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PAPER

The eyes have it: visual pop-out in infants and adults

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Abstract

Visual search studies with adults have shown that stimuli that contain a unique perceptual feature pop out from dissimilar distractors and are unaffected by the number of distractors. Studies with very young infants have suggested that they too might exhibit pop-out. However, infant studies have used paradigms in which pop-out is measured in seconds or minutes, whereas in adults pop-out occurs in milliseconds. In addition, with the previous infant paradigms the effects from higher cognitive processes such as memory cannot be separated from pop-out and selective attention. Consequently, whether infants exhibit the phenomenon of pop-out and have selective attention mechanisms as found in adults is not clear. This study was an initial attempt to design a paradigm that would provide a comparable measure between infants and adults, thereby allowing a more accurate determination of the developmental course of pop-out and selective attention mechanisms. To this end, we measured 3-month-olds' and adults' saccade latencies to visual arrays that contained either a + among Ls (target-present) or all Ls (target-absent) with set sizes of 1, 3, 5 or 8 items. In Experiment 1, infants' saccade latencies remained unchanged in the target-present conditions as set size increased, whereas their saccade latencies increased linearly in the target-absent conditions as set size increased. In Experiment 2, adults' saccade latencies in the target-present and target-absent conditions showed the same pattern as the infants. The only difference between the infants and adults was that the infants' saccade latencies were slower in every condition. These results indicate that infants do exhibit pop-out on a millisecond scale, that it is unaffected by the number of distractors, and likely have similar functioning selective attention mechanisms. Moreover, the results indicate that eye movement latencies are a more comparable and accurate measure for assessing the phenomenon of pop-out and underlying attentional mechanisms in infants.

Introduction

William James (1890) wrote that attention was the 'taking possession by the mind, in clear and vivid form, of one of what seem several simultaneously possible objects' (p. 403). This conceptual view of attention stems from the fact that our visual world contains many simultaneously available objects that are possible inputs for visual and cognitive processing and for guiding behavior. Since our processing resources are limited and we are constrained in the amount of visual information that can be processed at any particular moment, specific items in space must be selected as targets in order for visual processing and behavior to proceed efficiently (Broadbent, 1982; Deutsch & Deutsch, 1963; Fox, 1995; Treisman, 1964; Yantis & Johnson, 1990). For infants, selective attention mechanisms would seem to be crucial for filtering and making sense of their visual world with which they have little or no experience as they pursue the construction of a knowledge base.

Since attention and the selectivity of these mechanisms are important for infants' cognitive development to proceed, it is not surprising that a great deal of research over the last few decades has focused on this topic. In fact, the most widely used paradigms, habituation-dishabituation and novelty- and familiarity-preference, for studying aspects of infants' perceptual and cognitive development exploit overt attention (i.e. fixation) as their primary measure. These studies of visual attention in infants have generally shown that they preferentially attend and fixate either a novel or familiar stimulus after having been repeatedly presented with the familiar stimulus, thereby demonstrating the ability of infants to make various attentional and perceptual discriminations (Cohen, 1972; Colombo, Mitchell, Coldren & Atwater, 1990; Fagan, 1970; Fantz, 1964; Hunter & Ames, 1988; Rose, Gottfried, Melloy-Carminar & Bridger, 1982; Salapatek, 1975). In these studies, however, only a single stimulus is typically presented during initial stimulus processing, so attentional selection is not required as

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there is no competition from other stimuli. Consequently, although these studies have considerably expanded our knowledge of infants' perceptual processing capacities, they have shed little light on the development of attentional mechanisms responsible for selecting a target from amidst competing stimuli.

To directly explore the development of mechanisms of selection during initial allocation of attention, a number of studies have examined infants' ability to selectively attend to one stimulus that is superimposed on a second stimulus (Bahrick, Walker & Neisser, 1981), to shift attention between two simultaneously presented stimuli (Atkinson, Hood, Wattam-Bell & Braddick, 1992), to disengage visual attention from one stimulus to attend to a second, subsequently presented stimulus (Hood & Atkinson, 1993; Richards & Hunter, 1997) and to inhibit a shift of attention back to a stimulus that they had previously selected and allocated attention (Hood, 1993). Many studies have also examined the ability of infants to exhibit 'pop-out', in which their attention is captured by a stimulus (or patch of stimuli) that is surrounded by dissimilar but simultaneously presented stimuli (Adler, Inslicht, Rovee-Collier & Gerhardstein, 1998; Atkinson & Braddick, 1992; Colombo, Ryther, Frick & Gifford, 1995; Rovee-Collier, Hankins & Bhatt, 1992; Sireteanu & Rieth, 1992).

Visual search in adults

In adults, visual search and texture segregation paradigms and the phenomenon of pop-out have been used to assess the functioning of selective attention mechanisms. The functioning of these mechanisms has been formalized in two influential theories of adults' visual information-processing that have proposed two-stage models. In an initial preattentive stage of processing, stimuli in the visual array are decomposed into their basic perceptual features (Julesz, 1984; Treisman, 1988). The basic perceptual features have been hypothesized to include elongated blobs, orientations, width and length, size, color, motion and elongated blob terminators – a list that agrees well with the properties that physiological evidence suggests are processed in parallel by the early visual system (Deco, Pollatos & Zihl, 2002; Livingstone & Hubel, 1981). A later attentive stage selectively focuses processing resources to individual stimuli for the purpose of binding the features into a unified object percept and for object recognition (Julesz, 1984; Treisman, 1988).

Pop-out, consequently, can be described as the situation in which stimuli that are defined by a unique perceptual feature automatically and selectively guide attention (e.g. Treisman & Gelade, 1980; Wolfe, Butcher, Lee & Hyle, 2003). That is, as a consequence of the initial decomposition of stimuli into their basic features, a stimulus unique for a particular feature is indicated at a particular location on that feature map and attentive processes are then selectively allocated to that stimulus. As a result, regardless of the number of stimuli in the array, the amount of time it takes for an individual to detect the stimulus with the unique feature remains relatively stable. In contrast, when there is no stimulus that consists of a single unique identifying feature or the stimulus is defined by a unique combination of features, it does not pop out. Instead, the attentive mechanism allocates processing resources to each stimulus (or each stimulus with a particular feature as in the Guided Search model; Wolfe, Cave & Franzel, 1989) in order to select one of the stimuli in the array or detect the stimulus in the array with the unique conjunction of features (Treisman & Sato, 1990; Woodman & Luck, 2003). As a result, the amount of time it takes for an individual to detect the stimulus with the unique conjunction increases as the number of stimuli in the array increases.

Though there continues to be considerable interest in understanding the nature of the preattentive and attentive mechanisms (Egeth & Dagenbach, 1991; Luck, Girelli, McDermott & Ford, 1997; Wolfe, 1994), recent theories of visual search indicated that all search tasks require some amount of attentional allocation (Cave, 1999; Duncan & Humphreys, 1992; Wolfe, 1994; Wolfe *et al.*, 1989). For example, Joseph, Chun and Nakayama (1997) demonstrated that when adults were required to perform a letter identification task concurrently with a 'preattentive' feature search, slopes to detect the target defined by the unique feature increased. This would seem to indicate that even in a search task historically shown to produce pop-out, the detection of primitive perceptual features is sensitive to the amount of attentional resources available (also see Di Lollo, Kawahara, Zuvic & Visser, 2001; Theeuwes, Kramer & Atchley, 1999). Furthermore, in a meta-analysis in which the distribution of search slopes across a wide variety of 'preattentive' and 'attentive' search tasks was assessed, the amount of attentional allocation was shown to be unimodal rather than bimodal as would be predicted if separate processing mechanisms were responsible for the two types of search (Wolfe, 1998). Consequently, the distinction between parallel and serial search functions is no longer accurate but rather the distinction is between search that is efficient and not limited by attentional resources (e.g. pop-out) or inefficient and sensitive to attentional resources.

Pop-out in infancy

One of the first studies to suggest that pop-out occurs in early infancy was reported by Salapatek (1975). Salapatek found that 3-month-olds always oriented to a unique patch of squares embedded in an array of horizontal lines (or vice versa) whereas 2-month-olds did not orient to the unique patch, suggesting that the unique patch captured 3-month-olds' but not 2-month-olds' attention. This suggests that the mechanism responsible for pop-out might not come online until around 3 months of age.

In the last ten years or so, there has been considerable interest in this prospect and numerous studies have investigated pop-out in infants. In 1992, motivated by Salapatek's findings, two studies further investigated the development of pop-out of discrepant patches or textures (Atkinson & Braddick, 1992; Sireteanu & Rieth, 1992). Atkinson and Braddick found, in good agreement with Salapatek (1975), that 4-month-old infants but not 2- to 3-month-olds oriented to a patch of oriented lines embedded in a texture of orthogonally oriented lines, suggesting that the ability to exhibit pop-out on the basis of orientation differences does develop around 3 months of age. However, when the patch of lines differed from the surrounding texture on the basis of their size (and luminance), even the youngest infants exhibited pop-out.

Sireteanu and Rieth (1992) also found that infants as young as 2 months preferentially oriented towards the discrepant patch when it was defined by size, suggesting that it popped out. In contrast to Atkinson and Braddick (1992), however, Sireteanu and Rieth found that a discrepant patch defined by orientation was not preferentially oriented until approximately 12 months of age. The reason for the discrepancy between the two studies in the age at which infants exhibit pop-out of the orientation-defined patch is not clear, but may be due to methodological differences (Sireteanu, 2000). Regardless, these studies demonstrate that pop-out and the segregation of textures, at least those defined by size or luminance differences, is evident in infants as young as 2 months of age.

A number of other studies using different stimuli and paradigms have demonstrated pop-out in 3-month-old infants (Adler, Gerhardstein & Rovee-Collier, 1998; Colombo *et al.*, 1995; Quinn & Bhatt, 1998; Rieth & Sireteanu, 1994; Rovee-Collier *et al.*, 1992). Rovee-Collier *et al.* (1992), for example, had as a basis for their study the finding by Julesz (1981) that a patch of +s pops out for adults when it is embedded in a surrounding texture of Ls, presumably because the +s contain the unique perceptual feature of the line crossing. Rovee-Collier *et al.*, using the mobile-conjugate reinforcement paradigm (Rovee & Rovee, 1969), trained 3-month-olds to kick to move an overhead seven-block crib mobile that displayed either Ls or +s on every block side and then tested them with a mobile that consisted of either a single unique 'L' block among six '+' blocks or a single unique '+' block among six 'L' blocks. They found that the familiarity or novelty of the unique characters on the single block irrespective of the familiarity or novelty of the characters on the surrounding blocks determined infants' recognition performance. This suggested that the unique character popped out from amidst the surrounding dissimilar characters, similar to the findings of pop-out in visual search and texture segregation studies with adults.

Collectively, the studies described above and others (for review, see Bhatt, 1997) seem to indicate that infants as young as 3 months exhibit the phenomenon of 'pop-out'. This would further suggest that the mechanisms for selectively allocating early visual processing resources are functioning in early infancy. However, there are a couple of issues that have yet to be resolved by the infant 'pop-out' studies that would provide definitive evidence for pop-out and efficient processing in infancy. First, in adults, pop-out typically occurs on the order of milliseconds (e.g. Treisman & Gelade, 1980). In the infant studies described, however, paradigms are used in which results are measured in minutes or seconds at the very least. In the mobile-conjugate reinforcement paradigm, for example, assessment of pop-out is done during a test phase that lasts 3 minutes or 180,000 msec (Adler *et al.*, 1998; Rovee-Collier *et al.*, 1992) – sufficient time for infants' behavior to be due to the allocation of attentive resources in an inefficient search rather than to pop-out and efficient search.

Infant pop-out studies using looking time paradigms have a similar limitation as does the mobile paradigm. For example, in the Colombo *et al.* (1995) study which used preferential looking to an array that contained a pop-out target among distractors versus an array that contained homogeneous stimuli, pop-out was measured by requiring the infants to accumulate a total of 5 sec (5000 msec) of looking – a factor of 10 greater than is typically found in adult pop-out studies – and more than enough time for later attentive and cognitive mechanisms to be responsible for infants' performance. Similarly, in studies using the novelty-preference methodology, tests for pop-out might occur on trials that last 15 sec (15,000 msec). Interestingly, if infants had exhibited pop-out and their attention had been automatically guided by the pop-out target in these looking studies then it should have been evident in their first looks but yet none of these studies report any data concerning infants' first looks.

A consequence of the timing issues for measuring pop-out in infants and the use of methods such as preferential-looking, novelty-preference and mobile-conjugate reinforcement is that the functioning of other cognitive mechanisms besides attention cannot be discounted from playing a role in observed effects. For example, in novelty-preference and mobile-conjugate reinforcement, infants' behavior, including evidence of pop-out, is determined by recognition and discrimination processes. Consequently, memory (and forgetting) might play a role in determining infants' performance on search tasks using these paradigms. The present study was designed to overcome this issue.

A second issue that has yet to be addressed in the infant studies is that a key demonstration of pop-out is that detection exhibits a flat search function. This means that the amount of time necessary to respond to the pop-out target remains relatively the same even as the number of distractor items increases. No infant study has yet examined the effect of the number of distractors or set size on pop-out. One study (Rovee-Collier, Bhatt & Chazin, 1996) has examined the effect of the number of distractors on infants' recognition and discrimination of the pop-out target, but because it too used the mobile paradigm in which there is no response time measure and the amount of time allocated to assess performance is so large (as described earlier), it is impossible to know whether infants in this study detected the pop-out target.

Consequently, due to these two limitations of the infant studies, protracted test phase for assessing pop-out and failure to test for set size effects, whether infants actually exhibit the phenomenon of pop-out and a functioning parallel processing mechanism as found in adults has yet to be definitively demonstrated. The present research, therefore, measured 3-month-olds' eye movement latencies, which are assessed in milliseconds, to further investigate whether infants exhibit pop-out due to the output of a parallel processing mechanism. Specifically, infants were presented with visual arrays in which the pop-out target was either present or absent and in which the number of distractor items varied, and infants' latency to make an eye movement to the target in the target-present conditions and to one of distractors in the target-absent conditions was measured. Furthermore, whether pop-out occurs in parallel for the infant was able to be measured by assessing the effect of increasing set sizes on infants' eye movement latencies. Finally, in order to make a direct comparison to pop-out in adults, the same stimuli and conditions that were presented to infants were also presented to adults and their eye movement latencies were likewise assessed.

Experiment 1: infants' eye movements and pop-out

Many studies have indicated that the programming and execution of voluntary eye movements are intimately linked with the allocation of visual attention (Adler, Bala & Krauzlis, 2002; Crawford & Müller, 1992; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Jonides, 1981; Klein, 1980; Kowler, Anderson, Dosher & Blaser, 1995; Posner, 1980). Hoffman and Subramaniam (1995), for example, found that target detection prior to eye movement initiation is superior when target and saccade location coincide than when they do not, suggesting that the allocation of spatial attention is an important element of generating a saccadic eye movement. Similarly, Kowler *et al.* (1995) found that attention could not be allocated to one location while at the same time preparing to make a saccadic eye movement to a different location. These findings and others demonstrate an intimate link between saccadic eye movements and spatial attention in the selection of targets (e.g. Rizzolatti, Riggio, Dascola & Umilta, 1987).

Given the tight linkage between eye movements and attentional allocation, a number of studies have measured the relation between adults' eye movements and attentional processing in visual search tasks. Findings from these studies that the number of distinct eye movements was positively correlated with search times and with the geometric pattern of eye movements to a visual search array revealed that an initial parallel processing mechanism functioned to affect eye movements in a visual search task (Zelinsky, 1996; Zelinsky & Sheinberg, 1997). Research has also shown that latency and accuracy of the initial saccade to a visual search target is a function of the spatial certainty of the target (Findlay, 1997) and the number of distractors in the visual array (McSorley & Findlay, 2003; Motter & Belky, 1998). These findings indicate that an assessment of eye movements can be used as an accurate measure of visual search, pop-out and mechanisms of attentional processing. These studies, therefore, motivated us to examine the viability of using the latency of infants' eye movements in a visual search paradigm to assess 'pop-out'.

In the current experiment, we assessed the latency of 3-month-old infants' saccadic eye movements to arrays in which a target was either present or absent and that consisted of different numbers of distractors for set sizes of 1, 3, 5 or 8 items. Specifically, the target in the present experiments was a + sign and the distractors were Ls. These stimuli have been used extensively in both adult studies of texture segregation (Julesz, 1981) and infant studies of pop-out and perceptual discrimination (Adler & Rovee-Collier, 1994; Rovee-Collier *et al.*, 1992). Julesz (1981) has hypothesized that +s pop out from amidst Ls because the +s contain an additional perceptual feature – the line crossing – that is not part of the Ls. As a result, the feature map for 'line crossing' is activated by the + but not by the Ls, leading to pop out of the +.[1]

In the present study, we only assessed pop-out of a + from amidst Ls and not an L from amidst +s. There were a number of reasons for doing this. First, because the primary focus of the present study was an assessment of the viability of using infants' eye movements to study early perceptual processing and the mechanisms of pop-out, and not an investigation of the particular features processed by the perceptual system, counterbalancing the pop-out target was deemed not to be relevant. Second, due to the timing nature of the trial sequence, we were only able to present infants with 4 trials of each of the 8 conditions (target present vs. target absent × 4 set size conditions). Consequently, because of these two reasons, we wanted to maximize the likelihood that infants would exhibit pop-out. Because previous studies with infants have suggested that a feature-present target pops out more readily than a feature-absent target (Adler *et al.*, 1998; Colombo *et al.*, 1995) and that a + may be attended more and processed more deeply than an L (Adler & Rovee-Collier, 1994; Adler *et al.*, 1998), we decided that pop-out of a + from among Ls would more likely be exhibited by infants than pop-out of an L from among +s.

Method

Participants

Infants were recruited from advertisements placed in the local newspaper as well as from a local Toronto hospital. Once names were obtained, parents were sent a letter inviting them to have their infant participate in studies at the Centre for Early Cognition at York University. Those interested in participating returned the postcard, telephoned, emailed or volunteered online and they were then contacted by phone. The data from 20 infants (11 males, 9 females), who ranged in age from 84 to 114 days (M = 101.6, SD = 10.5) were included in the study. Infants were Caucasian (n = 14), African (n = 3) and Asian (n = 3), and were primarily from middle SES backgrounds. Infants were all born at full term, in good health, with no apparent visual, neurological or other abnormalities. The data from an additional 7 infants who participated were excluded from the study because of equipment or software failure during testing (n = 1), and because insufficient data (i.e. data on less than 65% of the pictures) were collected due to fussiness (n = 2) or inattentiveness (i.e. disinterested or looked at their hands or other parts of the visual field; n = 4).

Stimuli and apparatus

The stimuli were computer-generated graphic images of a white fixation triangle, a red + and red Ls and were presented on a 19-inch IBM color monitor with 1024 × 768 pixel resolution, a refresh rate of 75 Hz and an 8 bit/pixel gray scale. The infant viewed the images from a distance of 40 cm. The stimuli were arranged on a circular grid that had a radius of 5° from a central fixation triangle on a black background. The +s and Ls each subtended a visual angle of 4° and the fixation triangle subtended a visual angle of 1°. Two types of visual search arrays were constructed with the + and Ls, target-present and target-absent arrays. Further, the number of Ls in the arrays were varied such that the arrays could consist of set sizes of either 1, 3, 5 or 8 items (see Figure 1). Target-present arrays consisted of a single + target randomly presented at either the 12, 3, 6 or 9 o'clock position on the circular pattern amidst either 0, 2, 4 or 7 distractor Ls randomly presented at any of the other positions. Target-absent arrays consisted of 1, 3, 5 or 8 distractor Ls randomly presented at any of the positions on the circular pattern.

Infants sat in an infant car seat that was placed on a wooden platform and was situated 40 cm from the computer screen on which the stimuli were presented. A remote, pan-tilt infrared eye tracking camera (Model 504, Applied Science Laboratories [www.a-s-l.com], Bedford, MA) using bright pupil technology, placed directly below the stimulus screen, recorded the participant's eye movements at a temporal resolution of 60 Hz. Infrared light emitted from diodes on the camera was reflected back from the participant's retina through the pupil producing a backlit, white pupil and from the corneal surface of the eye. Black felt curtains were hung around the immediate testing area to reduce distraction. Behind the curtains were two IBM computers, one that generated the stimuli and one that controlled the eye-tracker camera and collected the eye movement data.

The experimenter viewed the stimuli and the infant's eye movements on one of the computer monitors as a picture-in-picture video via video capture software on the data-collecting computer, and controlled the stimuli and camera by keyboard and remote control. The picture-in-picture video and the digital data were written to the data-collecting computer and synchronized in real time with a unique, stimulus-dependent, numerical code received from the stimulus-generating computer. That is,

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[1] Remember that early perceptual processing decodes features and not the relation between features; therefore, the different relations of the same horizontal and vertical lines in the + and L is not detected by the initial perceptual processing system. Instead, in order for pop-out to occur with these stimuli, the early, parallel processing system needs to detect a feature difference between them; in this case, the presence versus absence of the line crossing.

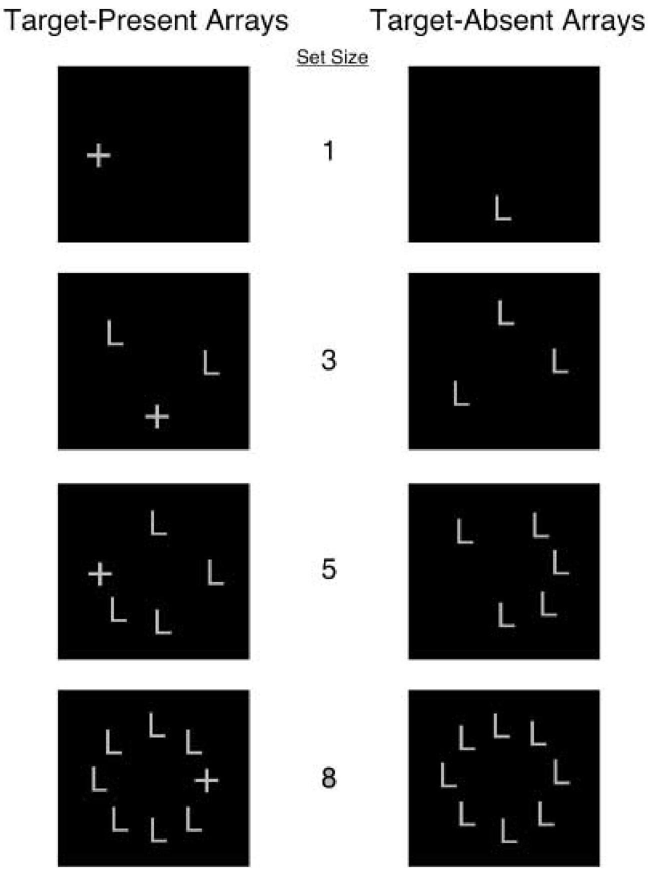

Figure 1 *Example of the visual search arrays used in this study. Shown are target-present and target-absent search arrays with set sizes of 1, 3, 5 and 8. The stimuli in the array shown to infants were actually red in color. On those trials when a target was present it could randomly occur at either the 3, 6, 9 or 12 o'clock locations, and the distractors randomly occurred in any of the remaining locations.*

to be able to coordinate the eye movement data with a specific stimulus array, the stimulus-generating computer sent a unique, time-stamped numerical code via the parallel port to the data-collecting computer indicating the onset of the stimulus array and indicating the type of stimulus array. The digital data indicating the fixation locations and change of locations of the eye and therefore the eye movements themselves were calculated from the relation between the centroid of the pupil and the corneal reflection by use of a proprietary algorithm (Applied Science Laboratories).

Procedure

A pacifier was offered to the infant as the eyetracker camera was focused, and minor adjustments to the position of the infant's head were made. During this time, the monitor screen displayed a magenta solid circle which moved in a circular path to hold the infant's interest. Before beginning the experimental trials, the eyetracker was calibrated by having the infant look at stimuli (concentric squares that loomed in and out) successively presented at known locations on the monitor and recording the eyetracker values for eye fixation location. All subsequent eye data were filtered through these calibration values.

An experiment trial began with the presentation of the fixation triangle for 1000 msec followed by a fixation-visual search array interval of 250 msec during which the monitor was blank. This was followed by the visual search array with a duration of 1000 msec during which either a target-present array (containing the + target) or a target-absent array was presented. Whether a target-absent or target-present array was presented and the particular set size was randomly determined on each trial. Finally, after an inter-trial interval of 250 msec, the fixation triangle was presented and the next trial began.

Across all trials, for each set size, the infant was randomly presented with the target occurring once in each of the four possible positions for four trials with each set size and a total of 16 target-present trials. To be consistent with target-present arrays, 4 trials of each set size were presented with the positions of the Ls randomized across these trials, for a total of 16 target-absent trials. Moreover, when only a single L was presented, it could occur either at the 12, 3, 6 or 9 o'clock position of the circular pattern, as was the case when only a single + was presented. Thus, each infant saw 32 trials of interleaved target-present and target-absent arrays.[2]

Data reduction and analysis

The raw digital data recorded by the eyetracker were imported into a MATLAB toolbox called ILAB (Gitelman, 2002) for subsequent analysis. The ILAB toolbox software allowed 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 provided a means by which to display the scan path of the eye on a trial-by-trial basis and thereby determine whether or not the eye first fixated

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[2] More trials were not run with each infant mainly because of issues of timing. The cumulative amount of time that was allocated (see the Procedure for details) for the fixation triangle duration, the fixation-array interval, visual search array duration and array-fixation interval was sufficiently long that we were concerned that infants would become bored and inattentive. This would be exacerbated by the fact that the stimuli used in this study were single color, static and non-dynamic images. In fact, pilot testing revealed that infants would not maintain their attention levels for much longer than the 32 trials used in this experiment.

the fixation stimulus and the nature of the eye movement (direction and distance) relative to the search array.

In order for an eye movement to be included in the final data sample, it needed to meet a number of criteria. First, since pop-out was being assessed in this study, the latency of the infants' first eye movement after the visual search array appeared was measured. Second, anticipatory eye movements that occurred within the first 133 msec after onset of the visual search array were excluded from the final data sample even if they happen to correctly fixate the target in the target-present array. This latency was chosen as the cut-off for anticipations because it has been determined that 3-month-old infants cannot typically make eye movements in reaction to the onset of a stimulus faster than 133 ms (Canfield, Smith, Brezsnyak & Snow, 1997). Third, the infants were required to be fixating the fixation triangle before the visual search array was presented. As mentioned above, this was determined by examination of the scan path on each trial. Finally, the eye movement to a stimulus in the target-present and target-absent arrays had to trace a path that was more than 50% of the distance between the fixation triangle and the stimulus. This was assessed by analysis of the infants' scan path overlayed on top of an image of the the stimulus array on a trial-by-trial basis. The 50% criterion has been used in previous studies using infants' eye movements (e.g. Adler & Haith, 2003) and is typically taken as an indication that the eye movement was intentional and not random.

To summarize, in the target-present conditions, the latency of the first eye movements that traced a path at least 50% of the distance between fixation and target were measured. If the first eye movement traced a path to a distractor or to a location where no item was present, then that latency was not included and the trial was considered incorrect even if a subsequent eye movement went in the direction of the target. In the target-absent conditions, the mean latencies of the first eye movements that traced a path at least 50% of the distance between fixation and any one of the stimuli in the target-absent array were analyzed. For example, in the target-absent condition with a set size of 3, the latency of the first eye movement that traced a path in the direction of one of those three stimuli was measured. If, however, the first eye movement traced a path to a location where no stimulus was present, then that latency was not included and the trial was considered incorrect even if a subsequent eye movement went in the direction of one of the stimuli. As a consequence of these criteria, the percentage of trials in each array type × set size condition that were usable ranged from 65 to 76.25%.

Infants' mean saccade latencies to the target in the target-present arrays and to one of the distractor stimuli in the target-absent arrays as a function of the different set size conditions served as the dependent measure. Since each infant provided at most 4 latency values, and at minimum only 1 value, for each array type × set size condition; in order to increase the power of our statistical tests we pooled infants' saccade latencies in each condition and based our analyses on the pooled data. This is a common practice when eye movement latencies are the dependent measure (e.g. Adler *et al.*, 2002).

Results and discussion

Preliminary analyses

Accuracy: Before comparing infants' latencies to the target-present and target-absent arrays, it was necessary to determine that the accuracy in detecting the + target was equivalent across set sizes to eliminate a speed–accuracy tradeoff as a cause for increasing latency as a function of set size. In support of the importance of assessing the relation of accuracy and set size is the fact that Dannemiller (2002) found, when studying motion pop-out in young infants, that 7- to 11-week-olds' orienting toward a moving target fell to chance as the number of static distractors (i.e. set size) increased. In contrast, Dannemiller found that selective orienting improved with increasing set size in 17- to 21-week-olds. Dannemiller (2002), however, did not measure the latency to orient, so it is not clear how the effect of set size on accuracy to orient would affect latency. Please note that in the present study pop-out was assessed in 12- to 16-week-olds – between the ages used in Dannemiller's study.

In terms of measuring eye movement latencies to assess pop-out, the relation between accuracy and set size is important because as set size increases and the array density therefore increases, infants may be less accurate in making a saccadic eye movement to the target due to the continuing development of fine motor control over the spatial goal of their eye movements (Shea, 1992). Consequently, the latency of infants' saccadic eye movements to the target may increase with set size due to poor motor control and not because the target did not pop out. A one-way ANOVA was conducted, therefore, to assess whether accuracy to the target in the target-present arrays remained consistent across set size. This analysis revealed that accuracy to make a saccade to the target did not differ, $F(2, 57) = 1.08$, *ns*, when the set size was 3, 5 or 8.[3] Thus, although there was a slight

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[3] Please note that the set size of 1 was not included in this analysis because when infants did make a saccade to a stimulus in this condition it was always a target, resulting in every infant having 100% accuracy. This represents a floor effect in that infants could do no worse and therefore accuracy in the condition of a set size of 1 is not a precise measure.

increase in mean accuracy as a function of set size, consistent with the findings of Dannemiller (2002), it did not reach significance. Since the age of the infants used in the present study fell between the age ranges used in the Dannemiller study, perhaps the present accuracy findings represent a transition from the poorer performance of younger infants to the improving performance of older infants with increasing set size.

Target location: Since the + target in the target-present arrays occurred in four locations (3, 6, 9 and 12 o'clock) and it has been demonstrated that young infants' saccadic eye movements are more reliable along the horizontal dimension than the vertical (Hainline, Turkel, Abramov, Lemerise & Harris, 1984; Shea, 1992), it was necessary to make sure that there was no latency differences due to target location. A 4 × 4 ANOVA was performed on infants' saccadic latencies in the target-present conditions with set size (1, 3, 5 and 8) and target location (top, right, left and bottom) as within factors. This analysis revealed that the main effect of set size, $F(3, 223) = 1.30$, *ns*, was not significant, indicating that the latency of infants' saccades to the + target in the target-present arrays did not differ as function of the number of distractors – a finding that will be examined more specifically below. The main effect of target location, $F(3, 223) = 0.88$, *ns*, was also not significant, indicating that infants' saccadic latencies did not differ as a function of the location of the target. In addition, the interaction of set size with target location was not significant, $F(9, 223) = 1.35$, *ns*.

Because the distinction in the reliability in infants' eye movements is between horizontal and vertical eye movements, infants' saccadic latencies were collapsed along the horizontal and vertical dimensions and a 4 × 2 ANOVA was conducted with set size (1, 3, 5 and 8) and target axis (horizontal versus vertical) as within factors. This analysis also did not find any significant main effects (set size: $F(3, 223) = 1.54$; target axis: $F(1, 223) = 1.33$) or interaction ($F(3, 223) = 0.58$). The insignificant results of this second analysis confirm that infants' saccadic latencies to the + target did not differ as a function of the number of distractors or the location of the target. The lack of difference between infants' horizontal and vertical latencies – contrary to previous studies (Hainline *et al.*, 1984; Shea, 1992) – could be due to the timing of the stimulus presentation, the low number of trials, or some other aspect of the task. The exact cause, however, is not discernable from the current data.

Analysis of saccade latencies

A 2 × 4 ANOVA was performed on infants' saccade latencies across array type (target-present vs. target-absent) and set size (1, 3, 5 and 8). This analysis revealed a significant main effect of array type, $F(1, 440) = 63.04$, $p < .001$, indicating that across all set sizes, infants' saccades to a stimulus were faster to the target-present array ($M = 405.66$ ms) than to the target-absent array ($M = 538.54$ ms). The main effect of set size was also significant, $F(3, 440) = 7.11$, $p < .001$, suggesting that across array type, the latency of infants' saccades to a stimulus was different depending on the set size. Post-hoc directional *t*-tests comparing the mean saccade latencies in the different set size conditions (see Figure 2) revealed that infants' saccades were faster for a set size of 1 than with any of the larger set sizes (1 vs. 3: $t(218) = 2.16$, $p < .02$; 1 vs. 5: $t(220) = 3.04$, $p < .002$; 1 vs. 8: $t(219) = 3.97$, $p < .001$) and were faster for a set size of 3 than for a set size of 8 ($t(219) = 2.07$, $p < .02$).

The interaction of array type and set size was also significant, $F(3, 440) = 2.84$, $p < .05$, suggesting that the differences in saccade latencies as a function of set size differed between the target-present and target-absent arrays. To further explore this interaction, directional *t*-tests with Bonferroni adjustment of the alpha level were conducted to compare the mean saccade latencies in the different set size conditions within each array type and to compare the mean saccade latencies to the different array types within each set size condition. These analyses revealed that mean saccade latencies to target-present arrays did not significantly differ regardless of set size (see Figure 3). Analyses further revealed that latencies to target-absent arrays were significantly slower for a set size of 5 than for a set size of 1, $t(111) = 3.07$, $p < .002$,

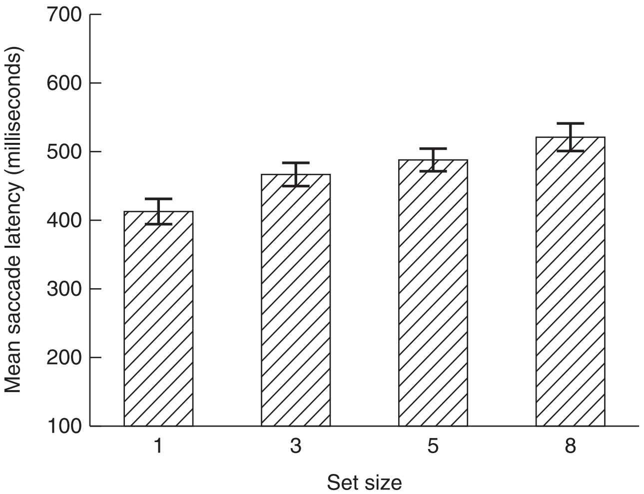

Figure 2 *Infants' mean saccade latencies in each set size condition pooled across array type (target-present and target-absent). Latencies increased with increasing set size. Vertical bars indicate +/– SE.*

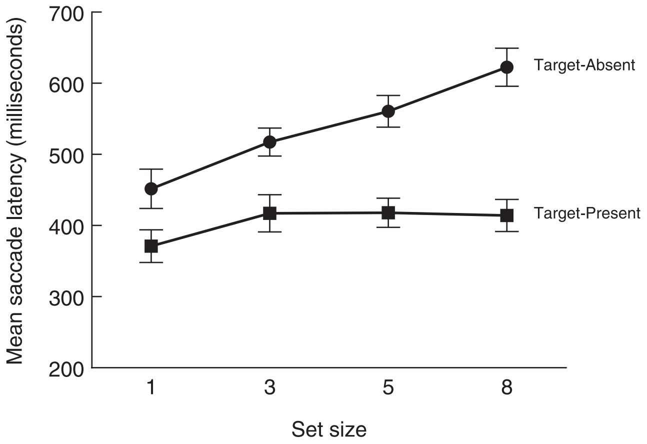

Figure 3 *Infants' mean saccade latencies in each set size × array type (target-present and target-absent) condition. Latencies to target-present arrays remained relatively unchanged as set size increased. Latencies to target-absent arrays increased as set size increased. Vertical bars indicate +/– SE.*

and slower for a set size of 8 than for either a set size of 3, $t(119) = 3.17$, $p < .001$, or a set size of 1, $t(113) = 4.44$, $p < .001$. Finally, the analyses showed that, except for a set size of 1, saccade latencies were longer to the target-absent arrays than the target-present arrays (set size of 3: $t(115) = 3.06$, $p < .002$; set size of 5: $t(114) = 4.71$, $p < .001$; set size of 8: $t(113) = 5.95$, $p < .001$).

The finding that the latencies to the + in the target-present arrays did not differ as a function of set size suggests that the + 'popped out' from amidst the distractors and that infants were engaged in an efficient search. In contrast, that latencies to target-absent arrays increased as a function of set size suggests that infants' search of the items in the array was inefficient because none popped out.

Relation of latencies to set size: An interpretation of pop-out has relied on finding that detection of the target is unaffected by the number of distractors. This is typically measured by a relatively flat RT slope in relation to set size indicating efficient processing and pop-out (e.g. Treisman & Gelade, 1980). Although the preceding analyses revealed no latency differences between the various set size conditions with the target-present arrays, suggesting that the target popped out and search was efficient, whereas there were some significant differences between set sizes with the target-absent arrays suggesting search was inefficient, the relation of saccade latencies to set size was not directly assessed. To this end, linear regression analyses were separately performed for the target-present and target-absent arrays.

The dependent variable in these analyses was the mean saccade latencies, and the independent variable was the set size. For target-present arrays, this analysis revealed a nonsignificant regression, $r^2 = 0.47$, indicating that saccade latencies did not increase with increasing set size. Further support is provided by the fact that the slope of the regression line was 5.2 ms per item, indicating a relatively flat slope (see Figure 4A). These results are consistent with findings with adults and support the interpretation that the + target popped out irrespective of the number of distractors and, therefore, the latency of infants' eye movements to the target were unaffected by set size.

For target-absent arrays, this analysis revealed a significant regression, $r^2 = 0.99$, $p < .01$, indicating that saccade latencies increased with increasing set size. The slope of the regression line was 23.9 ms per item, further indicating that saccade latencies increased with increasing set size (see Figure 4B). Thus, search with target-absent arrays was inefficient and did not result in pop-out. These target-absent results, however, conflict with previous studies of pop-out (Treisman & Gelade, 1980; Treisman & Souther, 1985; Wolfe, 1994) which predict that parallel search functions should be obtained even in target-absent conditions because all items should be processed in parallel regardless of whether the target is present or not. However, because items in the target-absent array are equally weighted (no pop-out feature or precue biasing), for the infant to select a goal for their eye movement, they must search the array and choose a target from among the competing items. Consequently, and consistent with findings of adults' eye movements to multiple item arrays (Adler *et al.*, 2002; Beintema, van Loon & van den Berg, 2005; Krauzlis, Zivotofsky & Miles, 1999), as the number of competing items in an array increases so too do saccade latencies. Such an eye movement decision mechanism would account for the current results and is supported by findings that saccade latency is a function of the number of distractors in the array (McSorley & Findlay, 2003; Motter & Belky, 1998).

Experiment 2: adults' eye movements and pop-out

The previous experiment demonstrated that the latency of infants' saccadic eye movements to stimulus arrays in which a unique + target was present among Ls were unaffected by the number of distractors, indicating that the + target popped out from among the distractors and search was efficient. In contrast, the latency of infants' eye movements to stimulus arrays in which the + target was absent increased with an increase in the number of

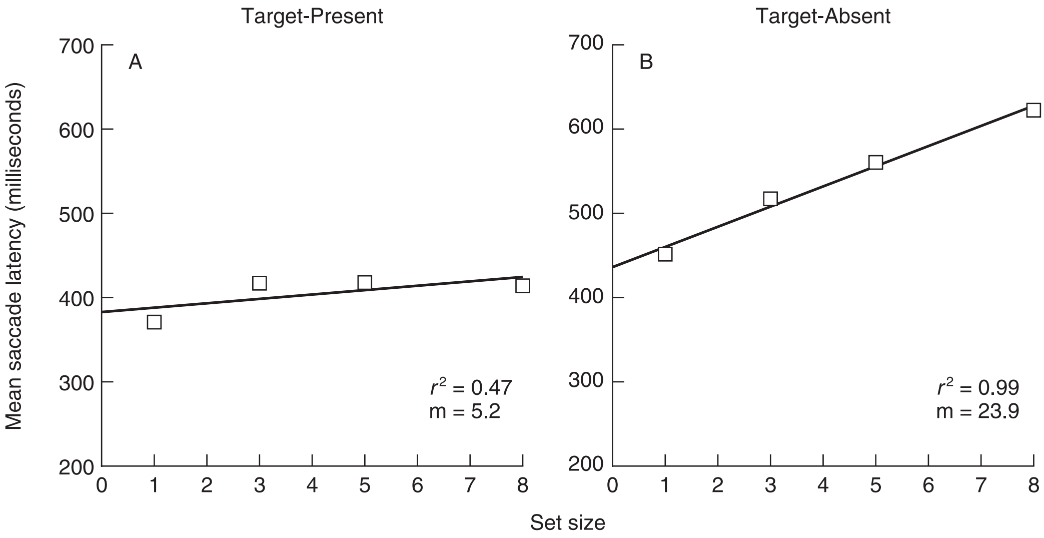

Figure 4 *Comparison of infants' mean saccade latencies and set size in Experiment 1. In the bottom right corner of each graph is the value of the regression score (r^2) and the slope of the regression line (m). A. Saccade latencies to target-present arrays plotted as a function of set size. B. Saccade latencies to target-absent arrays plotted as a function of set size.*

distractors, indicating that search was inefficient and requiring that significant attentional resources be allocated to the distractors. These findings are consistent with findings with adults, both simple detection studies (Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Sato, 1990) and eye movement studies (McSorley & Findlay, 2003; Motter & Belky, 1998), and suggest that the selective attentional processing mechanisms responsible for visual search are present early in development.

However, the manner in which pop-out was assessed with infants in the preceding experiment has no direct comparison experiment with adults. That is, measuring the latency of eye movements as a function of both set size and the presence versus the absence of a + target in arrays that are arranged in a circular pattern around a central fixation has not been explicitly investigated with adults. Consequently, though the results from the previous experiment are highly suggestive of pop-out, there are no adult data from a comparable paradigm with which to compare the infant data. Such comparison data are necessary for making more definitive statements about the capacity for pop-out early in development, but are also important for providing a framework for understanding the nature of these selective attention mechanisms in infancy and their developmental course.

In this experiment, therefore, evidence of pop-out in adults was obtained with the same paradigm as with infants, namely, by measuring their saccade latencies as a function of both set size and the presence versus the absence of a + target in arrays that are arranged in a circular pattern around a central fixation. Moreover, all of the timings and eccentricities of the stimuli were identical to those used with the infants.

Method

Participants

Five adult subjects (aged 22, 23, 26, 28 and 38 years) participated in this experiment. Only one had previous experience in eye-movement studies. All were naïve to the experimental conditions and hypotheses of this study. All subjects gave their informed consent before participating in this experiment. The subjects were Caucasian (*n* = 4) and Asian (*n* = 1), and were primarily from middle SES backgrounds.

Stimuli and apparatus

The stimuli and apparatus were the same as used in Experiment 1 with infants. The adult subjects sat in a high-back chair so that their heads were resting against the back of the chair for stability and they were situated 40 cm from the stimulus monitor, as were the infants in Experiment 1.

Procedure

The procedure was the same as with infants in the previous experiment, with two exceptions. First, the number of trials run was increased such that across all trials, for each set size, the adult was randomly presented with the target occurring six times in each of the four possible positions for 24 trials with each set size and a total of 96 target-present trials. To be consistent with target-present arrays, 24 trials of each set size were presented with the positions of the Ls randomized across these trials, for a total of 96 target-absent trials. Thus, each adult saw 192 trials of interleaved target-present and target-absent arrays. Second, adults were instructed before the experimental session began that stimuli would be presented on the screen in a circular pattern and they were to make an eye movement to one of those stimuli. Since the infants did not receive instructions and therefore could not be susceptible to this top-down attentional bias, in order to minimize top-down bias in the adults, the instructions did not include any information about different set sizes, target-present versus target-absent arrays, or that they should make an eye movement as quickly and accurately as possible. In this way it was hoped that performance would be comparable between the adults and infants, and direct comparisons could be made.

Data reduction and analysis

The raw digital data from the adults were recorded, reduced and analyzed in the same manner as with the infants. In order for an eye movement to be included in the final data sample, the adults' eye movements needed to meet the same criteria as the infants'. As a consequence of these criteria, the percentage of trials in each array type × set size condition that were usable ranged from 73.9 to 86.8%. Moreover, as with the infants, to increase the power of the statistical tests, latencies in each array type × set size condition were pooled across subjects (e.g. Adler *et al.*, 2002).

Results and discussion

Preliminary analyses

Accuracy: As with the infants, a one-way ANOVA was conducted on adults' saccadic eye movements to assess whether accuracy to the target in the target-present arrays remained consistent across set size. This analysis revealed that accuracy to make a saccade to the target did not differ, $F(2, 12) = 0.67$, *ns*, when the set size was 3, 5 or 8. Thus, increasing the number of distractors in the search array had no effect on the accuracy of adults' saccades to the + target. In fact, mean accuracy for each of these set sizes was well above 90% correct.

Target location: To make sure that there were no latency differences due to target location, a 4 × 4 ANOVA was performed on adults' saccadic latencies in the target-present conditions with set size (1, 3, 5 and 8) and target location (top, right, left and bottom) as within factors. This analysis revealed that the main effect of set size, $F(3, 350) = 3.11$, $p < .03$, was significant, indicating that the latency of adults' saccades to the + target in the target-present arrays did differ as function of the number of distractors – a finding that will be explored in more detail in subsequent analyses. The main effect of target location, $F(3, 350) = 1.27$, *ns*, was not significant, indicating that adults' saccade latencies did not differ as a function of the location of the target. In addition, the interaction of set size and target location was not significant.

Analysis of saccade latencies

A 2 × 4 ANOVA was performed on adults' saccade latencies across array type (target-present vs. target-absent) and set size (1, 3, 5 and 8). This analysis revealed a significant main effect of array type, $F(1, 734) = 117.64$, $p < .0001$, indicating that across all set sizes, adults' saccades to a stimulus were faster to the target-present array ($M = 303.67$ ms) than to the target-absent array ($M = 448.96$ ms). The main effect of set size was also significant, $F(3, 734) = 17.03$, $p < .0001$, suggesting that across array type, the saccade latencies to a stimulus differed as a function of set size. Post-hoc directional *t*-tests comparing the mean saccade latencies in the different set size conditions revealed that, as with infants, adults' saccades were faster for a set size of 1 than with any of the larger set sizes (1 vs. 3: $t(349) = 4.28$, $p < .0001$; 1 vs. 5: $t(369) = 5.44$, $p < .0001$; 1 vs. 8: $t(370) = 6.29$, $p < .0001$) and were faster for a set size of 3 than for a set size of 8 ($t(361) = 1.97$, $p = .05$). Selecting and making a saccadic eye movement to a single item as compared to an array with multiple items is a consistent finding in the eye movement and target selection literature (Adler *et al.*, 2002).

The interaction of array type and set size was also significant, $F(3, 734) = 4.45$, $p < .005$, suggesting that the differences in saccade latencies as a function of set size differed between the target-present and target-absent arrays. To further explore this interaction, directional *t*-tests with Bonferroni adjustment of the alpha level were conducted to compare the mean saccade latencies in the different set size conditions within each array type and to compare the mean saccade latencies to the different array types within each set size condition. These analyses revealed that, except for a set size of 1 having a faster mean latency than a set size of 5 ($t(163) = 2.94$, $p < .002$), mean saccade latencies to target-present arrays did not significantly differ as a function of set size (see

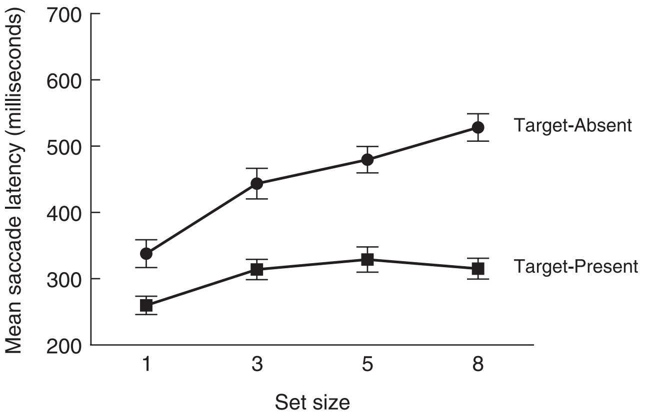

Figure 5 *Adults' mean saccade latencies in each set size × array type (target-present and target-absent) condition. Latencies to target-present arrays remained relatively unchanged as set size increased. Latencies to target-absent arrays increased as set size increased. Vertical bars indicate +/– SE.*

Figure 5). This suggests that the significant main effect of set size found in the preliminary analysis of target location was due to the difference between set sizes of 1 and 5, rather than systematic differences between all set sizes. Analyses further revealed that latencies to target-absent arrays were significantly faster for a set size of 1 than for a set size of 3 ($t(171) = 3.75$, $p < .0002$), 5 ($t(191) = 4.68$, $p < .0001$) and 8 ($t(190) = 6.47$, $p < .0001$). None of the other set size comparisons of adults' saccade latencies to target-absent arrays reached significance as set by the Bonferroni adjustment. Finally, the analyses showed that for each set size, saccade latencies were longer to the target-absent arrays than to the target-present arrays (set size of 1: $t(163) = 3.11$, $p < .002$; set size of 3: $t(144) = 5.09$, $p < .0001$; set size of 5: $t(186) = 5.24$, $p < .0001$; set size of 8: $t(178) = 8.21$, $p < .0001$).

The finding that the latencies to the + in the target-present arrays did not generally differ as a function of set size suggests that the + 'popped out' from amidst the distractors and that search was efficient. In contrast, in the target-absent arrays, latencies showed some increases for some set sizes suggesting that search was inefficient.

Relation of latencies to set size: Again, although the preceding analyses revealed no latency differences between the various set size conditions with the target-present arrays suggesting that the target popped out, whereas there were some significant differences between set sizes with the target-absent arrays suggesting search was inefficient, the relation of saccade latencies to set size was not directly assessed. Since a relatively flat RT slope in relation to set size is indicative of efficient search and pop out (e.g. Treisman & Gelade, 1980) and a positive slope is indicative of an inefficient search, linear regression analyses were again separately performed for the target-present and target-absent arrays.

The dependent variable in these analyses was the mean saccade latencies, and the independent variable was the set size. For target-present arrays, the regression analysis revealed a nonsignificant relationship, $r^2 = 0.49$, indicating that saccade latencies did not increase with increasing set size. Further support is provided by the fact that the slope of the regression line was 7.2 ms per item, indicating a relatively flat slope (see Figure 6A). This result supports the interpretation that the target popped out irrespective of the number of distractors and, therefore, the latency of adults' eye movements to the target was unaffected by set size.

For target-absent arrays, this analysis revealed a significant regression, $r^2 = 0.90$, $p < .05$, indicating that saccade latencies increased with increasing set size. The slope of the regression line was 25.7 ms per item, further indicating that saccade latencies increased with increasing set size (see Figure 6B). This result is consistent with the idea that when the target is absent there is no pop-out and, consequently, in order for the adult to select a goal for their eye movement, they inefficiently search the array and choose a target from among the competing items. Consequently, because items in the target-absent array are equally weighted (no pop-out feature or precue biasing), and consistent with previous findings of adults' eye movements to multiple item arrays (Adler *et al.*, 2002; Beintema *et al.*, 2005; Krauzlis *et al.*, 1999), as the number of competing items in an array increases so too do saccade latencies.

Relation of infants' latencies to adults' latencies: The results from this experiment and Experiment 1 indicate similar performance in terms of saccade latencies for infants and adults to the target-present and target-absent arrays as function of set size. For both infants and adults, mean saccade latencies to target-present arrays were unaffected by the set size and mean saccade latencies to target-absent arrays increased with increasing set size. This would seem to suggest that infants' attentive processing, search mechanisms and target selection for saccades are similar to adults'. Additional support for this position was provided by the slopes of the regression line that were very similar for infants and adults with both target-present arrays (5.2 vs. 7.2) and target-absent arrays (23.9 vs. 25.7). However, the latency results and the slopes of the regression lines are similar but not identical between infants and adults, suggesting that there is a developmental difference in the mechanisms supporting eye movement performance to visual search arrays.

To determine the nature of the developmental difference, infants' performance was compared to adults' for target-present arrays and for target-absent arrays by

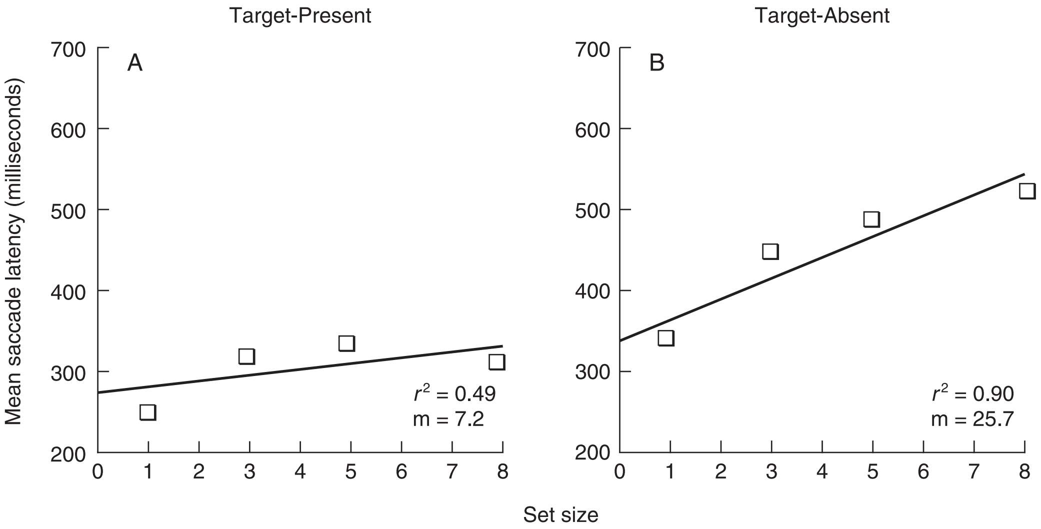

Figure 6 *Comparison of adults' mean saccade latencies and set size in Experiment 2. In the bottom right corner of each graph is the value of the regression score* (r^2) *and the slope of the regression line (m). A. Saccade latencies to target-present arrays plotted as a function of set size. B. Saccade latencies to target-absent arrays plotted as a function of set size.*

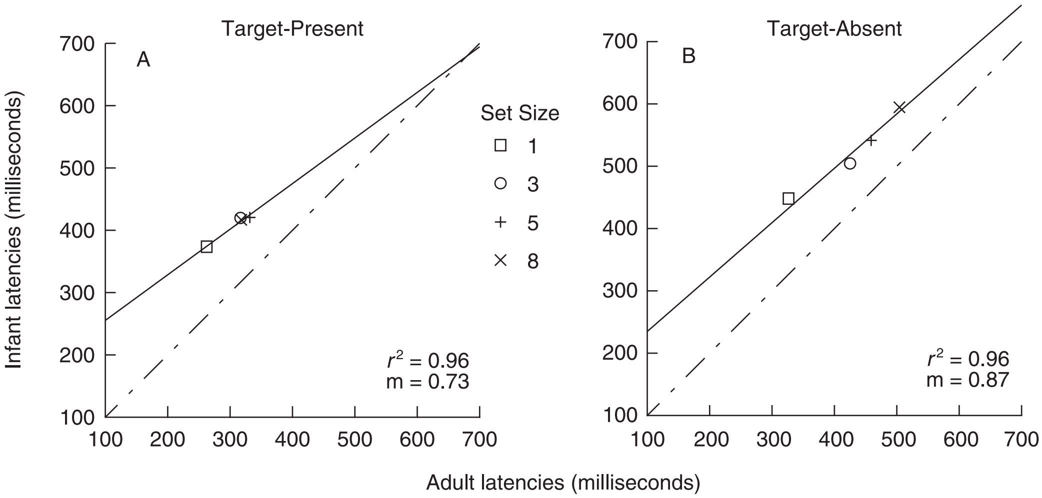

Figure 7 *Comparison of adults' mean saccade latencies and infants' mean saccade latencies. Each data point represents the mean latencies in one of the particular set size conditions, with each symbol indicating the set sizes of 1, 3, 5 and 8. In the bottom right corner of each graph is the value of the regression score* (r^2) *and the slope of the regression line (m). The dotted and dashed lines represent slopes of 1.00 and a theoretical perfect correlation between infants' and adults' performance. A. Infants' saccade latencies to target-present arrays plotted as a function of adults' saccade latencies to target-present arrays. B. Infants' saccade latencies to target-absent arrays plotted as a function of adults' saccade latencies to target-absent arrays.*

conducting regression analyses in which the independent variable was adults' latencies and the dependent variable was infants' latencies. For target-present arrays (see Figure 7A), a regression analysis revealed a significant relationship, $r^2 = 0.96$, $p < .02$, indicating that the pattern of latencies as a function of set size was similar for infants and adults. The slope of the regression line (m = 0.73), however, indicates that the infants' latencies were 27% slower than adults'. For target-absent arrays (see Figure 7B), a regression analysis revealed a significant relationship, $r^2 = 0.96$, $p < .02$, indicating that the pattern of latencies as a function of set size was again similar for infants and adults. The slope of the regression line (m = 0.87), however, indicates that infants' latencies were 17% slower than adults'. These findings indicate that infants exhibited a similar pattern of saccade latencies as a function of set size to target-present and target-absent arrays as did adults. However, these analyses also revealed for both array types across set sizes infants' saccades were consistently slower than adults', suggesting a developmental change in the mechanisms for initiating an eye movement in the visual search task. Sources for this developmental change are not addressed by the current data but the most obvious possibility is the maturation of eye movement generation mechanisms.

Discussion

Previous research with infants has suggested that they exhibit pop-out as early as 3 months of age. These studies, however, have used paradigms that leave open the interpretation of the mechanism responsible for the apparent pop-out. Paradigms such as preferential-looking and the mobile-conjugate reinforcement paradigm, because they assess performance over a span of seconds and minutes, allow the possibility that infants' performance was mediated by the allocation of attentional resources in an inefficient search and even higher-order processes such as memory, rather than mechanisms reflecting efficient search. Furthermore, none of these previous studies have examined a fundamental characteristic of pop-out, namely, that the search function is unaffected by the number of distractors (cf. Rovee-Collier *et al.*, 1996). The current study was undertaken to determine whether infants would exhibit pop-out on the millisecond scale and to determine whether their performance to detect a target among distractors would be unaffected by set size, as occurs in adults.

The findings of the present study are straightforward – infants exhibited pop-out of the + target from admist L distractors. This was evidenced with saccade latencies that were in milliseconds, the same time scale as pop-out is found with adults, rather than minutes or seconds as has been measured in previous studies of pop-out in infancy. Furthermore, for the first time in any infant study of pop-out, infants' response latencies to the pop-out target were shown to be unaffected by the number of distractors in the array, a classic finding in pop-out studies with adults and a critical demonstration necessary for interpreting that the apparent pop-out in infants reflected efficient search mechanisms. In contrast, when the target was absent there was no pop-out and infants' latencies increased with increasing set size, presumably due to attention-demanding inefficient search processes and target selection mechanisms necessary for choosing a goal for the eye movement. Finally, infants' pattern of saccade latencies to target-present and target-absent arrays as a function of set size was found to be nearly identical to adults' pattern, providing further support for infants' performance being due to 'pop-out' and efficient search mechanisms when the target was present.

Development of eye movements and pop-out

One discrepancy between infants' and adults' performance was that infants' initiation of saccades was consistently slower than adults'. Because the quantitative difference between infants and adults was relatively constant across all conditions, ranging from 73.81 to 113.77 msec (M = 95.61, SD = 14.03), the most likely mechanism responsible for this difference is the development in the speed of initiating a saccade. Previous research with adults has indicated that they will initiate a saccade to a single target that appears in their visual field within approximately 200 msec (Becker, 1989; Fischer & Weber, 1993). Considering the close linkage between eye movements and visual attention (Adler *et al.*, 2002; Crawford & Müller, 1992; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Jonides, 1981; Klein, 1980; Kowler *et al.*, 1995), the latency for initiating a saccade can be lowered or raised by manipulations of many different stimulus factors, all of which affect the allocation of attention (see Fischer & Weber, 1993). Perhaps infants' slower saccade initiation is due to development in the linkage between their attentional and eye movement mechanisms and circuitry.

Infants' slower saccade initiation being a consequence of development in the linkage of attentional and eye movement mechanisms seems unlikely, however. One particular effect of the attention–eye movement relation is that the base rate for initiating a saccade will increase due to competition for attentional selection induced by additional stimuli in the visual field (Adler *et al.*, 2002; Krauzlis *et al.*, 1999; Posner, 1980). Competition provides a good account for the nearly significant increase of 54.13 msec in adults' latencies to target-present arrays when the set size was increased from one to three items, whereas increasing the set size further incurred no real latency cost. Interestingly, even though infants' latencies to target-present arrays were slower than adults, increasing the set size from one to three items produced an almost identical 46.16 msec increase in their latencies. This suggests, therefore, that the attentional mechanisms responsible for the increase in saccade latencies due to competition for selection are functionally similar in infants as in adults and are not responsible for infants' overall slower latencies in this study. Furthermore, the similar effect of competition suggests that the tight linkage of attentional and eye movement mechanisms found in adults may be in place by early infancy.

The most likely candidate responsible for the slower infant latencies, therefore, must be the hardware and circuitry of the visual system that control the eye movements themselves, including incomplete myelination of the sensory and motor pathways. In terms of the visual system, research has demonstrated that the neural circuitry responsible for sending information from the eyes to the cortex (e.g. Hood & Atkinson, 1990) and for the signal to the eyes to make a movement is immature (Johnson, 1995). As a result, the transfer of information specifying the visual target to the cortical systems responsible for eye movement control and the signal to the eye to initiate a movement will likely be slowed. In addition, the hardware that supports eye movements has been shown to be immature in early infancy (Shea, 1992). Consequently, infants cannot generate the same torque and excitation necessary to initiate the eye movement, resulting in slower and more inaccurate eye movements. Together, if the information specifying the target is slowed getting to the eye movement control areas in the cortex, the signal to initiate an eye movement is slowed in reaching the eyes and their muscles, and it takes time to build up the excitation and torque to start the eye movement, then the latency to initiate the eye movement will be slowed relative to a system with mature circuitry and hardware.

Developmental neuroscience of pop-out

Johnson (1990, 1995) has proposed a theory of neural development, particularly as it relates to visual attention, in which attentional processing and behavior in the first few months of life is primarily controlled by the subcortical superior colliculus pathways but around 3 months of age the cortical pathway through the frontal eye fields (FEF) comes online. Not only is FEF implicated in saccadic eye movement initiation (Schall & Hanes, 1993; Schall, Hanes, Thompson & King, 1995), but also single-unit recordings in monkeys' brains and fMRI studies have established that neurons in FEF will show activity during presentation of a pop-out search array that discriminates the pop-out target from the distractors even in the absence of eye movements (Thompson, Bichot & Schall, 1997). The frontal eye fields also receive projections from the visual cortex, including V1, which have been consistently shown to process the primitive perceptual units (Deco *et al.*, 2002; Lee, 2003), such as those hypothesized to be processed by the early perceptual mechanism. Taken together, the neural apparatus to support saccadic eye movements, attentional processing and pop-out would seem to be available by 3 months of age, which is consistent with the present eye movement findings of pop-out. In the future, using the current visual search task with younger infants may be a means of establishing more concretely the time course in the neural development of these brain areas.

Conclusion

At the outset, the present study had two goals: to determine whether infants would exhibit pop-out on the millisecond scale and to determine whether their performance to detect a target among distractors would be unaffected by set size. On both counts, positive results were obtained. First, 3-month-old infants exhibited pop-out on a millisecond scale, rather than on a minute or second scale as in previous infant studies. Second, infants' saccade latencies to a target stimulus were unaffected by the number of distractors, an indication of efficient search. Moreover, it was shown that infants' pattern of latencies to target-present and target-absent arrays was identical to adults'. Together, these findings indicate that infants have functioning visual search mechanisms that are at least similar if not the same as adults'.

This study also establishes the measuring of eye movements as a comparable means to examine visual search, pop-out and the underlying attentional mechanisms in infants and through development. With this study as a foundation, future studies using eye movements will be able to examine the development in the mechanisms responsible for feature versus conjunction searches, the differential sensitivity to primitive perceptual features at different ages, top-down effects on visual search the different theoretical models proposed to account for visual search behavior, just to name a few. Together, these studies will give us a better picture of the development of attentional mechanisms, which are so crucial for efficient cognitive functioning, and how they are related to adults' attentional mechanisms, both behaviorally and neurally.

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