mechanisms that have been part of many influential models of visual search (Chan & Hayward, 2013; Eckstein, 2011; Wolfe, 1994) but had to rely more on bottom-up mechanisms. One such mechanism, discussed earlier, is the bottom-up detection of salient signals or large feature contrasts in the array (e.g., Wolfe, 1994). If infants use a bottom-up saliency map to determine their detection and localization of a unique target, they should exhibit an asymmetry in localizing a unique target defined by the presence of a feature thereby making it salient, relative to a target defined by the absence of a feature, which makes it less salient. The purpose of the present study, therefore, was to examine whether infants' will exhibit an asymmetry similar to that exhibited by adults. To this end, the eye movement latencies of both 3-month-old infants and adults to feature-present versus feature-absent targets will be assessed.

Experiment 1: search asymmetry in infants

To date, only one infant paradigm, in which eye movement latencies are measured, has enabled the assessment of infants' visual search performance in a manner similar to adults, by manipulating set size and measuring RT by set size functions (Adler, 2005; Adler & Orprecio, 2006; Bulf, Valenza & Simion, 2009). Because infants are not provided with information about the intended target and so cannot produce any top-down biasing, the findings from Adler and Orprecio suggest that infants might be processing the visual arrays in a bottom-up manner and producing a saliency map (Wolfe, 1994). From this saliency map, infants detected an area of high contrast when there was a unique target, which guided their eye movements to that area and localization of the unique target. Since the unique target would produce a high contrast on a saliency map irrespective of the number of distractors, an efficient "search" is produced. If infants' localization of a target is based on its saliency, then whether they produce an efficient or inefficient function for localizing a unique target should be based on the relative saliency of that target. A search asymmetry task provides just such conditions, since a feature-present target among feature-absent distractors is relatively salient, whereas a feature-absent target is not particularly salient among feature-present distractors. An asymmetry should result, with a feature-present target being localized in an efficient manner and a feature-absent target being localized in a relatively inefficient manner. The present experiment, therefore, was designed to assess, using the eye movement paradigm, whether 3-month-old infants exhibit such an asymmetry in localizing a feature-present target (e.g., an R) among an array of feature-absent distractors (e.g., Ps) with varying set sizes, relative to localizing a feature-absent target among feature-present distractors.

Method

Participants

Infants were recruited from mailing lists, compiled from sign-up lists publicly available from Toronto area maternity and toy stores, purchased from a local marketing company (Z Retail Marketing Inc., Toronto, Canada). Only parents' names, home address, and due date were provided on these lists, all of which was kept confidential. Families were sent a letter that included a brief description of the study and an invitation to have their infant participate. Interested parents returned a prepaid post-card, telephoned, e-mailed, or responded online and were then contacted to book a time to come to the Visual and Cognitive Development Project. Upon arriving at the Project, after being informed about the experiment procedures, parents filled out a consent form and a demographic questionnaire. The data from 24 infants (14 males, 10 females), ranging in age from 98 to 125 days ($M = 112.8$, $SD = 14.3$), participated in this experiment. Infants were Caucasian ($n = 17$), Hispanic ($n = 3$), Asian ($n = 1$), East Asian ($n = 1$), African ($n = 1$), and other ($n = 1$) and were primarily of middle socioeconomic status (SES). Infants were born full term, in good health, with no apparent visual or neurological abnormalities. Data from 10 additional infants who participated were excluded from the study because of fussiness ($n = 5$), equipment or software failure ($n = 1$), and inattentiveness (i.e., infant disinterested or looked away from visual field on more than 35 % of the trials; $n = 4$).

Stimuli and apparatus

The stimuli were computer-generated graphic images of a white fixation triangle, red Ps, and red Rs. The stimuli were presented on a 19-in. IBM LCD color monitor with 1,024 × 768 pixel resolution, a refresh rate of 75 Hz, and an 8 bit/pixel grayscale. The infant viewed the images from a distance of 48 cm. The stimuli were arranged on a circular grid with a radius of 5° from the central fixation triangle on a gray background. The Rs and Ps subtended visual angles of 4°, and the fixation triangle subtended a visual angle of 1°. Four array types were constructed with the Ps and Rs: homogeneous P arrays, homogeneous R arrays, feature-present arrays [a target R among distractor Ps, indicated by (R)Ps], and feature-absent arrays [a target P among distractor Rs, indicated by (P)Rs] (see Fig. 1). Note that the purpose of the homogenous arrays was to serve as a baseline for eye movement latencies when there was no target (relative to distractors) for them to localize. The array conditions were randomly interleaved with each other in a given session to any individual infant.

Furthermore, in order to determine the set size by target-directed saccade latency function that serves as the critical

diagnostic of whether the target was localized in an efficient (relatively flat latency-by-set size slope) versus inefficient (positively increasing latency-by-set size slope) manner, each array type was randomly presented with set sizes of 1, 3, 5, or 8 items.[1] Additionally, to decrease the likelihood of infants implicitly learning to predict the occurrence of a target and make anticipatory eye movements, the targets in the feature-present and the feature-absent arrays were randomly presented at either the 3, 6, 9, or 12 o'clock position. Lastly, the distractors in the target-present arrays were randomly presented at any of the other locations of the circular grid not occupied by a target (see Fig. 1) and, in homogeneous arrays, were randomly presented at any of the possible locations on the circular grid.

Infants were laid supine in a specialized crib and viewed the stimuli on a monitor that was situated directly overhead (see Fig. 2). Between the infant and the stimulus monitor was a 12 × 12 in. infrared-reflecting, visible transmitting "hot" mirror that allowed the infant a completely unobstructed view through the mirror of the stimuli on the monitor. A remote, pan-tilt infrared eye-tracking camera (Model 504, Applied Science Laboratories [www.a-s-l.com], Bedford, MA), using bright pupil technology, situated above the infant, emitted infrared light from diodes that was reflected to and back from the participant's retina through the pupil via the "hot" mirror. The eyetracker recorded the participant's eye movements at a temporal resolution of 60 Hz. In addition to the backlit, white pupil, the infrared light produced a point reflection from the corneal surface of the eye. The relation between the corneal reflection and the centroid of the backlit pupil was used to calculate, via proprietary ASL software, eye position. The eyetracker was calibrated by having the infant look at a stimulus (concentric squares that loom in and out) presented successively at known locations on either side of the screen. This calibration was done to equate recorded eyetracker values of eye location to known locations on the screen. All subsequent eye data were filtered through these calibration values.

Procedure

The experimental session and timing of the stimuli were programmed in Presentation software (Presentation Version 9.0, Neural Behavioural Systems, Albany, CA; http://www.neuro-bs.com) running on a Dell computer. A trial began with the presentation of the fixation triangle for 1,000 ms, followed

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[1] The set size of 1 was included as a control to ensure that infants' saccade latencies did not differ as to the two types of stimuli (R and P) used. Because a set size of 1 does not represent a "selection" condition in which an item needs to be chosen from among surrounding items and, consequently, likely requires different mechanisms than when selection is required (e.g., Adler et al., 2002), the set size 1 conditions were not included in any analysis of infants' search functions.
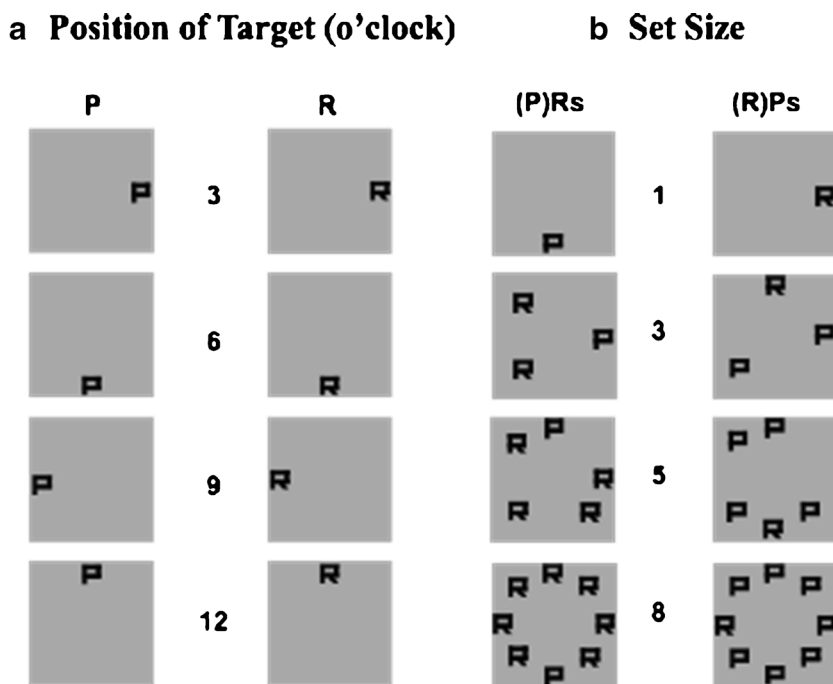
a Position of Target (o'clock)   b Set Size

Fig. 1 Examples of the stimuli used in both experiments with infants and adults. The actual stimuli presented were red in color. Shown are **a** the possible target locations (3, 6, 9, and 12 o'clock) and **b** a sample of the randomized item locations for the different set sizes in the feature-absent condition [(P)Rs] and the feature-present condition [(R)Ps]

by an interstimulus interval (ISI) of 250 ms, during which the monitor was blank. Immediately after this interval, a visual search array was displayed for 1,000 ms, during which a homogeneous (containing all Rs or Ps), a feature-present [(R)Ps], or a feature-absent [(P)Rs] array was presented on

Fig. 2 Image of the specialized crib used with infants, showing the monitor on which stimuli were presented, the Model 504 infrared eyetracking camera, and the infrared mirror

the screen (see Fig. 3). The particular visual array presented was randomized across trials, with the constraint that an equal number of trials of each array by set size condition were presented across the experiment. The next trial began after an intertrial interval of 250 ms when the screen was once again blank, at which point the fixation triangle was presented again (see Fig. 3).

Each infant was randomly presented with the target occurring once in each of the four possible locations (3, 6, 9, and 12 o'clock) for each set size (1, 3, 5, and 8) for each of the arrays. This sums to 64 distinct trials in each experimental session run (4 array types × 4 set sizes × 4 locations). Because infants will not look and provide usable data on each and every trial, to maximize the amount of data per infant each trial was presented twice, resulting in each infant receiving a total of 128 randomized trials for the entire experiment.

Data reduction and analysis

The raw digital data recorded by the eyetracker was imported into a MATLAB toolbox called ILAB (Gitelman, 2002) for subsequent analysis. The ILAB toolbox software allows for the analysis of eye movements, separating out and displaying individually the horizontal and vertical components of the eye movement, on a trial-by-trial basis. Moreover, ILAB provides a means by which to display the scan path of the eye on each trial and thereby determine whether or not the eye first fixates on the target and the nature of the eye movement (latency, direction, and distance), relative to the onset of the visual
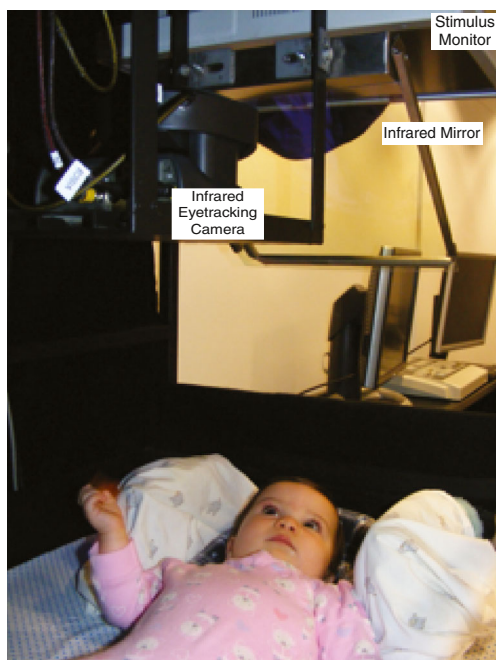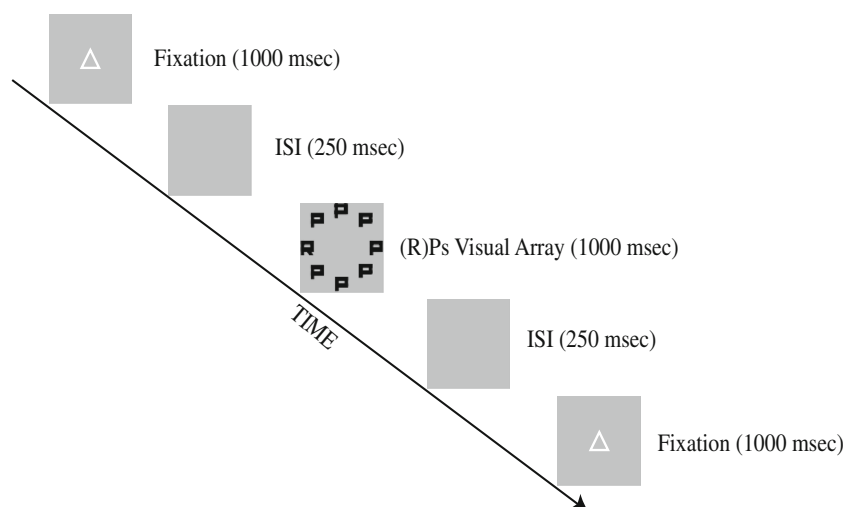
Fig. 3 Sample trial sequence for presentation of the visual arrays

array. Search behavior was assessed by measuring the latency value of the eye movement that localized the target for each target–distractor array condition (feature-present and feature-absent) or any one of the items (whichever one they first localize) in the homogeneous array conditions. Target-directed saccade latency was defined as the time taken from the onset of the visual array to the time of the saccade that actually localized the target in either the feature-present or feature-absent condition or one of the distractors in the homogeneous conditions was initiated.

In order for an eye movement to be included in the final data sample, it needed to meet a number of criteria. First, anticipatory eye movements, occurring before array onset and within the first 167 ms after array onset for all conditions, were excluded from the final data sample. The post-onset latency cut-off for defining anticipatory eye movements was chosen because it has been determined that 3-month-old infants typically cannot make eye movements in reaction to the onset of stimulus faster than 167 ms (Canfield et al., 1997). Second, infants were required to be fixating the central fixation triangle immediately prior to the array being presented. The purpose of requiring the infants to fixate on the triangle was to assess the scan path of each eye movement from the same single landmark that was equidistant from each item in the arrays and, thus, eliminate bias of producing eye movements that originate from random locations on the screen. Because infants cannot be told to remain fixated and can freely move their eyes at any time, this criterion ensures that the initial conditions for assessing infants' performance was as comparable as those for adults. Finally, for saccades in the direction of the localizing target or item to be included, they had to trace a path in the direction of an array item (i.e., the target in the feature-present and feature-absent conditions and any one of the distractors in the homogeneous conditions) that was more than 50 % of the distance between its position at

initiation and the location of the intended item in the array. The 50 % criterion has been used in previous studies (e.g., Adler & Haith, 2003; Adler & Orprecio, 2006) and is based on the fact that infants' saccades tend to be hypometric. An eye movement that transverses more than halfway from its starting position is taken as an indication that the eye movement was intentional and not random.

Infants' mean target-directed saccade latencies to the target in the feature-present and feature-absent conditions and to any one of the distractors in the homogeneous conditions as a function of increasing number of distractors or set size served as the dependent measure. Due to the number of array type X set size conditions presented, each infant provided, at maximum, eight latency values and, at minimum, potentially zero values for each array type X set size condition. In order to increase the power of our statistical tests, the individual trial data from all the infants were pooled for each array type X set size condition, and our analyses were based on the pooled data. This is a common practice when eye movement latencies are the dependent measure (e.g., Adler et al., 2002) and has been used in a previous study of infants' visual search (Adler & Orprecio, 2006). On the basis of the Adler and Orprecio study, which consisted of much the same parameters as the present study, to obtain power (1−ß) equal to .90, a minimum of 21 observations per condition was required. With the pooling of the data, the smallest number of observations in any condition was 26.

If infants exhibit an asymmetry in which their localization of a feature-absent target is inefficient, it is likely it will take multiple saccades to localize the target. Should this be the case, it is also possible that with increasing set size, the infants will require an increasing number of eye movements to find the feature-absent target, which might then produce an increasing latency X set size function for the feature-absent arrays. To determine whether this occurs, in addition to

saccade latencies, the number of eye movements to localize the target as a function of set size will be analyzed.

Results and discussion

Preliminary analysis

Stimulus type (R vs. P) To ensure that there were no inherent differences in performance to an R relative to a P, the saccade latencies to each of these characters with a set size of 1 were compared. Furthermore, since the stimulus characters could occur in four locations (3, 6, 9, and 12 o'clock) and because previous developmental research has indicated that infants' horizontal eye movements are more reliable than vertical eye movements (Gronqvist, Gredeback & von Hofsten, 2006; Shea, 1992), the determination of whether infants' saccade latencies differed due to stimulus location was necessary. A 2×4 ANOVA was conducted with stimulus type (R and P) and location (3, 6, 9, and 12 o'clock) as within factors. This analysis revealed that the main effect of stimulus type was not significant, $F(1, 51) = 0.12$, n.s., indicating that saccade latencies to an R ($M = 421.3$ ms) and to a P ($M = 430.3$ ms) did not significantly differ. Furthermore, neither the main effect of location, $F(3, 51) = 1.15$, n.s., nor the interaction of stimulus type and location, $F(3, 51) = 0.19$, n.s., was significant. Thus, any differences in saccade latencies between feature-present and feature-absent arrays or between the two types of homogeneous arrays could not be due to inherent differences in saccade latencies to these two types of stimulus characters or to their location on the stimulus grid.

Target location in search arrays As was noted above, developmental research has suggested that infants' eye movements are more reliable along the horizontal than along the vertical axis (Gronqvist et al., 2006). Although the above analysis indicated no differences in saccade latencies as a function of stimulus location when there was a set size of 1, perhaps saccade latencies to a target in a search array, in which there are simultaneously available distractor stimuli, might be sensitive to target location. A $3 \times 4 \times 2$ ANOVA was therefore performed on infants' target-directed saccade latencies with set size (3, 5, and 8), location (3, 6, 9, and 12 o'clock), and array type (feature-present and feature-absent) as within factors. This analysis revealed that the main effects of set size, $F(2, 176) = 3.30$, $p < .05$, and array type, $F(1, 176) = 11.56$, $p < .001$, were both significant. These results indicate that infants' target-directed saccade latencies differed as a function of set size irrespective of array type and latencies to feature-present and feature-absent arrays differed irrespective of set size—findings that will be examined more fully below. The main effect of location, $F(3, 176) = 2.55$, n.s., however, was not significant. Furthermore, none of the interactions involving location as a factor were significant. These results indicate

that infants' latencies to the target, either feature-present or feature-absent, based on the target's location in the visual array did not differ.

Because previous studies (Gronqvist et al., 2006) have indicated that differences are exhibited in infants' eye movements as a function of their having occurred along the horizontal versus vertical axis, rather than between specific locations, we collapsed infants' saccade latencies along the horizontal (left and right) and vertical (up and down) dimensions. A $3 \times 2 \times 2$ ANOVA was performed on infants' saccade latencies, with set size (3, 5, and 8), axis (horizontal and vertical), and array type (feature-present and feature-absent) as within factors. This analysis once again revealed that the main effect of array type was significant, $F(1, 188) = 14.93$, $p < .001$, indicating that saccade latencies to feature-present and feature-absent arrays differed irrespective of set size. The main effect of set size, in contrast, was not significant, $F(2, 188) = 2.87$, $p = .06$, n.s., suggesting that in this analysis, saccade latencies did not exhibit any differences as a function of set size irrespective of array type. The main effect of axis, $F(1, 201) = 0.52$, n.s., was also not significant. Additionally, none of the interactions involving axis as a factor were significant. These results, therefore, again indicate that saccade latencies to the target in the feature-present and feature-absent arrays did not differ as a function of target axis and whether infants needed to make a horizontal or a vertical saccade. Consequently, saccade latencies were collapsed across location in subsequent analyses.

Homogeneous arrays Previous adult research has demonstrated that homogeneous visual arrays fail to produce an efficient search (Wang, Cavanagh & Green, 1994) but, instead, elicit an inefficient search through each item, since there is no salient target. Consequently, in the present study, homogenous arrays are likely to similarly elicit an inefficient selection for localization of any one of the items in the arrays and, thereby, produce a saccade latency function that increases with increasing set size. Theoretically, there should be no difference in such target-directed saccade latency functions for homogenous arrays that consist of Ps or Rs. To determine whether target-directed saccade latencies differed between homogeneous P arrays and homogeneous R arrays as a function of set size, a 3×2 ANOVA was performed with set size (3, 5, and 8) and array type (homogeneous P and homogeneous R) as within factors. This analysis revealed no significant main effect for array type, $F(1, 307) = 0.01$, n.s., indicating that there were no differences in the mean saccade latencies between the homogeneous P and homogeneous R arrays. As was predicted, the analysis revealed a significant main effect for set size, $F(2, 307) = 3.96$, $p < .05$, indicating that latencies differed between the three set sizes irrespective of whether the array consisted of Ps or Rs (Fig. 4). Post hoc *t*-tests indicated that infants' target-directed saccade latencies

were not different between set sizes of 3 ($M = 431.5$ ms) and 5 ($M = 424.8$ ms), $t(271) = 0.32$, n.s. Saccade latencies did significantly differ between set sizes of 3 and 8 ($M = 508.2$ ms), $t(159) = 2.32$, $p < .05$, and between 5 and 8, $t(190) = 2.74$, $p < .01$. Additionally, the interaction between array type and set size was not significant, $F(2, 307) = 2.51$, n.s., indicating that both array types showed a similarly increasing target-directed saccade latency function. Thus, the present analysis revealed that there is no difference in saccade latencies as a function of set size whether the homogeneous arrays consisted of Ps or Rs. In subsequent analyses, therefore, data from the both sets of homogeneous arrays were pooled for each set size.

Saccade latencies as a function of set size

To investigate whether the bottom-up salience of the target would affect localization as a function of set size, the saccade latencies produced by the infants to localize the target in the feature-present, feature-absent, and one of the distractors in the homogenous arrays, were compared across the three different set sizes. To this end, a 3 × 3 ANOVA was performed on infants' target-directed saccade latencies as a function of set size (3, 5, and 8) and array type (feature-present, feature-absent, and homogeneous). A significant main effect was found for set size, $F(2, 504) = 6.58$, $p < .005$, indicating that collapsed across array type, saccade latencies were different across the set sizes. Post hoc t-tests comparing mean saccade latencies to the three set sizes revealed that there was no difference between set sizes of 3 ($M = 435.9$ ms) and 5 ($M = 435.4$ ms), $t(404) = 0.03$, n.s. Target-directed accade latencies did significantly differ between set sizes of 3 and 8 ($M = 507.9$ ms), $t(299) = 3.33$, $p < .005$, and between 5 and 8, $t(317) = 3.40$, $p < .001$. The main effect of array type was also significant, $F(2, 504) = 10.86$, $p < .001$, which indicates that infants performed significantly different for each array regardless of set size. Post hoc analyses indicated

that mean target-directed saccade latency for feature-present arrays ($M = 426.8$ ms) was faster than that for feature-absent arrays ($M = 537.3$ ms), $t(198) = 4.28$, $p < .001$, but not significantly different from that for homogeneous arrays ($M = 438.0$ ms), $t(432) = 0.61$, n.s. Mean saccade latencies to feature-absent arrays, however, were significantly slower than those for homogeneous arrays, $t(390) = 4.39$, $p < .001$. This pattern of results—in particular, the slower target-direct latencies to feature-absent arrays—suggests that localizing the target in feature-absent arrays is less efficient than localizing it in feature-present arrays or selecting any stimulus in homogeneous arrays. The interaction of set size and array type, surprisingly, was not significant, $F(4, 504) = 1.20$, n.s. (see Fig. 5).

Because there is no unique "target" to localize in the homogeneous condition, perhaps the homogeneous condition obscured a significant interaction of set size and array type when there was a unique target. To overcome this possibility, the ANOVA was rerun without the homogeneous condition. This 3 × 2 ANOVA yielded identical findings: significant main effects of set size, $F(2, 194) = 3.66$, $p < .05$, and array type, $F(1, 194) = 20.33$, $p < .001$. The interaction of set size and array type was once again not significant, $F(2, 194) = 1.96$, n.s. Thus, the lack of a significant interaction between set size and array type was not due to any obscuring effects of data from the homogeneous array conditions.

Although these findings indicate that there were no differences among the three different types of arrays across any of the set sizes, contrary to predictions, a more accurate assessment of whether target localization in any of the array types was efficient or inefficient requires examining trends in performance as a function of set size for each array type. To this end, as previous visual search studies with adults have done (Treisman & Gelade, 1980, Treisman & Gormican, 1988; Wolfe, 1994; Wolfe, Cave & Franzel, 1989), linear regression analyses were preformed to assess the relationship between latency (i.e. RT) and array set size.
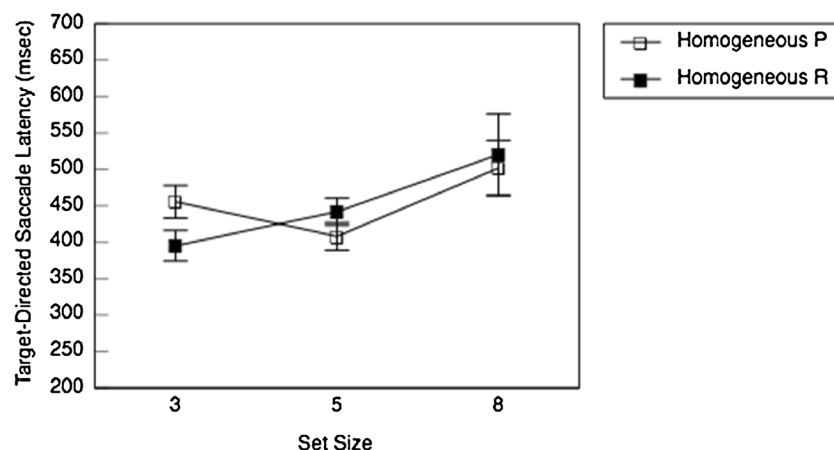

Fig. 4 Comparison of the infants' mean target-directed saccade latencies in each set size for the homogeneous conditions (Ps) and (Rs). Vertical bars indicate ± *SE*
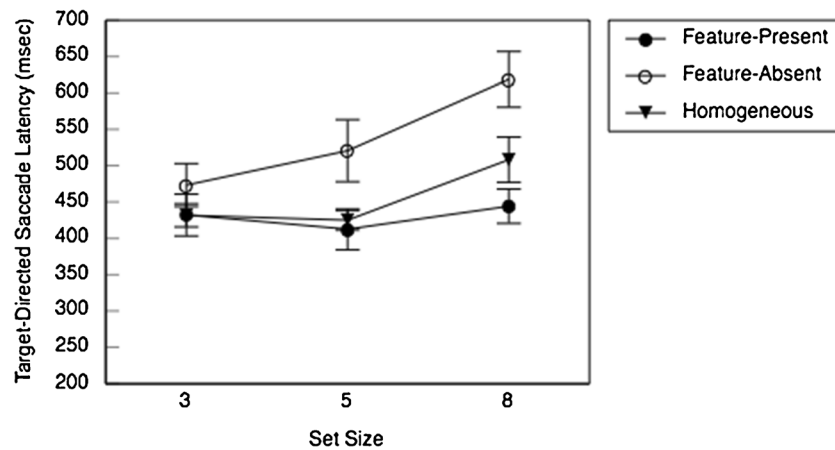
Fig. 5 Comparison of the infants' mean target-directed saccade latencies in each set size for the feature-present, feature-absent, and homogeneous array conditions. Vertical bars indicate ± *SE*

Regression of latencies to set size

The dependent variable in these analyses was the mean target-directed saccade latencies, and the independent variable was set size. For feature-present arrays, this analysis revealed a nonsignifcant relation, $r^2 = .23$, n.s., indicating that saccade latencies did not increase with increasing set size (see Fig. 6a). This finding is further supported by the fact that the slope of the regression line was relatively flat at 3.0 ms per item. These results are consistent with previous findings from adults as well as infants (Adler & Orprecio, 2006), indicating that the feature-present target popped out irrespective of the number of distractors and was localized efficiently, leading to infants' saccade latencies being unaffected by set size. For feature-absent arrays, in contrast, this analysis revealed a significant regression, $r^2 = .99$, $p = .05$, indicating that infants' target-directed saccade latencies increased with increasing set size (see Fig. 6b). The slope of the regression line was 29.4 ms per item, suggesting that infants' localization of the feature-absent

target was inefficient. For homogeneous arrays, the analysis indicated a nonsignificant regression, $r^2 = .78$, n.s., indicating that saccade latencies did not increase with increasing set size. The slope of the regression function was 16.3 ms per item, suggesting that localization of any of the items in the array was less efficient than when there was a feature-present target but more efficient than when there was a feature-absent target.

These regression analyses suggest that localization of the unique target in the feature-present arrays was efficient, whereas localization of the feature-absent arrays was relatively inefficient. Localization of any one of the items in the homogeneous arrays was intermediate to that of the targets in the feature-present and feature-absent arrays. Performance to the homogeneous arrays was initially intended to set the ceiling of eye movement latencies as a function of set size when there was no target. That localization was intermediate to the target conditions and more efficient than in the feature-absent condition likely represents the fact that assessment of latency was not restricted to localization of a stimulus at a
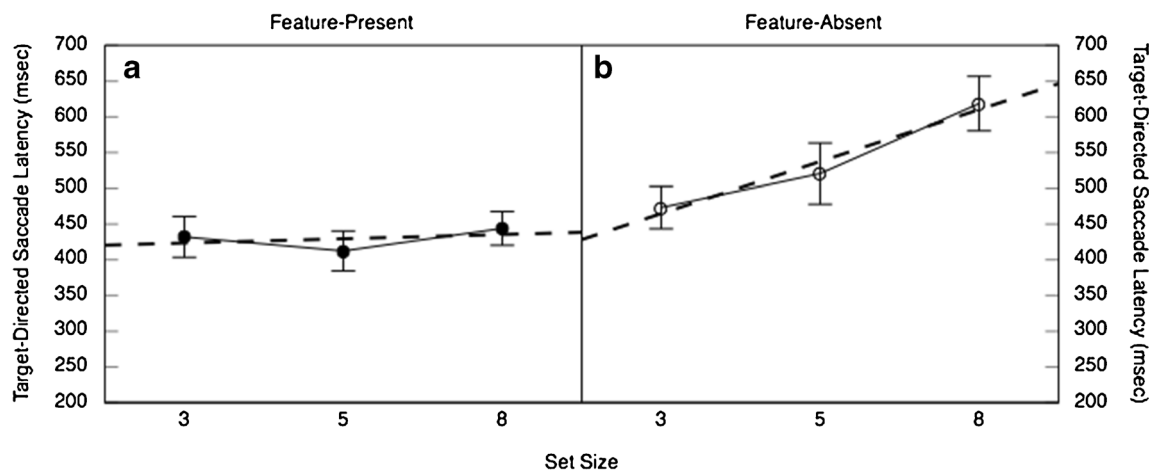

Fig. 6 **a** Regression analysis indicating target-directed saccade latencies for the feature-present condition plotted as a function of set size. **b** Regression analysis indicating target-directed saccade latencies for the

feature-absent condition plotted as a function of set size. Vertical bars indicate ± *SE*. Dashed lines indicate the regressions functions

specific location but to localization of any stimulus at any location, whereas even in the feature-absent condition, a specific stimulus at a specific location had to be localized on a given trial for a measure of latency to be recorded. Thus, infants' selective localization of a unique target that has a feature present amidst feature-absent distractors and for a target that has a feature absent amidst feature-present distractors is asymmetrical.

Number of eye movements to localize targets

Assessment of infants' target-directed saccade latencies as a function of set size that demonstrated an asymmetry was calculated on the basis of the eye movement that actually localized the target. For feature-present and homogeneous arrays, the eye movement that localized the target or one of the distractors in the homogeneous arrays was typically the first saccade. For feature-absent arrays, however, infants rarely made their first eye movement to the target, but required multiple eye movements to localize the target. As a result, if data collection for feature-absent targets was limited to the first eye movement, not enough data would be obtained for analysis. By not restricting data collection to just the first eye movement, more data were collected, but this then opened the possibility that a greater number of eye movements was required as the set size increased, which could then possibility effect target-directed saccade latencies. Therefore, in order to obtain a reliable number of latency measurements, the latency and the number of the eye movements produced to localize the target was recorded.

A 2×3 ANOVA, with array type (feature-present and feature-absent) and set size (3, 5, and 8) as within factors, revealed no significant main effect of set size, $F(2, 197) = 1.22$, n.s., and no interaction of set size and array type, $F(2, 197) = 1.87$, n.s., suggesting that infants executed approximately the same number of eye movements before localizing the target in either array type across each set size (feature-present: set size 3, $M = 1.05$; 5, $M = 1.09$; 8, $M = 1.05$; feature-absent: = 3, $M = 1.83$; 5, $M = 1.60$; 8, $M = 1.97$). The main effect of array type, however, was significant, $F(1, 197) = 75.17$, $p < .001$, indicating that infants required more eye movements to localize the target in feature-absent arrays ($M = 1.81$, $SD = 0.89$) than in feature-present arrays ($M = 1.06$, $SD = 0.24$). These results confirm that the increase in saccade latencies to feature-absent arrays as a function of set size was not due to an increase in the number of eye movements. Instead, the latency increase was likely due to an increase in the time to allocate attention and detect the feature-absent target. Furthermore, that infants required significantly more eye movements to localize the target in feature-absent arrays than in feature-present arrays is consistent with an asymmetry in localizing the targets in these arrays.

Experiment 2: adults' eye movements and search asymmetry

Although the preceding results indicate that infants exhibit an asymmetry similar to that found in adults' search (Treisman & Souther, 1985) and consistent with previous eye movement results with infants (Adler & Orprecio, 2006), as well as adults (Becker, 2010; McSorley & Findlay, 2003), the methodology used is relatively unique to the present study with infants, relative to what has been used with adults. In order to make direct comparisons between the apparent asymmetry exhibited by infants and that exhibited by adults, the present methodology needs to be applied to adults in order, thereby, to obtain comparable data. The purpose of this second experiment with adult participants, therefore, is to provide a direct comparison of the infants' and adults' eye movement and localization behavior, using the same paradigm, stimuli, and measures.

Method

Participants

Ten adult participants ($M_{age} = 25$ years, range: 21–32 years; 5 males and 5 females) participated in this experiment. Participants were recruited from the York University Research Pool and were offered partial course credit for their participation. All participants were asked to fill out a consent form and a brief demographic information questionnaire sheet prior to commencement of the experiment. All participants were naïve as to the experimental conditions and the hypothesis of the study. The participants were Caucasian ($n = 7$), Indian ($n = 2$), and African ($n = 1$) and were primarily from middle SES background.

Stimuli and apparatus

The stimuli and apparatus were the same as those in Experiment 1. The one exception was that, rather than lying in a crib, adults sat in a chair with the stimulus computer monitor situated approximately 48 cm in front of them. The eyetracker was then situated just below the computer monitor. Consequently, the visual angles of all the stimuli were the same as for the infants in Experiment 1.

Procedure

The procedure was identical to the procedure used with the infants in Experiment 1, with one exception. Because of the longer attention span of adults, to maximize the data per participant, the number of trials was doubled. Instead of the 64 total trials infants received composed from four search arrays (feature-present, feature-absent, and homogeneous),

four set sizes (1, 3, 5, and 8), and four locations (3, 6, 9, and 12 o'clock), adults were exposed to two consecutive sessions of the same 64 trials, for a grand total of 128 trials.

Although infants are incapable of following verbal instructions, adults typically require instructions to properly perform a task. To this end, adults were provided with minimal verbal instructions prior to the onset of the experiment. The adult participants were told that the experiment included the presentation of a fixation phase followed by a visual array. Participants were instructed to fixate on the fixation triangle and then to make an eye movement to a stimulus on the circular visual array after it was presented. To ensure a fair comparison between the infants and the adults, no further information was provided to the adult participants prior to commencement of the experiment regarding the nature of the target, the different types of search arrays, or the set sizes. Thus, the adults, like the infants, were not conducting a true search, in that they had no specific target in mind when presented with the arrays.

Data reduction and analysis

The raw digital data from the adults was recorded, reduced, and analyzed in the same manner as for the infants in Experiment 1. Furthermore, because adults are capable of making eye movements to the onset of a stimulus faster than 167 ms (e.g., Adler et al., 2002), the latency cutoff used with infants in Experiment 1 to separate anticipatory and reflexive saccades is not valid for adults. In order to facilitate direct comparisons between the infants and adults, however, the same latency cutoff and range were used for adults as were used for infants. Consequently, adult saccade latencies less than 167 ms were not included in the final analyses. Also, as with the infants and previous adult studies, adults' latencies in each array type by set size were again pooled across participants (Adler et al., 2002).

Results and discussion

Preliminary analysis

Stimulus type (R vs. P) As in Experiment 1, to ensure that there were no inherent differences in performance to an R relative to a P, the saccade latencies to each of these characters with a set size of 1 were compared. A 2 × 4 ANOVA was conducted with stimulus type (R and P) and location (3, 6, 9, and 12 o'clock) as within factors. This analysis revealed a nonsignficant main effect of stimulus type, $F(1, 49) = 0.70$, n.s., indicating that saccade latencies to an R ($M = 419.5$ ms) and to a P ($M = 404.8$ ms) did not significantly differ. Furthermore, neither the main effect of location, $F(3, 49) = 0.56$, n.s., nor the interaction of stimulus type and location, $F(3, 49) = 0.71$, n.s., was significant. Thus, any differences in saccade

latencies between feature-present and feature-absent arrays, between the homogeneous arrays, or as a function of location of the target could not be due to inherent differences in saccade latencies to these two types of stimulus characters or to their location on the stimulus grid.

Target location in search arrays Although there is no developmental or empirical basis to suspect that adults' saccade latencies to a target in a search array would differ as a function of location and the above analysis indicated no differences in saccade latencies as a function of the location of just a single target, to maintain consistent analysis to that conducted with infant data, adults' latencies to targets in search arrays were analyzed as a function of location. A 3 × 4 × 2 ANOVA was performed on adults' saccade latencies with set size (3, 5, and 8), location (3, 6, 9, and 12 o'clock), and array type (feature-present and feature-absent) as within factors. This analysis revealed that neither the main effect of set size, $F(2, 182) = 1.85$, n.s., nor that of location, $F(3, 182) = 0.37$, n.s., was significant. Additionally, none of the interactions involving location as a factor were significant. The main effect of array type, however, was significant, $F(1, 182) = 26.40$, $p < .001$, indicating that target-directed saccade latencies to feature-present targets ($M = 417.9$ ms) were significantly faster than those to feature-absent targets ($M = 579.8$ ms) across all set sizes and locations. Thus, these results indicate that adults' latencies to the target, either feature-present or feature-absent, did not differ on the basis of the target's location in the visual array.

Since we had analyzed infants' saccade latencies as a function of axis, adults' latencies were similarly analyzed. A 3 × 2 × 2 ANOVA was performed on adults' saccade latencies, with set size (3, 5, and 8), axis (horizontal and vertical), and array type (feature-present and feature-absent) as within factors. Consistent with the previous analysis, neither the main effects of set size, $F(2, 194) = 2.00$, n.s., nor that of axis, $F(1, 194) = 0.01$, n.s., was significant. Additionally, none of the interactions involving location as a factor were significant. This analysis again revealed that the main effect of array type was significant, $F(1, 194) = 36.17$, $p < .001$, indicating that saccade latencies to feature-present targets were faster than those to feature-absent targets. These results indicate that saccade latencies to the target in the feature-present and feature-absent arrays did not differ as a function of target axis. Consequently, target-directed saccade latencies were collapsed across location in subsequent analyses of the effects of set size and array type.

Homogeneous arrays As previously indicated, adult research has demonstrated that homogeneous visual arrays fail to produce an efficient search but, instead, elicit an inefficient search (Wang et al., 1994). Consequently, as they did for infants, homogenous arrays would be expected to similarly elicit an inefficient localization of any one of the items for adults. A 3 ×

2 ANOVA was performed on adults' saccade latencies, with set size (3, 5, and 8) and array type (homogeneous P and homogeneous R) as within factors. This analysis revealed no significant main effect for array type, $F(1, 297) = 0.02$, n.s., indicating that there were no differences in the mean saccade latencies between the homogeneous P and homogeneous R arrays. As was predicted, the analysis revealed a significant main effect for set size, $F(2, 297) = 3.61$, $p < .05$, indicating that latencies differed between the three set sizes irrespective of whether the array consisted of Ps or Rs (see Fig. 7). Post hoc t-tests indicated that adults' saccade latencies did not significantly differ between set sizes of 3 ($M = 422.5$ ms) and 5 ($M = 435.4$ ms), $t(263) = 0.64$, n.s. Saccade latencies were significantly faster for a set size of 3 than for 8 ($M = 506$ ms), $t(155) = 2.60$, $p < .05$, and faster for a set size of 5 than for 8, $t(182) = 2.28$, $p < .05$. The interaction between array type and set size, however, was not significant, $F(2, 298) = 1.34$, n.s., indicating that both array types showed a similarly increasing target-directed saccade latency function. Thus, the present analysis revealed no difference in saccade latencies as a function of set size whether the homogeneous arrays consisted of Ps or Rs. In subsequent analyses, therefore, data from the both sets of homogeneous arrays are pooled for each set size.

Saccade latencies as a function of set size

As with Experiment 1, to investigate whether the bottom-up salience of the target would affect localization as a function of set size, the target-directed saccade latencies produced for each array type were compared across the three different set sizes. A 3 × 3 ANOVA was performed on adults' saccade latencies as a function of set size (3, 5, and 8) and array type (feature-present, feature-absent, and homogeneous). A significant main effect was found for set size, $F(2, 500) = 4.98$, $p < .01$, indicating that, irrespective of array type, target-directed

saccade latencies were different across the set sizes. Post hoc t-tests comparing mean saccade latencies in the three set size conditions revealed that adults' saccades did not significantly differ between set sizes of 3 ($M = 436.6$ ms) and 5 ($M = 448.4$ ms), $t(395) = 0.68$, n.s. Saccade latencies were significantly faster for a set size of 3 than for 8 ($M = 503.7$ ms), $t(294) = 3.10$, $p < .005$, and faster for a set size of 5 than for 8, $t(323) = 2.56$, $p < .05$. The main effect of array type was also significant, $F(2, 500) = 23.65$, $p < .001$, which indicates that adults performed significantly differently for each array regardless of set size. Post hoc analyses indicated that mean target-directed saccade latencies to feature-present arrays ($M = 417.9$ ms) was faster than those to feature-absent arrays ($M = 579.8$ ms), $t(204) = 6.40$, $p < .001$, but was not significantly different from those to homogeneous arrays ($M = 433.2$ ms), $t(426) = 1.21$, n.s. Mean target-directed latencies to feature-absent arrays, however, were significantly slower than those to homogeneous arrays, $t(382) = 6.34$, $p < .001$. This pattern of results, in particular the slower latencies to feature-absent arrays, suggests that localizing the target in feature-absent arrays is less efficient than localizing the target in feature-present arrays or any stimulus in homogeneous arrays. The interaction of set size and array type, as for the infants, was not significant, $F(4, 500) = 1.05$, n.s. (see Fig. 8).

To once again account for the possibility that data from the homogeneous condition, in which there was no unique "target," might obscure a significant interaction of set size and array type, the ANOVA was rerun without the homogeneous condition. The main effect in this 3 × 2 ANOVA of set size was not significant, $F(2, 200) = 2.16$, n.s., whereas the main effect of array type continued to be significant, $F(1, 200) = 41.91$, $p < .001$. Most important, the interaction of set size and array type was again not significant, $F(2, 194) = 1.96$, n.s. Thus, the lack of a significant interaction between set size and array type was not due to any obscuring effects of data from the homogeneous array conditions.
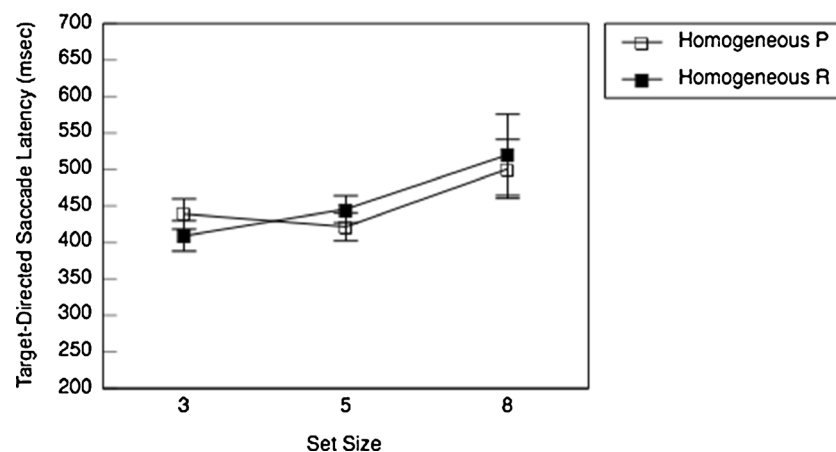

Fig. 7 Comparison of the adults' mean target-directed saccade latencies in each set size for the homogeneous conditions (Ps) and (Rs). Vertical bars indicate ± *SE*
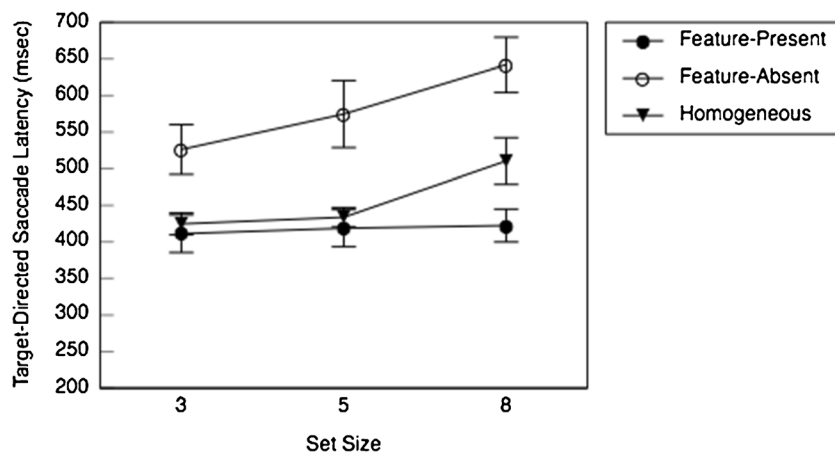
Fig. 8 Comparison of the adults' mean saccade latencies (in milliseconds) at each set size for the feature-present, feature-absent, and homogeneous array conditions. Vertical bars indicate ± *SE*

Again, although these results suggest, contrary to predictions, that the three different types of arrays did not differ across any of the set sizes, to more accurately assess how efficiently localization of the target occurred typically requires examining the regression of individual trends in performance to each array type as a function of set size (Treisman & Gelade, 1980, Treisman & Gormican, 1988; Wolfe, 1994, 1998; Wolfe et al., 1989).

Regression of latencies to set size

For feature-present arrays, this analysis revealed a nonsignficant relation between target-directed saccade latency and set size, $r^2 = .91$, n.s., with the slope of the regression line being 2.2 ms per item, indicating that saccade latencies did not increase with increasing set size (see Fig. 9a). The relatively flat slope indicates that localization of the feature-present target was efficient. For feature-absent arrays, the analysis revealed a significant relation between target-directed saccade latency and set size, $r^2 = .99$, $p < .05$, with the slope of the

regression line being 23.1 ms per item, indicating that adults' saccade latencies increased with increasing set size (see Fig. 9b). Thus adults' localization of the feature-absent target was accomplished by a relatively inefficient process. These results are consistent with previous adult findings, as well as the preceding experiment with infants, indicating an asymmetry between efficient localization of a feature-present target and a relatively inefficient localization of a feature-absent target.

For homogeneous arrays, the analysis revealed a nonsignificant relation, $r^2 = .93$, n.s., indicating that saccade latencies did not increase with increasing set size. The slope of the regression line was 17.2 ms per item, suggesting that localization of any of the items in the array was less efficient than for a feature-present target but more efficient than for a feature-absent target. Again, that localization was intermediate to the target conditions and more efficient than in the feature-absent condition was likely due to the latency assessment not being restricted to localization of a stimulus at a specific location but to any stimulus at any location, whereas in the
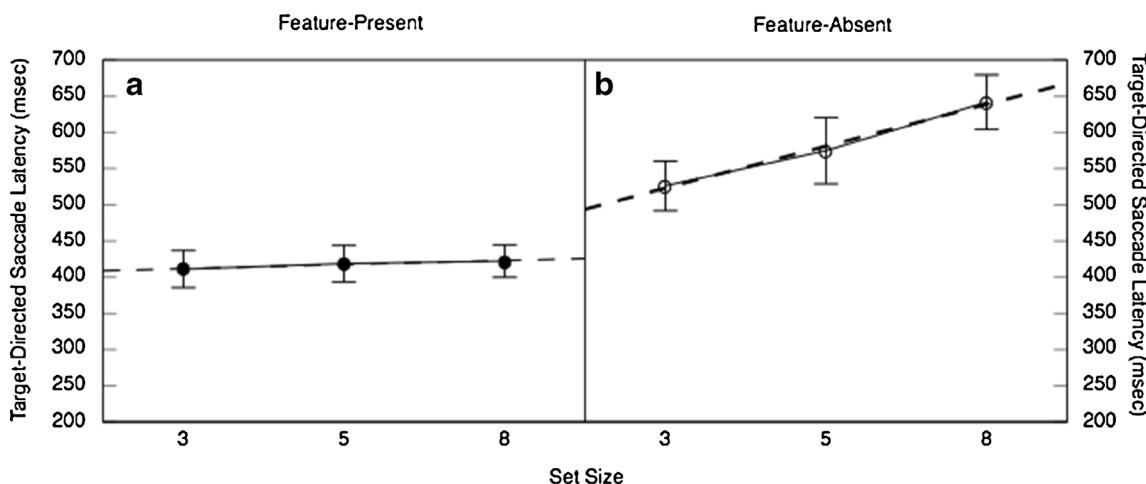

Fig. 9 a Adult target-directed saccade latencies for the feature-present condition plotted as a function of set size. **b** Adult target-directed saccade latencies for the feature-absent condition plotted as a function of set size. Vertical bars indicate ± *SE*

feature-absent condition, a specific stimulus at a specific location had to be localized on a given trial for a measure of latency to be recorded. These analyses reveal that adults', like the infants', target localization was asymmetrical, with efficient localization of a salient target in feature-present arrays and an inefficient localization of a less salient target in feature-absent arrays.

Number of eye movements to localize targets

As with infants, adults' performance was also assessed by measuring the latency and counting the number of eye movements prior to localizing the target for set sizes of 3, 5, and 8. Because adults always localized the feature-present target with a single eye movement, data from this condition could not be included in the model, since there was no variability. Instead, a one-way ANOVA was conducted just on the number of eye movements that was required to localize the feature-absent target across set sizes (3, 5, and 8). This analysis revealed that the main effect of set size was not significant, $F(2, 78) = 1.23$, n.s., indicating there was no significant difference in the number of eye movements required to find the feature-absent target across the different set sizes. This finding indicates that adults executed approximately the same number ($M = 1.85 \pm 0.20$) of eye movements across the various set sizes (3, $M = 1.76$; 5, $M = 1.72$; 8, $M = 2.07$) in order to localize the feature-absent target. Thus, the increase in adults' saccade latencies to localize the feature-absent target with increasing set size is not due to an increase in the number of eye movements required to localize the target.

In summary, the trends in adults' and infants' results were strikingly similar across set sizes and array types, and both demonstrated a clear asymmetry in their latency performance to the search arrays. Findings demonstrated that for both adults and infants, target-directed saccade latency functions across set size for the feature-present arrays were flat, where the slopes of the functions for infants (3.0 ms/item) and adults (2.2 ms/item) were similar, indicating that the target was localized efficiently. The target-directed saccade latency functions across set size for the feature-absent arrays, in contrast, was increasing for both infants and adults, with the slopes of the search functions (29.4 vs. 23.1 ms/item, respectively) also fairly similar, indicating an inefficient localization of the target. These findings are consistent with previous studies in which adults exhibit a search asymmetry (Boutsen & Marendaz, 2001; Levin & Angelone, 2001; Malinowski & Hübner, 2001; Levin & Angelone, 2001; Royden et al., 2001; Shen & Reingold, 2001; Treisman & Gormican, 1988; Treisman & Souther, 1985) and suggest that infants can exhibit an asymmetry for the presence and absence of a feature in a manner similar to that for adults that is based on the same bottom-up mechanisms of detecting salience gradients across the visual field to identify items of interest (Wolfe, 1994, 2007).

General discussion

Although previous research on attentional development in infants has been rather extensive (e.g., Ruff & Rothbart, 1996), the research literature has been essentially devoid of systematic investigations of the development of infants' *selective* attention, in which attention to a particular stimulus is assessed in the presence of simultaneously available competing stimuli. There have been sporadic studies, though, analyzing infants' capacity to attend to one of two simultaneously available stimuli and, more recently, their capacity for "visual search." That the development of selective attention has not received more research focus is surprising, considering that the ability to selectively attend is crucial because it provides a mechanism for segregating items in the visual field and selectively focusing on unique items of interest, while at the same time ignoring less relevant and perhaps redundant information. Selective attention is especially important for infants, since their knowledge base is made up of information deduced from the environment. That environment is typically cluttered with multiple items, any of which can be the focus of attention at a given moment. The ability to selectively attend allows infants to search and attend to those items of interest in a dense environment of stimulation (Adler et al., 1998; Colombo et al., 1990). The aim of the present study was to add to our understanding of infants' ability to selectively attend to particular items in the presence of competing stimuli by examining the development of selective attention mechanisms involved in visual search, particularly the role of bottom-up processing of stimulus salience, using a paradigm that is similar to that used with adults and that has previously been shown to provide evidence of adultlike visual search functions (Adler & Orprecio, 2006). A similar asymmetry was clearly observed for both infants and adults in the present study, indicating that infants at a very young age are able to selectively extract information from the environment in a similar manner as adults.

Visual search in infants and adults

Previous research of adult visual search suggests that during an efficient search, attentional resources are allocated across items in the array in a manner that enables parallel processing of those items. As a consequence, detection of the unique target item is relatively unhindered by the presence of competing items, and RTs (e.g., the latency of saccadic eye movements) are, consequently, unaffected by the number of distractors (Adler, 2005; Vincent, 2011; Wolfe, 2001; Zelinsky & Sheinberg, 1997). In contrast, an inefficient search has been shown to engage attentional resources that are allocated in a serial manner, so that detection of the target item competes with processing of the distractors and, consequently, RTs increase with the number of distractors (Zelinsky &

Sheinberg, 1997). The present results provide a good indication that, like adults, 3-month-old infants also exhibit an asymmetry. Target-directed saccade latencies produced to the unique target in the feature-present arrays were unaffected by increasing set sizes for both infants and adults, whereas target-directed saccade latencies produced to localize the feature-absent target were significantly different across the different set sizes. Together, these results are in agreement with previous findings with adults (Treisman & Souther, 1985; Wolfe, 2001) and suggest that the mechanisms responsible for search asymmetry in adulthood may be available at 3 months of age.

Consistent with the study by Adler and Orprecio (2006), the present study demonstrates that young infants have the attentional capacity and mechanisms to selectively localize simple feature targets from amid distractors. In the Adler and Orprecio study, infants needed to localize a + among Ls, a selection that, according to Julesz (1984), is based on the detection of a single feature, whereas in the present study, infants needed to detect the presence or absence of a single feature (i.e., the diagonal line in an R). Thus, in both studies, infants localized a feature target in a manner consistent with adults' search performance—a search that most models of visual search suggest is more sensitive to bottom-up attentional mechanisms (Wolfe, 1994, 2007; for a review of different models, see Humphreys & Mavritsaki, 2012). That these "searches" by infants relied primarily on bottom-up mechanisms is further supported by the fact that no prior information about the nature of the target was presented to them. Wolfe, Butcher, Lee and Hyle (2003) have previously shown that search in adults who have not been given prior information about the nature of the target rely on bottom-up processing, although over time.

The bottom-up mechanism that likely accounts for the asymmetry findings would be the generation of a saliency map (e.g., Wolfe, 1994). When a location on the map consists of a large salience contrast relative to surrounding locations, the item at that location is efficiently detected irrespective of the number of items in the surround. When a location produces a weak salience contrast, the item at that location is inefficiently detected, with the detection of the salience contrast being more greatly masked as more items are in the surround. As a consequence, an asymmetry is generated in that feature-present targets (e.g., an R among Ps) produce high salient contrasts and are, therefore, detected or localized efficiently, whereas feature-absent targets (e.g., a P among Rs) produce weak salient contrasts and are, therefore, detected or localized inefficiently. This perfectly characterizes the asymmetric performance in the present study.

Top-down influences, however, cannot be completely dismissed from having played some role in performance, since a top-down set could be formed by implicitly extrapolating the nature of the targets across trials, as has been shown can occur in adults (Wolfe et al., 2003). Since the present results can be accounted for by a bottom-up process of saliency, or even signal detection (Palmer et al., 2011) or uncertainty of sensory information (Vincent, 2011), it is unlikely that implicit top-down biases were required to detect the target. These models of visual search (Palmer et al., 2011; Vincent, 2011; Wolfe, 1994, 2007), however, would predict that more sophisticated searches, such as detection of a conjunction of multiple features, do require the recruitment of top-down attentional influences. That is, top-down influences on attentional allocation would be required in order to bind feature information of a conjunction target, due to the much lower saliency, signal-to-noise ratios, and more uncertainty of any of its individual features. Models of attentional development (Atkinson, 2000; Braddick & Atkinson, 2011; Johnson, 1995), interestingly, have postulated that the neural and attentional mechanisms necessary for selectively processing information in particular feature maps, such as orientation and color, are functional in the first few months of life. The mechanisms that are necessary for binding feature information and top-down control of attentional allocation, including eye movements, are postulated to become fully functional only as early as 3 months of age and perhaps not until 6 months of age. The present findings and the Adler and Orprecio (2006) findings would thereby seem to be consistent with both visual search and attentional development models.

If the visual search models and attentional development models are correct, then together they would predict that infants would not be able to perform a search for a target defined by the conjunction of features in a manner similar to adults—the reason being that if a conjunction search requires top-down attentional influence, even if produced from implicit mechanisms, for the purpose of binding feature information in order to detect the unique combination of features, then infants younger than 6 months, whose top-down and binding mechanisms are not yet fully mature, would not be able to properly conduct a conjunction search in an adult-like manner. That this might be the case is suggested by a recent study by Bulf et al. (2009), in which 6-month-old infants' and adults' eye movements were assessed in their detection of a Kanisza illusory figure. Bulf et al. found that the adults, but not the infants, localized the illusory figure, leading them to speculate that this was due to a lack of binding mechanisms in the infants—consistent with attentional development models. Neither the Bulf et al. nor any other infant visual search study has systematically examined infants' capacity to conduct a search for a conjunction target, so the exact relation between the development of selective attentional mechanisms (e.g., bottom-up vs. top-down) and visual search has yet to be determined.

Number of eye movements, saccade latencies, and visual search

In the present study, across all conditions and set sizes, there was no systematic effect as a function of set size on the

number of eye movements made in order to localize the target. This suggests that the increase in target-directed saccade latencies was not due to infants requiring more eye movements with greater set sizes in order to localize the target. Additionally, the lack of a relation between number of eye movements and target-directed saccade latencies might suggest that these two oculomotor measures may be differentially related to visual search and the underlying attentional mechanisms.

Previous work with adults (Zelinsky & Sheinberg, 1997) that investigated the relationship between different measures of oculomotor behavior and manual RT in a search asymmetry task revealed that the number of eye movements, but not fixation durations, was related to the traditional manual RT in a visual search task. That is, search tasks in which RTs increased as a function of set size, the number of eye movements to localize the target also increased, thereby suggesting a common processing source for the two measures. This contrasts with the present study which found that the number of eye movements did not increase as a function of set size in conditions (i.e., feature-absent target) in which a manual RT typically would. Note, however, in the Zelinsky and Sheinberg study, that participants were provided with top-down information indicating the search item, whereas in the present study, participants were not provided with any top-down information regarding the target. Thus, the possibility exists that the number of eye movements reflects top-down influences and that, since there were few if any top-down influences in the present study, no effect on eye movement number was found.

If eye movement number reflects top-down processing influences that were unavailable in the present study, then saccade latencies, which are affected by set size manipulation, might be more influenced by bottom-up selection processes such as saliency. Many other studies have demonstrated the tight linkage between eye movement initiation and attentional selection (Adler et al., 2002; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Smith et al., 2004; Van der Stigchel & Theeuwes, 2007), with many of these tasks assessing target selection as a function of bottom-up cuing. These studies have demonstrated that precuing a target, which likely increases its saliency, lowers eye movement latencies to localize it. Consequently, the target-directed saccade latencies in the present task likely represent a strongly reliable oculomotor measurement that can be related to the underlying selective attentional mechanisms responsible for localization of unique targets present among other simultaneously available items.

This idea that eye movement latencies and other measures of oculomotor behavior (e.g., fixation duration) assess different processes or phases of attention even has a parallel in a proposition about infant oculomotor behavior. Cohen (1972) proposed that infants' latency to orient to a stimulus represents the product of an attention-getting mechanism, whereas fixation duration represents the behavior produced by an

attention-holding mechanism. Consistent with this idea, we had earlier laid out an argument that previous infant paradigms could not be relied upon as providing valid measures for determining the development of visual search. The reasons given were that habituation, novelty preference, and mobile conjugate reinforcement paradigms did not measure infants visual search behavior on the time scale typically associated with visual search behavior (i.e., milliseconds), nor did they assess search behavior as a function of set size. Moreover, none of these paradigms assessed response latency but, instead, assessed some other behavior, such as fixation duration, that has not been associated with the relevant attentional mechanisms responsible for visual search performance (e.g., Zelinsky & Sheinberg, 1997). The present finding of an asymmetry, as well as the Adler and Orprecio (2006) finding, demonstrate that the eye movement paradigm used in these studies provides a valid assessment of the development of visual search behavior and the underlying attentional mechanisms that is consistent with the manner in which visual search is assessed in adults.

Conclusions

The present study was designed to investigate the nature of infants' ability to selectively attend by examining the development of mechanisms involved in visual search, particularly the role of bottom-up processing of stimulus salience. The present results indicated that like adults, infants exhibit an asymmetry in that infants efficiently localized the target in feature-present arrays (R among Ps), whereas their localization of the target in feature-absent arrays (P among Rs) was more inefficient. The similarities in exhibition of a localization asymmetry provide support for the contention that attentional mechanisms, particularly those based on bottom-up stimulus information such as target saliency, used by adults in their selective processing are already available by 3 months of age. Whereas visual search in adults typically consists of top-down biasing based on an attentional set, the nature of the present study does not easily allow for the influence of top-down mechanisms. The present study therefore cannot inform about the development of bottom-up versus top-down mechanisms. Perhaps bottom-up and top-down attentional mechanisms show differential developmental timelines, as implied by attentional development models; then, visual search tasks that require the deployment of top-down attentional mechanisms might highlight this developmental difference.

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