Available online at www.sciencedirect.com
SCIENCE DIRECT®

J. Experimental Child Psychology 89 (2004) 72–90

Journal of Experimental Child Psychology

www.elsevier.com/locate/jecp

Selective search for conjunctively defined targets by children and young adults

Edward C. Merrill[a,*] and Regan Lookadoo[b]

[a] *Department of Psychology, University of Alabama, Tuscaloosa, AL 35487-0348, USA*
[b] *Department of Psychology, Georgetown College, Georgetown, KY 40324, USA*

Received 9 December 2003; revised 5 April 2004
Available online 28 May 2004

Abstract

Two experiments were conducted to investigate age-related differences in visual search for targets defined by the conjunction of two features. In the experiments, 7- and 10-year-old children and young adults searched visual displays for a black circle among distractors consisting of gray circles and black squares. In Experiment 1 ($N = 60$), we compared performance in the standard search task (where an equal number of each type of distractor appeared across all display sizes) with performance in a modified search task (where the number of black squares was fixed at two and the number of gray circles increased as the display size increased). In Experiment 2 ($N = 60$), the ratio of black stimuli to gray stimuli was varied systematically as the display size increased. Results of both experiments indicated that all participants were able to restrict search to an appropriate subset of the display rather than conduct an exhaustive search. However, the young adults were more efficient in their ability to do so than were either the 7- or 10-year-old participants. The 10-year-olds were as efficient as the young adults when the number of black stimuli in the display was relatively small. However, these children became relatively less able to restrict search effectively as the number of black stimuli increased. Discussion focused on possible preattentive and attentive processes that may change systematically with age.

Keywords: Visual search; Guided search; Conjunctive search

* Corresponding author. Fax: 1-205-348-7520.
E-mail address: emerrill@gp.as.ua.edu (E.C. Merrill).

0022-0965/$ - see front matter
doi:10.1016/j.jecp.2004.04.001

Introduction

Effective visual functioning often involves searching through the environment for a desired target and selecting that target from among other distracting items for additional processing. Laboratory experiments of visual search have indicated that the efficiency of search can be influenced by several factors. For example, search efficiency depends on the similarity between the target and distractors such that searches tend to be more efficient when the target is less similar to the distractors (e.g., Duncan & Humphreys, 1989). In addition, search efficiency depends on the goal of the search; for example, searching for the presence of a feature usually is more efficient than searching for the absence of a feature (e.g., Treisman & Gormican, 1988; Treisman & Souther, 1985). Also, researchers have recently reported that visual search efficiency is related to age. Young adults are highly proficient at visual search and selection. However, it appears that the efficiency of visual search undergoes a relatively long developmental progression (Brodeur, Trick, & Enns, 1997), and the efficiency of search reverts to a less efficient form for older adults relative to younger adults (e.g., Madden, 1990; Madden, Gottlob, & Allen, 1999; Scialfa, 1990).

Visual information processing in the form of visual scanning and visual search has long been studied as a means to evaluate cognitive changes that occur with development (see, e.g., Day, 1975). Indeed, two of the general factors identified in the previous paragraph as influencing the visual search performance of young adults are associated with general cognitive skills that become more efficient with increased age through young adulthood. For example, the perceived similarity between the target and the distractors is likely to be related to perceptual processing differences observed across developmental levels (e.g., Aslin & Smith, 1988; Goldstone, 1998; Smith, 1989; Smith & Evans, 1989). The perceptual processing advantage of adults relative to children may also be due, at least in part, to differences in perceptual learning, a skill that also improves with experience and developmental level (Goldstone, 1998). In addition, the ability to select, effectively use, and monitor task-specific, goal-directed strategies influences visual search performance and varies with developmental level (e.g., Day, 1978; Enns & Aktar, 1989; Miller, Haynes, & Weiss, 1985; Pick, Christy, & Frankel, 1972). Hence, performance differences in visual search may also reflect general age-related differences in executive functions (e.g., Borkowski & Burke, 1996; Denkla, 1996).

A typical experimental study of visual search consists of having participants search an array of stimuli for a target designated by the experimenter. The number of items in the array is varied such that there are relatively few or relatively many nontarget stimuli in the array. In addition, it is possible to vary the features that distinguish the target from the nontarget stimuli in the array. Search rate is measured in terms of the slope of the function that relates response times to the number of nontargets in the visual array. In a feature search, the target has a single feature that distinguishes it from all nontargets (e.g., the target is a circle and the nontargets are squares). Most feature searches are assumed to occur preattentively and in parallel (e.g., Treisman & Gelade, 1980) because the number of nontargets in the array does not influence the time it takes to locate the target. In a typical conjunctive search, the target is defined by two features (e.g., black and a circle) and is presented with two types of distracting nontargets. Each nontarget shares one of the defining features of the target (e.g., a black square and a gray circle). The conjunctive search requires attentional guidance across several display stimuli to be completed; hence, response times increase as the number of nontargets in the visual array increases (Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989). Age-related differences in search rate are typically observed when participants perform a conjunctive search, but these differences are less common when participants perform a feature search (Trick & Enns, 1998).

Trick and Enns (1998) conducted a series of studies to investigate the locus of age-related differences in the conjunctive search task. Based on their results, they concluded that two aspects of search were more efficient for young adults relative to children. First, children were more susceptible to general interference from distracting nontargets than were adults; that is, the presence of even a single nontarget interfered with the performance of children more than it did with that of adults. Second, children were slower than young adults at moving attention from one item to the next (i.e., a slower search rate) during the search; that is, children exhibited much steeper slopes for the response time function associated with number of items in the display than did young adults.

The purpose of this study was to examine an alternative, but not mutually exclusive, explanation for the age-related decrease in search rate between children and young adults that was observed by Trick and Enns (1998) based on the guided search model (Wolfe, 1994; Wolfe et al., 1989). According to this model, it is possible for participants to limit their search for the target to a subset of items in the visual array. This is accomplished through a combination of preattentive and attentive processes across several phases of search (Wolfe, 1994). First, preattentive processes construct feature maps in parallel that separate items in the displays on the basis of individual features. The feature maps reflect activation levels that are based on local differences between an item in the display and surrounding items as well as broadly defined task goals. Second, these levels of activation based on independent feature differences are combined to form a single general activation map. During search, attentive processes are used to search the activation map serially, beginning with the item with the highest level of activation, proceeding to the next highest level, and so on until a target is found or the search is terminated because activation has fallen below some basic threshold (e.g., Chun & Wolfe, 1996). Assuming that young adults typically perform some sort of selective search through the visual array, it is possible that a portion of the differences in search rate between adults and children reflects the fact that children are less efficient in restricting their search to an appropriate small subset of the array and, as a result, typically search more items in the array than do young adults. With respect to the search task used by Trick and Enns (1998), where displays contained the same number of each distractor type, less efficient search would result in children searching on average more than half of the items in the display, whereas adults restrict search to half of the items. A difference in the ability to exhibit an efficient selective search would be observed as steeper slopes associated with display size for the younger children such as those reported by Trick and Enns (1998).

Taylor, Shakeela, and Malone (1999) reported evidence that is consistent with the possibility that children and young adults differ in their ability to efficiently use processes that are necessary for selective search. These authors recorded event-related potentials (ERPs) in children between 7 and 12 years of age while they were performing either feature searches or conjunctive search. The target was defined by color for one feature search, and the target was defined by size for the other feature search. The target was defined by both color and size for the conjunctive search. Results indicated that there was an asymmetry in the P3 latency associated with the two stimulus features in that color yielded faster latencies than did size. Furthermore, the authors observed slower age-related changes associated with the feature of size than with the feature of color; that is, children's performance improved with color at a faster rate than it did with size. Because selective search is typically guided by the salience of stimulus features (which can be determined by top-down or bottom-up processing), it is reasonable to suggest that age-related differences associated with the salience of various features as observed by Taylor and colleagues may result in large differences in selective search between children and adults.

The primary purpose of the experiments reported in this article was to evaluate possible age-related differences in the efficiency of restricting search to an appropriate subset of the stimulus display during visual search. In Experiment 1, we evaluated the performance of children and young adults under conditions where the difference in the number of distractors of each type was relatively large and selective search would be likely to be observed for all groups. In Experiment 2, we systematically manipulated the relative number of distractors of each type to provide a more fine-grained analysis of performance differences among groups.

Experiment 1

Experiment 1 was designed to evaluate age-related differences in response times in a conjunctive search task to determine whether children and young adults differ in their ability to limit search through small subsets of stimuli in the display. Our procedure was based on Egeth, Vizri, and Garbart (1984). In their variation of the standard conjunctive search task, participants were also presented displays consisting of a conjunctive target and two types of distractors (e.g., a red O in a field of black Os and red Ns). However, the number of one type of distractor was held constant at a small number, whereas the number of the other type of distractor was allowed to vary. Hence, the number of distractors of each type was not completely confounded as in the standard version of the search task (Egeth et al., 1984). The value of this manipulation is that it is possible to determine whether the participants were able to limit their search to the smaller subset rather than search the entire display. If participants were searching only the small constant-size subset of distractors, response times should not increase as the number of other distractors increased. Egeth and colleagues found this to be the case for young adults in their experiment. In our Experiment 1, second-grade children, fifth-grade children, and young adults participated in the standard version of the search task and a version adapted from Egeth and colleagues. Participants searched for a black circle in a display consisting of black squares and gray circles. In the standard search task, the number of each type of distractor increased by the same amount as display size increased. In the adapted version of the search task, the number of black squares was held constant and the number of gray circles increased as display size increased. If slope values of the functions relating response time to the total number of distractors in the array are smaller in the adapted version of the search task than in the standard version of the task, we can conclude that participants are limiting search to relatively fewer stimuli in the adapted version relative to the standard version of the search task. This would be consistent with the guided search model (Wolfe, 1994; Wolfe et al., 1989). Age-related differences in the efficiency of selective search would be evidenced by age-related differences in the degree to which slope values in the adapted search task approach zero.

Method

Participants

Participants were 20 second-grade children (11 females and 9 males, mean age = 7.5 years, $SD = 0.5$), 20 fifth-grade children (10 females and 10 males, mean age = 10.3 years, $SD = 0.4$), and 20 college-age young adults (15 females and 5 males, mean age = 18.5 years, $SD = 0.9$). Children were recruited from classes in the local public schools and received a \$5 gift certificate for participating. Young adults were recruited from introductory psychology classes at the University of Alabama. Adult participants received course credit for participating.

Apparatus and materials

Stimulus displays were presented on a Dell Inspiron 3500 computer using the experimental laboratory program software *Superlab* (Cedrus). The *Superlab* program recorded response time and response accuracy. A response box with two response keys—a designated target-present key and a designated target-absent key—was used to record participants' manual responses. A continuous performance procedure was used to present the stimuli during the experiment.

In both the standard and adapted versions of the search task, the target was defined by a conjunction of the features black and circle. The distractors were black squares and gray circles. Half of the displays included a target and half did not. In the adapted version, there were always three black stimuli presented in each display: one black circle and two black squares when the display included a target and three black squares when the display did not include a target. There were 2, 12, and 22 gray circles for the 5-, 15-, and 25-stimuli displays, respectively. In the standard version, there was an equal number of each distractor type in the displays that included a target (2, 7, and 12 for the 5-, 15-, and 25-stimuli displays, respectively). When there was not a target in the display, the black circle was replaced with a black square. The displays were presented within a white 10×10-cm square area in the center of the computer screen. Individual items in the display were approximately 0.75 cm in height and width, with no two stimuli in the display being any closer together than 0.75 cm.

Participants were seated approximately 50–60 cm from the computer screen. Hence, each stimulus display fell within approximately 9.0° of visual angle (4.5° from central fixation in all four directions), and each stimulus subtended approximately 0.7° of visual angle. The particular location of stimuli in the standard task displays was essentially random with the restriction of distance between stimuli. The location of the targets and distractors was identical across the two versions of the task, with the adapted task displays being constructed from the standard displays by randomly replacing all but two black squares with gray circles.

Design and procedure

The variables in the experiment were grade (second grade, fifth grade, and college), task (standard and adapted), display size (5, 15, and 25 stimuli), and response type (target present and target absent). Grade was a between-participants variable, whereas task, display size, and response type were within-participant variables. The primary dependent measure was response time for identifying whether a target was present in each display. Response times were recorded automatically to the nearest millisecond. Displays were presented in random order for each participant.

Each participant was tested individually. At the beginning of the experimental session, participants received 20 practice trials to familiarize them with the experimental procedure. They were instructed to search each display for a black circle and to press the left response button if a target was present, and to press the right response button if no target was present, as rapidly as possible without making errors. Practice was followed by the experimental trials. All participants received both tasks. The standard and adapted tasks were presented in blocks such that each participant received one third of the trials for one task followed by one third of the trials for the other task. This was repeated three times until all trials were presented. Half of the participants in each group received the standard task first, and half received the adapted task first. Participants received 15 trials in each condition formed by the combination of the task, display size, and response type variables for a total of 180 experimental trials. The entire session took approximately 20–25 min to complete. Participants were given the opportunity to take a break during the session if they so desired.

Results

Median response times were calculated for each participant in each condition. The means of these response times are presented in Table 1. Errors were infrequent (3.6, 2.0, and 2.1% for second grade, fifth grade, and college, respectively) and were not analyzed further. Response times were converted to slope values relating response times to the number of items in the stimulus arrays. These values are reported in Table 2. Slope values for the target-present and target-absent conditions were analyzed separately. Separate analyses were conducted for two reasons. First, all primary predictions were based on trials in which a target was located. Second, we expected that performance on the target-absent trials would be more influenced by several extraneous variables (e.g., response bias, decision criterion) that may vary both within and across groups, adding nonsystematic variability to the basic results.

Table 1
Mean response times for Experiment 1 as a function of age, task, and response type

	Standard task display size			Adapted task display size		
	5	15	25	5	15	25
	Target present					
Grade						
Second	812 (80)	1061 (185)	1197 (166)	821 (107)	889 (99)	912 (118)
Fifth	717 (120)	884 (114)	989 (210)	714 (141)	738 (116)	755 (95)
College	504 (123)	620 (142)	671 (147)	527 (107)	549 (95)	564 (94)
	Target absent					
Grade						
Second	960 (123)	1148 (198)	1341 (215)	942 (114)	907 (134)	898 (141)
Fifth	780 (113)	947 (181)	1132 (191)	733 (101)	692 (93)	709 (134)
College	544 (121)	636 (136)	886 (210)	533 (116)	517 (104)	630 (106)

Note. Standard deviations are in parentheses.

Table 2
Mean slope values for Experiment 1 as a function of age, task, and response type

	Standard task	Adapted task
	Target present	
Grade		
Second	19.4 (8.9)	4.6 (4.3)
Fifth	13.6 (10.2)	2.1 (3.7)
College	8.4 (4.4)	1.9 (2.9)
	Target absent	
Grade		
Second	19.1 (8.9)	−2.2 (6.0)
Fifth	17.5 (10.5)	−1.3 (4.2)
College	17.0 (13.1)	1.5 (6.0)

Note. Standard deviations are in parentheses.

Indeed, a quick inspection of the data confirmed our concerns in that we obtained negative slope values for two groups in the target-absent condition of the adapted task (Table 2).

A 3 (Grade) × 2 (Task) analysis of variance (ANOVA) was conducted on the slope values for the target-present condition, with task being treated as a within-participants variable. The analysis revealed a significant main effect of grade, $F(2,57) = 12.64$, $p < .01$, and a main effect of task, $F(1,57) = 88.79$, $p < .01$. The main effect of grade indicated that the second-grade participants exhibited steeper slopes than did the fifth-grade participants, who in turn exhibited steeper slopes than did the college participants (all means significantly different at the .05 level using Tukey's HSD). The main effect of task indicated that significantly steeper slopes were obtained in the standard task than in the adapted task. However, both main effects were qualified by the significant Grade × Task interaction, $F(2,57) = 4.29$, $p < .05$. The interaction was evaluated by analyzing the effect of grade for the standard and adapted tasks separately. For the standard task, the analysis indicated a significant main effect of grade, $F(2, 57) = 9.35$, $p < .01$. The second-grade participants exhibited a significantly steeper slope than did the other two groups, and the fifth-grade participants exhibited a significantly steeper slope than did the college participants (all ps $< .05$). For the adapted task, the analysis also indicated a significant main effect of grade, $F(2, 57) = 3.47$, $p < .05$. The second-grade participants exhibited a significantly steeper slope than did the two older groups, with the fifth-grade and college students not differing significantly from each other. Simple effects tests also indicated that slope values were smaller in the adapted task than in the standard task for each group (second-grade participants: $F(1, 19) = 39.74$, $p < .01$; fifth-grade participants: $F(1, 19) = 25.07$, $p < .01$; college participants: $F(1, 19) = 31.42$, $p < .01$). Supplemental analyses revealed that the slope values of the adapted task were greater than 0 for all three groups (second-grade participants: $t(19) = 4.84$; fifth-grade participants: $t(19) = 2.53$; college participants: $t(19) = 4.45$; all ps $< .05$). Hence, search rate was influenced by overall display size for all groups.

A 3 (Grade) $\times$ 2 (Task) ANOVA was also conducted on the slope values for the target-absent condition. This analysis indicated a main effect of task, $F(1, 57) = 143.90, p < .01$, with slopes in the standard task being significantly steeper than those in the adapted task. Neither the main effect of grade nor the Grade $\times$ Task interaction was significant. Nevertheless, one unusual result was observed and warrants discussion. Slope values of the second- and fifth-grade participants were actually negative in the adapted search condition, indicating that response times were longer for the smaller search displays than for the larger search displays. We believe that this result indicates a strategic difference in the way in which the children searched displays with and without targets. In displays that contain a target, a correct decision can be made as soon as a target is detected. In displays that do not contain a target, not locating a target can mean that the display did not contain a target or that the target was missed. It would be reasonable to recheck the display to be certain that a target was not present, especially when the display is relatively small and will not sacrifice much in the way of speed. If young children chose to recheck smaller target-present displays, a negative slope for the adapted target-absent condition might result.

Discussion

Two primary results are relevant to whether age-related differences in conjunctive search can be attributed to corresponding differences in the ability to limit search to a suitable subset of the stimulus array. First, the analysis of the standard task revealed the typical steeper slopes indicating a slower search rate for the younger participants than for the older participants. The ratio of the difference among adults, older children, and younger children was essentially identical to what has been reported elsewhere (Trick & Enns, 1998). Second, we observed a significant reduction in slope values in the adapted task for all ages of participants. In fact, the two older groups exhibited slopes values of less than 2 ms, and the youngest group exhibited a slope value of less than 5 ms. These slope values were 5–10 times less than what was observed in the standard task. Hence, we concluded that all of the groups were able to restrict their search to some subset of the stimulus array and not search the entire display during conjunctive search. However, it appears that none of the groups was able to restrict search to the same-size subset in the larger displays as it was able to for the smaller displays because the slope values were greater than zero for all groups. In addition, the slope values obtained for the second-grade participants were still significantly steeper than those obtained for the fifth-grade and college students. Therefore, we tentatively concluded that the efficiency with which individuals were able to restrict search on the basis of stimulus features increased with age.

An alternative conclusion is also possible. It might be that all groups were equally efficient at selecting the same number of stimuli to search in both tasks but that the younger participants searched the subset more slowly than did the older participants. However, two additional features of our data are not consistent with this alternative conclusion. First, we did not find group differences associated with the target-absent conditions. In fact, the slope values of the two older groups were as large as that of the younger group in the target-absent standard task. It seems unlikely that the older groups were searching at a faster rate and still taking the same amount of time to determine that a target was not present. Second, the fifth-grade participants exhibited slower search rates than did the college students in the standard task conditions but exhibited equal search rates in the adapted task conditions. Again, this pattern of data is not explained by the suggestion of a difference in search rate alone. Rather, it is more consistent with the possibility that the efficiency of restricting search to a small subset of the stimulus array is greater when there is a relatively large discrepancy in the number of the two distractor types in comparison with when the ratio between distractor types is more equal (Egeth et al., 1984).

Experiment 2

The results of Experiment 1 suggested that all of our groups of participants were able to restrict search to less than the entire display on the basis of stimulus features in the adapted task conditions when the ratio between distractor types was relatively high (i.e., few black distractors vs many light gray circle distractors). Indeed, the performance of the fifth-grade students was identical to that of the college students under these conditions. However, the visual search performance of the children was relatively less efficient than that of the young adults in the standard search condition when the number of distractors of each type was equal. The fifth-grade students were clearly different from the adults in the standard search condition, indicating that important developmental changes in visual search occur relatively later in development. On the basis of this pattern of results, we reasoned that the selective search efficiency of children is influenced more by variations in the ratio between distractor types relative to the search performance of young adults. Experiment 2 was designed to investigate the possibility that selective search efficiency is determined by an interaction of age and the relative number of stimuli in the smaller distractor subset.

In Experiment 2, we systematically manipulated both the total number of distractors in the stimulus arrays and the number of black vs gray circle distractors in the arrays. More specifically, each display could have 4, 8, 16, or 32 total stimuli. In addition, each display could have 2, 4, 8, or 16 black stimuli with the restriction that no more than half of the stimuli in any display could be black. Hence, we were able to compute slope values in two different ways from the same response times. First, we computed a slope value based on the standard displays in which both the total number of stimuli varied and included an equal number of each type of distractor. The standard slope value was used as a baseline of comparison against which to evaluate participants' ability to restrict search to a subset of the total display. Second, we computed slope values for displays in which the number of black stimuli remained the same but the number of total stimuli increased. This procedure yielded three additional slope values: one slope value associated with 2 black stimuli out of 4, 8, 16, or 32 total stimuli; one slope value associated with 4 black stimuli out of 8, 16, or 32 total stimuli; and one slope value associated with 8 black stimuli out of 16 or 32 stimuli. To the extent that participants can restrict search to a subset of stimuli based on the selected stimulus feature of black, each of these slope values should approach zero. Based on the results of Experiment 1, we expected that the efficiency with which at least the younger participants would be able to restrict search to the black stimuli to locate the target would decrease as the number of black stimuli in the display increased.

Method

Participants

Participants were 20 second-grade children (10 males and 10 females, mean age = 7.3 years, $SD = 0.5$), 20 fifth-grade children (9 males and 11 females, mean age = 10.3 years, $SD = 0.4$), and 20 college-age young adults (7 males and 13 females, mean age = 18.2 years, $SD = 1.0$). Participants were recruited in a manner similar to that in Experiment 1.

Apparatus and materials

The basic equipment was identical to that in Experiment 1. The stimulus displays were patterned in a similar manner with the exception of the number of stimuli in the displays. As mentioned earlier, each display could have 4, 8, 16, or 32 total stimuli, and each display could have 2, 4, 8, or 16 black stimuli with the restriction that no more than half of the stimuli in any display could be black. Hence, the black stimuli again represented the smaller subset. When a target was present in the display, one of the black stimuli was a target. Size and positioning of individual stimuli were essentially identical to those in Experiment 1 except that the number of stimuli was slightly greater in the largest displays of Experiment 2 than in those of Experiment 1.

Design and procedure

The variables in the experiment were grade (second grade, fifth grade, and college), total display size (4, 8, 16, and 32 stimuli), smaller subset size (2, 4, 8, and 16 black stimuli), and response type (target present and target absent). Grade was a between-participants variable, whereas total display size, smaller subset size, and response type were within-participant variables. The primary dependent measure was response time for identifying whether a target was present in each display. Response times were recorded automatically to the nearest millisecond. Displays were presented in random order for each participant.

Each participant was tested individually. At the beginning of the experimental session, participants received 20 practice trials to familiarize them with the experimental procedure. They were instructed to search each display for a black circle and to press the left response button if a target was present, and to press the right response button if no target was present, as rapidly as possible without making errors. Practice was followed by the experimental trials. All trials were presented randomly. Participants received 15 trials in each condition formed by the combination of the total display size, smaller subset size, and response type variables for a total of 300 experimental trials. The entire session took approximately 30 min to complete. Participants were given the opportunity to take a break halfway through the session if they so desired.

Results

Median response times were calculated for each participant in each condition. The means of these response times are presented in Table 3. Again, errors were infrequent (2.5, 1.6, and 1.1% for second grade, fifth grade, and college, respectively) and were not analyzed further. Response times were converted to slope values relating response times to the number of items in the stimulus arrays. As mentioned earlier, four different slope values were calculated for each participant in Experiment 2. One slope value was calculated for response times based on the standard version of the search task, represented by the diagonal scores in Table 3. Three additional slopes were calculated associated with the conditions in which the subset size remained the same at 2, 4, or 8 and in which the total set size increased, represented by the horizontal values in Table 3. Slope values are reported in Table 4. We chose to analyze the diagonal slope values separately from the horizontal slope values because the scores were not entirely independent.

During the first phase of the analysis, we compared grade-related differences using the standard slope computations separately for the target-present and target-absent conditions. The analysis was a one-factor ANOVA for independent samples. The analysis indicated a significant effect of grade, $F(2,57) = 25.25$, $p < .01$. Tukey's HSD indicated that all mean slope values were significantly different from each other, with the second-grade participants exhibiting the largest slopes and the college participants exhibiting the smallest slopes. The obtained slope values and pattern of data are essentially the same as those observed in the standard task of Experiment 1. The analysis of the target-absent data was also very similar to that in Experiment 1 and indicated no significant differences as a function of grade, $F(2,57) < 1.0$.

During the second phase of the analysis, we compared grade-related differences in slope values obtained for conditions in which the subset size remained the same and

Table 3
Mean response times for Experiment 2 as a function of age, subset size, and response type

	Subset size	Display size			
		4	8	16	32
	Target present				
Grade					
Second	2	856 (130)	853 (130)	891 (177)	942 (172)
	4		871 (150)	954 (182)	1017 (184)
	8			950 (203)	1039 (221)
	16				1191 (210)
Fifth	2	697 (115)	703 (84)	691 (91)	743 (111)
	4		710 (97)	732 (108)	833 (109)
	8			758 (99)	861 (103)
	16				937 (163)
College	2	538 (60)	545 (78)	550 (59)	560 (77)
	4		553 (59)	559 (66)	591 (71)
	8			573 (77)	591 (64)
	16				667 (100)
	Target absent				
Grade					
Second	2	973 (111)	954 (140)	986 (119)	1038 (184)
	4		957 (155)	994 (174)	1071 (190)
	8			1047 (174)	1083 (277)
	16				1218 (237)
Fifth	2	696 (101)	736 (109)	765 (139)	775 (108)
	4		685 (92)	744 (118)	788 (100)
	8			760 (95)	830 (133)
	16				966 (153)
College	2	570 (69)	567 (69)	568 (72)	662 (139)
	4		571 (59)	586 (70)	631 (90)
	8			610 (93)	648 (84)
	16				795 (131)

Note. Standard deviations are in parentheses.

the total set size increased. The analysis of target-present data was conducted using a 3 (Grade) × 3 (Subset Size) ANOVA with subset size treated as a within-participants variable. The analysis revealed a significant main effect of grade, $F(2, 57) = 16.24$, $p < .01$, with the second-grade students exhibiting the largest slope values (5.1 ms), the fifth-grade students exhibiting the second largest slope values (4.3 ms), and the college students exhibiting the smallest slope values (1.2 ms). All three slopes values differed significantly from each other at the .05 level using Tukey's HSD. There was also a significant main effect of subset size, $F(2, 57) = 11.56$, $p < .01$, with the largest slope values observed when the subset contained 8 stimuli (4.6 ms), the next largest slope values obtained when the subset contained 4 stimuli (4.2 ms), and the smallest slope values obtained when the subset contained 2 stimuli (1.8 ms). Tukey's HSD revealed that the slope of the 2-stimuli subset was significantly smaller than the slopes of the two larger subsets (both ps $< .05$), with the two larger subsets not

Table 4
Mean slope values for Experiment 2 as a function of age, subset size, and response type

	Standard computation	Subset size		
		2	4	8
	Target present			
Grade				
Second	12.7 (4.3)	3.4 (3.8)	5.8 (3.9)	6.2 (6.3)
Fifth	8.3 (4.0)	1.2 (2.8)	5.2 (2.6)	6.4 (3.2)
College	4.5 (2.4)	0.8 (1.5)	1.7 (2.5)	1.1 (3.8)
	Target absent			
Grade				
Second	9.4 (7.2)	2.2 (4.8)	4.8 (3.9)	2.9 (5.5)
Fifth	10.4 (4.8)	2.7 (2.8)	4.3 (3.4)	4.3 (4.4)
College	8.4 (4.8)	3.5 (3.8)	3.5 (3.7)	2.4 (2.4)

Note. Standard deviations are in parentheses.

differing from each other. There was also a significant Grade × Subset Size interaction, $F(4, 114) = 2.58$, $p < .05$. The interaction was evaluated by analyzing the effect of grade separately for each subset size. At the 2-stimuli subset size, the effect of grade was significant, $F(2, 57) = 4.57$, $p < .01$. Slope values were larger for the second-grade participants than for the two older groups ($p < .05$), and the two older groups did not differ from each other. At the 4-stimuli subset size, the effect of grade was also significant, $F(2, 57) = 10.32$, $p < .01$. In this analysis, the slope values of the college students were significantly smaller than those of the two younger groups ($p < .05$), and the two younger groups did not differ from each other. At the 8-stimuli subset size, there was again a significant effect of grade, $F(2, 57) = 8.40$, $p < .01$, with the college students exhibiting slope values that were significantly smaller than those of the two younger groups ($p < .05$), and the two younger groups did not differ from each other.

A 3 (Grade) × 3 (Subset Size) ANOVA conducted on the target-absent trials did not indicate any significant difference among conditions. As in Experiment 1, slope values in several of the target-absent conditions were actually smaller than those in the target-present conditions for the second- and fifth-grade participants. Again, we believe that it is reasonable to suggest that strategic differences in the decision to recheck smaller displays in which a target was not found may account for these anomalies; however, there is no independent evidence to confirm the use of such a strategy by the children.

Discussion

The results of Experiment 2 support and extend the basic results of Experiment 1. First, the pattern of slope values indicated that all ages were able to restrict search to a subset of the stimulus array to some degree. When the number of black items was held constant, the change in response times associated with increases in the total number of distractors was smaller than when the number of black items also increased. This was true for all set size comparisons. Second, slope values for the subset-constant comparisons were sensitive to age differences. These values were much smaller for the college students than for either the fifth-grade or second-grade students and were smaller for the fifth-grade students than for the second-grade students. As suggested in Experiment 1, it seems likely that this reflects differences in the ability to restrict search to the smaller target subset because differences in slopes for the nontarget trials were not found. Third, the age-related differences that we observed in Experiment 2 varied with the number of items in the smaller subset. More specifically, the differences in slopes associated with age increased as the number of items in the smaller set increased. In fact, the fifth-grade participants' performance and the college participants' performance were the same when the small subset was very small, with differences emerging only when the subset was larger. This last observation helps to clarify the basic inconsistency observed in Experiment 1. We found that the fifth-grade participants performed like the college students in the adapted search conditions but not in the standard search conditions. Apparently, the ability of the fifth-grade participants to restrict their search to the smaller subset of items was relatively efficient when the subset was very small but not when the subset was even slightly larger. The standard version of the search task always includes conditions in which the subset is relatively large and, hence, elicited performance differences between the fifth-grade and college participants that were not observed in the adapted version of the task.

General discussion

Age-related improvements in conjunctive search between children and young adults have been well documented. In our research, we investigated the possibility that at least a portion of the difference reflects different degrees of efficiency in the use of selective search processes. The results of two experiments indicated that children as young as 6 years of age were able to restrict search to an appropriate subset of a stimulus display during conjunctive search. We believe that this is the first direct behavioral evidence that young children engage in selective search when searching for targets defined by a conjunction of features, although Taylor et al. (1999) suggested that asymmetries observed for the features of shape and color in the search performance of young children are more consistent with the guided search model (Wolfe, 1994) and revised feature integration theory (Treisman, 1988) than with the original feature integration theory (Treisman & Gelade, 1980). The observation of selective search in young children is important because it suggests a fundamental similarity between children and young adults in the operation of preattentive mechanisms of visual processing; that is, it seems likely that features are processed and integrated in much the same way for children and adults during visual search. We cannot, based on our data, distinguish between models of search that rely on feature activation to guide attention toward particular features, such as the guided search model (Wolfe, 1994; Wolfe et al., 1989), and models that rely on feature inhibition to essentially guide attention away from particular features (Treisman, 1988; Treisman & Sato, 1990). In either case, young children appear to be able to use information gathered preattentively to selectively search for a conjunctively defined target.

Despite some basic similarities in the search for conjunctively defined targets by children and young adults, we also observed a significant difference in the efficiency with which that search is conducted. The young adults in Experiment 2 exhibited slope values that varied little with the total number of distractors in the display so long as the number of black items remained the same. This was true when the number of black items was relatively small (two items) and when the number of black items was relatively large (eight items). The fifth-grade students were able to match the young adults when the number of black items in the display was small but were less efficient than the young adults when the number of black items increased to four or eight. The second-grade students were less efficient than the fifth-grade and adult participants when there were only two black items in the small subset, but the second-grade students were equivalent to the fifth-grade participants (with both younger groups being less efficient than the adult participants) when the number of black items increased to four or eight.

There are several ways in which to explain group differences in search rate. First, it may simply be that the search is fundamentally the same for children and young adults but that it happens at variable paces. This possibility is consistent with the conclusions of Trick and Enns (1998) and is consistent with a major portion of research comparing response time performance differences of children with those of young adults (for a review, see Kail, 1991). However, we do not believe that slow search is sufficient to account for the data of our experiments. In particular, we found roughly equivalent slope values across both experiments in all target-absent conditions for our three groups of participants. If it were simply that search speed was different for the three groups, we should have observed significant group differences in search rate for target-absent trials as well as target-present trials, but we did not observe this. Of course, search speed can be manipulated fairly easily by target-distractor similarity (Duncan & Humphreys, 1989). Because subjective similarity is likely to differ as a function of age, we would anticipate finding general speed differences to be associated with age for some stimulus comparisons but not for others. Hence, our results are not necessarily inconsistent with those of Trick and Enns (1998), who did report such differences.

Additional ways in which to account for group differences in search rate are suggested by the guided search model (Wolfe, 1994; Wolfe et al., 1989). Two explanations are based on the possibility that levels of activation represented in the activation map are less distinct for children relative to adults, resulting in more time being spent in nontarget locations. One explanation focuses on bottom-up processes that help to generate feature maps, and the second focuses on top-down processes that serve to enhance the activation of specific task-relevant features in the feature maps. The degree of bottom-up activation received by any location in the display is based on local differences among items. More specifically, level of activation for a particular item is determined by how different that item is from all adjacent items. Hence, a black stimulus surrounded by all gray stimuli receives a lot of activation, a black stimulus surrounded by some gray and some black stimuli receives less activation, and a black stimulus surrounded by all black stimuli receives no activation with respect to the feature represented by black–gray. A similar scenario plays out for other features represented in the display. Perceptual learning experience plays a role in the efficiency of visual search for young adults by enhancing the difference between features (e.g., Sireteanu & Rettenbach, 1995, 2000). As discussed earlier, Taylor et al. (1999) reported that P3 latencies varied with age between 7 and 12 years of age for the features of color and size and that the learning trajectories associated with age were different for the two features. If the features used in our experiments undergo age-related changes in subjective salience through perceptual learning processes, the level of activation associated with the bottom-up processing of each feature would be different for younger children relative to older individuals. As a result, attention will be guided less efficiently through the activation map for the younger participants than for the older participants. Bottom-up processes are particularly important in the use of selective search mechanisms when the ratio of the two types of distractors is relatively large (Bacon & Egeth, 1997) because they can be used to determine which stimulus features should receive additional top-down activation.

Age-related differences in search efficiency may still be found even if bottom-up processes operate the same for all age groups. Top-down control of feature activation permits participants to enhance the activation level of certain categorically defined features (e.g., Wolfe, 1994; Wolfe et al., 1989). Selective search is achieved by limiting top-down activation to one of the possible target features. Top-down activation is particularly efficient when the proportion of distractors possessing the selected target feature is relatively small (Cave & Wolfe, 1990). A number of researchers have demonstrated that younger children have difficulty in making use of visual search strategies as effectively as do older children and adults (e.g., Day, 1978; Pick & Frankel, 1973). To the extent that these differences are indicative of similar differences in top-down control of feature activation, fundamentally different activation maps would be generated by participants of different ages. This would again lead to less efficient attentional guidance through the activation map, resulting in significantly steeper slopes relating search times to the number of items in the search set.

Attentive processes may also be responsible for age-related changes in visual search for conjunctive targets. One relatively simple way in which attentive processes could affect search rate and vary with age concerns the ability to overcome eccentricity effects (Carrasco & Chang, 1995; Carrasco, Evert, Chang, & Katz, 1995). In general, targets that are presented near the center of fixation are easier to detect and locate than are targets that are presented farther from the center. Wolfe, O'Neill, and Bennett (1998) indicated that eccentricity effects appear to be attentional in nature. It is also possible that there are systematic individual differences associated with eccentricity effects of this type (e.g., Efron, Yund, & Nichols, 1987). If younger children are more susceptible to the effects of this attentional bias, they may be more likely to spend time searching central fixation items that are not part of their restricted subset than are older children and adults when the target is outside of central vision. The result would again be steeper slopes.

One domain of developmental change that may explain a portion of the age-related differences we observed in visual search is perceptual development. The efficient use of bottom-up processes to preattentively direct visual search depends on the ability to distinguish features of the distractors from features of the target. It is clear that this ability changes with age (Aslin & Smith, 1988). For example, there is a developmental trend indicating a general shift from holistic perception to a focus on constituent parts (e.g., Smith, 1989) that occurs after 5 or 6 years of age. This process of differentiation is integral to perceptual learning (Goldstone, 1998). Furthermore, it is clear that perceptual learning has a significant influence on visual search efficiency in young adults (Yund & Efron, 1996). Yund and Efron (1996) found that familiarity with stimulus features over extended practice using adult participants increased search efficiency through the operation of preattentive processes and that the improvement they observed was maintained for a period of 3 years. In our view, basic perceptual development and perceptual learning play a prominent role in the increased efficiency of visual search observed between 7 and 10 years of age.

Executive functioning is a second domain of developmental change that is also likely to be involved in increased efficiency in visual search by older children and young adults. Executive functioning allows for the effective selection, execution, and monitoring of task-appropriate strategic behavior (e.g., Borkowski & Burke, 1996). Both top-down preattentive processes and attentive processes of search are likely to be influenced by executive processes (Wolfe, 1994) because they are subject to choice (e.g., participants elect to search for one feature rather than another feature) and require that participants keep track of where they have already looked to prevent recursions. It is well known that executive functions undergo a relatively long period of development, with many executive skills not becoming proficient until late adolescence (e.g., Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001). Continued improvements in the efficiency of visual search beyond 10 years of age may be the result of increased proficiency in executive functions.

Conclusions

The visual search performance of both children and adults is characterized by selective search. However, young children are less efficient in their ability to limit search to an appropriately small number of potential targets in the search display. This age-related difference in search efficiency may result from the less efficient operation of preattentive processes, attentive processes, or some combination of both. Two domains of developmental change that seem particularly relevant to improved visual search with age are perceptual development and the development of executive functions. Whatever mechanisms may be responsible, it is important that future investigations of age-related differences in visual search for conjunctive targets consider the role that is played by selective search processes.

References

Anderson, V. A., Anderson, P., Northam, E., Jacobs, R., & Catroppa, C. (2001). Development of executive functions through late childhood and adolescence in an Australian sample. *Developmental Neuropsychology, 20*, 385–406.

Aslin, R. N., & Smith, L. B. (1988). Perceptual development. *Annual Review of Psychology, 39*, 435–473.

Bacon, W. F., & Egeth, H. E. (1997). Goal-directed guidance of attention: Evidence from conjunctive visual search. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 948–961.

Borkowski, J. G., & Burke, J. E. (1996). Theories, models, and measurements of executive functioning: An information processing perspective. In G. R. Lyon & N. A. Krasnegor (Eds.), *Attention, memory, and executive function* (pp. 235–261). Baltimore, MD: Paul Brookes.

Brodeur, D., Trick, L., & Enns, J. T. (1997). Selective attention over the lifespan. In J. Burack & J. Enns (Eds.), *Attention, development, and psychopathology* (pp. 74–93). New York: Guilford.

Carrasco, M., & Chang, I. (1995). The interaction of objective and subjective organizations in a localization search task. *Perception & Psychophysics, 57*, 1134–1150.

Carrasco, M., Evert, D. L., Chang, I., & Katz, S. M. (1995). The eccentricity effect: Target eccentricity affects performance on conjunctive searches. *Perception & Psychophysics, 57*, 1241–1261.

Cave, K. R., & Wolfe, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology, 22*, 225–271.

Chun, M. M., & Wolfe, J. M. (1996). Just say no: How are visual searches terminated when there is no target present?. *Cognitive Psychology, 30*, 39–78.

Day, M. C. (1975). Developmental trends in visual scanning. In H. W. Reese (Ed.), *Advances in child development and behavior* (Vol. 10). New York: Academic Press.

Day, M. C. (1978). Visual search by children: The effect of background variation and the use of visual cues. *Journal of Experimental Child Psychology, 25*, 1–16.

Denkla, M. B. (1996). A theory and model of executive functioning: A neuropsychological perspective. In G. R. Lyon & N. A. Krasnegor (Eds.), *Attention, memory, and executive function* (pp. 263–278). Baltimore, MD: Paul Brookes.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychology Review, 96*, 433–458.

Efron, R., Yund, E. W., & Nichols, D. R. (1987). Scanning the visual field without eye movements: A sex difference. *Neuropsychologia, 25*, 637–644.

Egeth, H. E., Vizri, R. A., & Garbart, H. (1984). Searching for conjunctively-defined targets. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 32–39.

Enns, J. T., & Aktar, N. (1989). A developmental study of filtering in visual attention. *Child Development, 60*, 1188–1199.

Goldstone, R. L. (1998). Perceptual learning. *Annual Review of Psychology, 49*, 585–612.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin, 109*, 490–501.

Madden, D. J. (1990). Adult age differences in attentional selectivity and capacity. *European Journal of Cognitive Psychology, 2*, 229–252.

Madden, D. J., Gottlob, L. R., & Allen, P. A. (1999). Adult age differences in visual search accuracy: Attentional guidance and target detectability. *Psychology and Aging, 14*, 683–694.

Miller, P. H., Haynes, V. F., & Weiss, M. G. (1985). Metacognitive components of visual search in children. *Journal of Genetic Psychology, 146*, 249–259.

Pick, A. D., Christy, M. D., & Frankel, G. W. (1972). A developmental study of visual selective attention. *Journal of Experimental Child Psychology, 14*, 165–175.

Pick, A. D., & Frankel, G. W. (1973). A study of strategies of visual search in children. *Developmental Psychology, 9*, 348–357.

Scialfa, C. T. (1990). Adult age differences in visual search: The role of non-attentional processes. In J. T. Enns, *The development of attention: Research and theory* (Advances in Psychology, vol. 69, pp. 509–526). Amsterdam: North-Holland.

Sireteanu, R., & Rettenbach, R. (1995). Perceptual learning in visual search: Fast, enduring, but non-specific. *Vision Research, 35*, 2037–2043.

Sireteanu, R., & Rettenbach, R. (2000). Perceptual learning in visual search generalizes over tasks, locations, and eyes. *Vision Research, 40*, 2925–2949.

Smith, L. B. (1989). A model of perceptual classification in children and adults. *Psychological Review, 96*, 125–144.

Smith, L. B., & Evans, P. (1989). Similarity, identity, and dimensions: Perceptual classification in children and adults. In B. E. Shepp & S. Ballesteros (Eds.), *Object perception: Structure and process* (pp. 325–356). Hillsdale, NJ: Lawrence Erlbaum.

Taylor, M. J., Shakeela, S. C., & Malone, M. A. (1999). Parallel and serial attentional processes: A developmental ERP study. *Developmental Neuropsychology, 15*, 351–358.

Treisman, A. (1988). Features and objects: The Fourteenth Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology A, 40*, 201–237.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*, 97–136.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review, 95*, 15–48.

Treisman, A. M., & Sato, A. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 459–478.

Treisman, A., & Souther, J. (1985). Search asymmetry: A diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General, 114*, 285–310.

Trick, L. M., & Enns, J. T. (1998). Lifespan changes in attention: The visual search task. *Cognitive Development, 13*, 369–386.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review, 1*, 202–238.

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 419–433.

Wolfe, J. M., O'Neill, P., & Bennett, S. C. (1998). Why are there eccentricity effects in visual search? Visual and attentional hypotheses. *Perception & Psychophysics, 60*, 140–156.

Yund, E. W., & Efron, R. (1996). Guided search: The effects of learning. *Brain & Cognition, 31*, 368–386.