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Age-Related Preservation of Top-Down Attentional Guidance During Visual Search

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Younger (19–27 years of age) and older (60–82 years of age) adults performed a letter search task in which a color singleton was either noninformative (baseline condition) or highly informative (guided condition) regarding target location. In the guided condition, both age groups exhibited a substantial decrease in response time (RT) to singleton targets, relative to the baseline condition, as well as an increase in RT to nonsingleton targets. The authors conclude that under conditions that equate the physical structure of individual displays, top-down attentional guidance can be at least as effective for older adults as for younger adults.

The distinction between bottom-up and top-down forms of attentional control is prominent in current theories of visual search performance (Wolfe, 1998; Wolfe, Butcher, Lee, & Hyle, 2003; Yantis, 1998). A paradigmatic form of bottom-up attention is the involuntary orienting to a target item distinguished from nontarget (distractor) items on the basis of local salience of display properties (e.g., a red target letter among gray distractor letters). In top-down processing, in contrast, search is driven more by the observer's knowledge and goals than by the properties of the display. Most forms of visual search represent the combined influences of bottom-up and top-down attentional control.

Jonides and Yantis (1988) proposed that when the top-down information is minimized, not all forms of local salience capture attention. These authors reported that in a conjunction search for letters, the effect of display size on response time (RT) was eliminated when the target letter occurred as an onset singleton (i.e., one letter was presented at a blank location among other letters presented by the removal of lines from figure-8 characters). Attentional capture by the onset singleton appeared to be automatic because the singleton was the target on only $1/N$ trials (where N is display size), and thus the abrupt onset was not informative about the location of the target. When either color or luminance was the singleton dimension, however, a noninformative singleton did not influence the effect of display size on RT, leading Jonides and Yantis to conclude that abrupt onsets are a form of local salience with a unique ability to capture attention. Other evidence suggests that although abrupt onsets are particularly effective at capturing attention, under certain conditions the features of color, form, and luminance can also guide attention in a bottom-up manner, even when these features are uninformative regarding the target (Folk, Remington, & Johnston, 1992; Theeuwes & Berger, 1998; Turatto & Galfano, 2001).

The bottom-up versus top-down distinction is also potentially useful for characterizing the age-related changes observed in visual search performance (Hartley, 1992; Madden & Whiting, 2004; McDowd & Shaw, 2000). An age-related decline in top-down attentional guidance would be expected on the basis of the age-related deficits that have been noted in executive control processes more generally, especially in contexts requiring the coordination of tasks or switching between different types of preparatory sets (Kramer, Hahn, & Gopher, 1999; Mayr & Liebscher, 2001). Consistent with this expectation, the ability to use motion-related features in a top-down manner appears to decline as a function of age (Folk & Lincourt, 1996; Watson & Maylor, 2002). Older adults are also more vulnerable to attentional capture by irrelevant singleton distractors that occur with an abrupt onset (Pratt & Bellomo, 1999), which may represent an age-related decline in the ability to maintain an inhibitory set (Colcombe et al., 2003; Kramer, Hahn, Irwin, & Theeuwes, 2000).

In contrast, advance information regarding the spatial location or color of a search target typically leads to improved performance

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that is at least as great in magnitude for older adults as for younger adults (Madden & Plude, 1993; Plude & Hoyer, 1986), implying a preservation of top-down guidance. Older adults also exhibit significant improvements in search RT when the feature composition of the display increases the salience of the target (Humphrey & Kramer, 1997), although the proportional improvement may be somewhat less than for younger adults (Madden, Pierce, & Allen, 1996). In these previous investigations of age differences in the improvement of search, however, the structure of the visual displays usually varied in some way across the task conditions: the homogeneity of distractor features in the case of Madden et al. (1996) and the proportion of features shared by targets and distractors in the case of Humphrey and Kramer (1997). Thus, in these previous investigations, the relative influence of top-down and bottom-up attentional processes is difficult to determine.

In this experiment, we investigated age-related changes in the top-down attentional guidance afforded by color singletons. Previous studies of age differences in visual search that included color singletons have most often focused either on cuing effects (Pratt & Bellomo, 1999) or on the degree of distraction when the singleton is task irrelevant (Colcombe et al., 2003; Kramer et al., 2000). The present experiment, in contrast, was concerned primarily with the improvement in search performance associated with top-down attentional guidance by the singleton. To this end, we compared search RT in two conditions: baseline and guided. In the baseline condition, the singleton was the target on $1/N$ trials (where $N =$ display size) and was thus not informative regarding which display item was the target. In the guided condition, the singleton was the target on $(N - 1)/N$ trials, and the singleton was consequently highly predictive of target location.

An advantage of this design is that the structure of the individual display on each trial—one color singleton among either four or six letters—was identical in the two search conditions, and thus top-down effects in search RT were not attributable to differences in the physical structure of the displays (Humphrey & Kramer, 1997; Madden et al., 1996). If, in the guided condition, participants are allocating attention preferentially to the singleton location, then responses to singleton targets should be relatively faster than in the baseline condition, but responses to nonsingleton targets should be relatively slower, as a shift of attention away from the singleton (i.e., disengagement) would be required on nonsingleton target trials. An age-related decline in top-down attentional guidance would be most clearly evident as a decline in both the facilitative effects of a singleton target and the disruptive effects of a nonsingleton target, in the guided condition relative to the baseline condition. In testing the potential age-related change in top-down effects, we also assessed the degree to which the age differences in search RT could be attributed to attention specifically, rather than to a more generalized effect of age-related slowing of elementary perceptual processing (Madden, 2001; Salthouse, 1996, 2000).

Method

Participants

The research procedures were approved by the Institutional Review Board of the Duke University Medical Center, and all subjects gave written informed consent. Twenty younger adults (10 women) between 19 and 27 years of age and 20 older adults (11 women) between 60 and 82 years of age participated; their characteristics are presented in Table 1. The participants were community-dwelling individuals who were free of significant health problems (e.g., hypertension and atherosclerosis), as determined by a screening questionnaire, and were not taking medication known to affect cognition. Most of the participants (15 of the younger adults and 16 of the older adults) also took part in a related study using functional magnetic resonance imaging that will be reported in future studies. All participants scored a minimum of 27 on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975), a minimum of 12 on the Dvorine pseudoisochromatic plates (Dvorine, 1963), and possessed a minimum corrected binocular acuity for near point of 20/40.

Table 1
Participant Characteristics by Age Group

Variable	Younger *M*	Younger (*SD*)	Older *M*	Older (*SD*)
Age (in years)	22.80	(1.91)	67.45	(5.87)
MMSE	29.75	(0.44)	28.90	(1.12)
Education (in years)	16.15	(1.46)	17.20	(1.44)
Vocabulary	65.35	(3.56)	66.10	(3.02)
Acuity	16.50	(3.66)	22.75	(8.35)
Color vision	14.00	(0.00)	13.75	(0.64)
Digit-symbol RT (in ms)	1,331.00	(183.00)	1,713.00	(250.00)
Digit-symbol accuracy (%)	98.00	(1.84)	97.71	(2.31)

Note. $N = 20$ per age group. Mini-Mental State Examination (MMSE) = raw score (maximum of 30) on the MMSE (Folstein et al., 1975); Vocabulary = raw score (maximum of 70) on the Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981); Acuity = denominator of the Snellen fraction for corrected near vision; Color vision = raw score (maximum of 14) on the Dvorine color plates (Dvorine, 1963); Digit-symbol = computer test of digit-symbol coding (Salthouse, 1992); RT = response time.

Apparatus and Stimuli

Presentation of the visual displays and measurement of participants' RT and accuracy were controlled by a Pentium 4 microcomputer with a 19-in. LCD flat panel. Viewing distance was approximately 60 cm, although head movement was not restrained. On each trial, one target letter was present among distractor letters, and participants made a two-choice response regarding which target was present in the display (Figure 1). Each display contained one red letter (a color singleton) plus either three or five gray letters against a black background. The proportion of trials on which the color singleton was also the target varied between the baseline and guided search conditions. This proportion was relatively high in the guided search condition, providing a basis for top-down attention, but was relatively low in the baseline condition.

The target letters were *E* and *R*, and the distractor letters were *F*, *H*, *K*, *N*, *P*, *S*, *T*, and *X*. The display items were arranged in a six-position circle with a diameter of 6.06°, and the character space for each display position was approximately 1.21° × 1.52°. The midpoints of the six display positions were arranged to be equidistant at clock positions 12, 2, 4, 6, 8, and 10 o'clock. The separation between the edges of adjacent characters was approximately 1.91°. On the four-item trials, the remaining two display positions were filled with gray outline squares that were always diametrically opposite each other (e.g., 12 o'clock and 6 o'clock). Thus, all displays contained six items, one of which was a red singleton. The displays varied with regard to whether these items comprised four or six letters (the display size variable) and whether the target was the singleton or one of the nonsingleton display items (the target type variable). The Commission Internationale de l'Eclairage (CIE) values were $x = 0.65$, $y = 0.34$ for the red items and $x = 0.33$, $y = 0.34$ for the gray items. Luminance of red and gray display items was 38.07 cd/m^2 and 49.91 cd/m^2, respectively, against the black background.

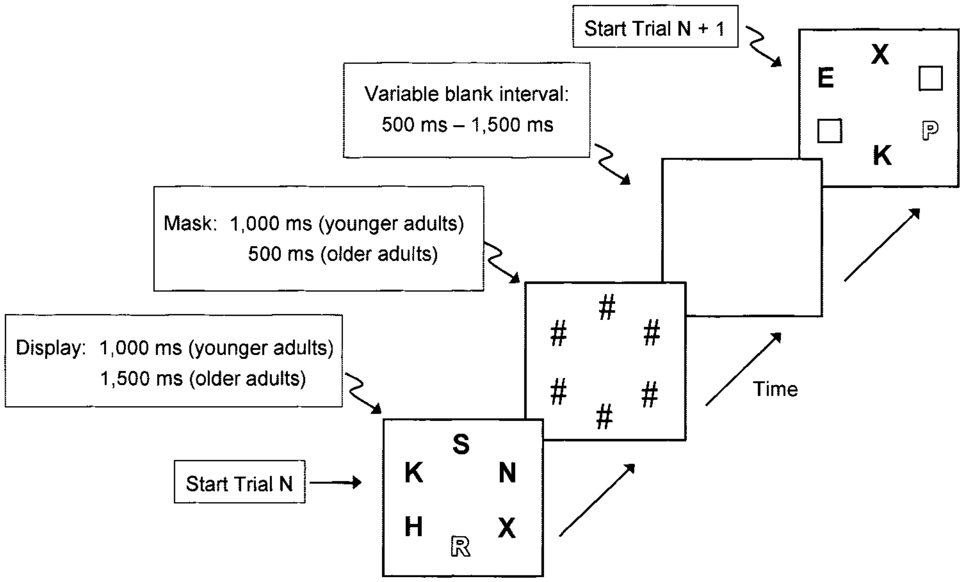

Figure 1. Sequence of events within each trial. Each display contained one color singleton letter, in red, among gray letters against a black background. The singleton is represented in the figure by the letter presented in outline. On each trial, one target letter (either *E* or *R*) was present among either three or five distractor letters, and participants made a two-choice response regarding which target was present in the display. The singleton was either likely (guided condition) or unlikely (baseline condition) to be the target.

Design and Procedure

Participants performed 864 test trials comprising 216 trials for each combination of search condition (baseline and guided) and display size (four item and six item). In the baseline condition, the singleton was a target letter on 1/*N* trials, where *N* is display size. Thus, in the baseline condition, the singleton was the target on 0.25 of the four-item displays and on 0.17 of the six-item displays. In the guided condition, the singleton was the target on $(N - 1)/N$ trials, which comprised 0.75 of the four-item displays and 0.83 of the six-item displays. On both singleton-target and nonsingleton-target trials, the target was divided approximately equally between *E* and *R*. Nontarget display items were selected without replacement, on each trial, from the nontarget letter set.

Participants responded as to whether the *E* or *R* target was present in the display by pressing the *Z* and / response keys on the computer keyboard, with the left and right index fingers, respectively. The assignment of target letters to response keys remained constant within participants but was counterbalanced across participants. We divided the 432 test trials in each of the baseline and guided search conditions into three blocks of 144 trials, each of which maintained approximately the same proportion of the display size and target type variables (distributed randomly) as the larger list. Participants performed the baseline and guided blocks in an alternating sequence. At the beginning of each trial block, a message was displayed on the computer screen indicating whether the singleton in the upcoming trial block was either unlikely (baseline condition) or likely (guided condition) to be the target. We counterbalanced the assignment of the two mappings of target letters to response keys and two block orders (*ABABAB* vs. *BABABA*) across participants within each age group. Participants performed a block of 36 practice trials in each of the baseline and guided conditions before beginning the test trials.

On each trial, there was a sequence of three events (Figure 1): the letter display, a mask (six # characters in the display positions), and a blank intertrial interval. To provide some compensation for age-related slowing of visual information processing, we set display duration at 1,000 ms for younger adults and 1,500 ms for older adults. The mask duration was 1,000 ms for younger adults and 500 ms for older adults so that the total duration of the display characters was 2,000 ms for both age groups. To reduce the predictability of display onset, the blank intertrial interval was varied randomly (in equal proportions) among three values: 500 ms, 1,000 ms, and 1,500 ms within each trial block. The experimenter encouraged the participants to respond as quickly as possible while still maintaining a high level of accuracy, although the display remained on the screen for the specified duration regardless of when the response occurred. Responses were recorded from the onset of the letter display through the blank intertrial interval. Participants received no feedback on their responses, and the next trial began immediately after the blank intertrial interval.

Results

Task Condition Effects

The main results of the experiment are the means of RT medians presented in Figure 2. Error rate did not differ significantly between the age groups (2.41% for younger adults and 1.47% for older adults) and was less than 4.50% in all task conditions. We nevertheless included error rate as a covariate in all analyses to control for potential influences of speed–accuracy trade-offs. The expected top-down attention effect was evident as a greater RT difference between singleton and nonsingleton targets in the guided condition than in the baseline condition. In addition, the absolute magnitude of this top-down effect was significantly greater for older adults than for younger adults. This finding was confirmed by an analysis of covariance (ANCOVA) that included age group as a between-subjects variable, search condition (baseline vs. guided), target type (singleton vs. nonsingleton), and display size (four item vs. six item) as within-subjects variables and error rate as a covariate. The most relevant finding is the Age Group × Search Condition × Target Type interaction, $F(1, 38) = 30.44$, $p < .0001$.

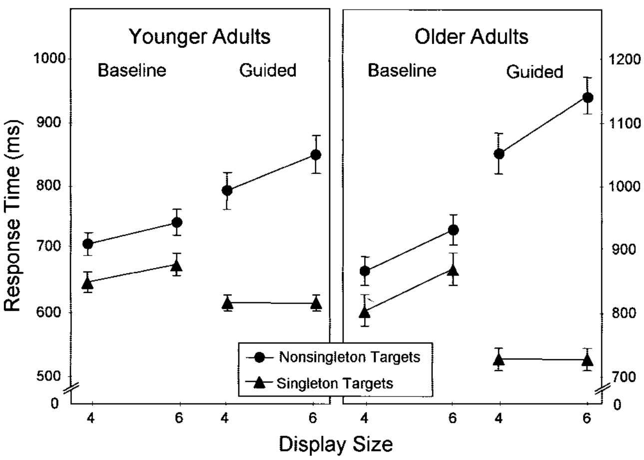

Figure 2. Mean response time as a function of age group, search condition, target type, and display size. Error bars represent ±1 *SE*. Participants performed the baseline and guided conditions in alternating blocks of trials. Target type (singleton vs. nonsingleton) and display size (four vs. six items) were varied randomly within each block.

In addition to the three-way interaction, the ANCOVA yielded several other significant effects. All of the main effects were significant, with $F(1, 38) > 29.00$, $p < .0001$, in each case. RT was 188 ms higher for older adults than for younger adults, 28 ms higher in the guided condition than in the baseline condition, 177 ms higher for nonsingleton targets than for singleton targets, and 43 ms higher for six-item displays than for four-item displays. Significant interactions of the within-subjects variables included Search Condition × Target Type, $F(1, 38) = 216.83$, $p < .0001$, Search Condition × Display Size, $F(1, 38) = 3.93$, $p = .05$, Display Size × Target Type, $F(1, 38) = 50.38$, $p < .0001$, and Search Condition × Display Size × Target Type, $F(1, 37) = 51.44$, $p < .0001$. These interactions represent a pattern in which increased top-down control in the guided condition (relative to the baseline condition) led to a decrease in RT for singleton targets but to an increase in RT for nonsingleton targets. Both of these effects were evident at each display size, and when the four-item and six-item trials were analyzed separately, the Search Condition × Target Type interaction was significant in each case, with $F(1, 37) > 144.00$, $p < .0001$. The absolute magnitude of the RT change across the search conditions, however, was greatest for singleton targets in six-item displays.

In addition to the Age Group × Search Condition × Target Type interaction noted previously, several interactions involving age group were significant. The Age Group × Display Size interaction, $F(1, 38) = 13.65$, $p < .001$, represents a larger display size effect (six-item RT minus four-item RT) for older adults (55 ms) than for younger adults (31 ms), and the Age Group × Target Type interaction, $F(1, 38) = 13.59$, $p < .001$, represents a greater effect of target type (nonsingleton RT minus singleton RT) for older adults (215 ms) than for younger adults (139 ms). The four-way interaction of Age Group × Search Condition × Display Size × Target Type, $F(1, 37) = 4.77$, $p < .05$, was also significant because the age-related increase in the improvement of RT for singleton targets in the guided condition was also relatively greater on six-item trials, whereas the age-related increase in the slowing of responses for nonsingleton targets in the guided condition was constant across display size.

Simple effect tests conducted within the guided condition demonstrated that top-down attention to the color singleton eliminated the display size effect. In the guided condition, the Target Type × Display Size interaction was significant, $F(1, 37) = 77.87$, $p < .0001$, because there was a display size effect for nonsingleton targets (75 ms) but not for singleton targets (−1 ms). This latter interaction did not vary significantly as a function of age group. Even in the baseline condition, however, in which the singleton was not predictive of target location, there was some influence of the singleton on search performance. Within the baseline condition, the simple main effect of target type was significant, $F(1, 38) = 68.67$ $p < .0001$, representing a 64-ms RT advantage for singleton targets relative to nonsingleton targets, which did not vary as a function of either display size or age group. This latter effect was surprising because Jonides and Yantis (1988) found that when a singleton was not informative, attentional capture was limited to onset singletons; color singletons were not effective. To examine the baseline target type effect further, we limited the analysis to those participants (half of each age group) who performed the baseline condition as their first block of test trials. Even in this first block of trials, there was a 68-ms advantage for singleton targets relative to nonsingleton targets, $F(1, 17) = 31.20$, $p < .0001$.

RT Transformation for Generalized Slowing

To control for the effects of generalized age-related slowing, we transformed the younger adults' RT data by the Brinley plot function characterizing the relation between the task condition means of the two age groups (Madden, Pierce, & Allen, 1992). The assumption of this analysis is that Age Group × Task Condition interactions that remain significant in analyses of variance of mean RT, following this transformation, can be interpreted as being independent of the generalized slowing represented in the Brinley function (see Faust, Balota, Spieler, & Ferraro, 1999, and Salthouse & Kersten, 1993, for related approaches). The Brinley function for the eight task condition means in this experiment yielded Equation 1 ($r^2 = .98$). When the younger adults' RT data were transformed by this equation, in an ANCOVA of the RT data (using the variables described previously in the *Task Condition Effects* section), none of the original interactions involving age group remained significant, suggesting a generalized slowing effect.

$$\text{Older adult RT} = 1.66(\text{younger adult RT}) - 276. \quad (1)$$

Discussion

In the present experiment, we varied the probability that a color singleton would correspond to a target letter as a method of eliciting top-down attentional control. As predicted, there was a significant decrease in RT for singleton targets and an increase in RT for nonsingleton targets, in the guided condition relative to the baseline condition, demonstrating a substantial degree of top-down attentional guidance. In addition, both the facilitative effect of a singleton target and the disruptive effect of a nonsingleton target, in the guided condition, were greater for older adults than for younger adults, as reflected in the Age Group × Search Condition × Target Type interaction. This age-related increase in the top-down effects was magnified further, on singleton-target trials, by increasing display size. For both age groups, the occurrence of the target as color singleton, in the guided condition, was sufficient to eliminate entirely the effect of display size on search RT, turning a difficult search task into a highly efficient form of letter discrimination. These findings demonstrate that even with the physical structure of individual displays equated across search task conditions, the influence of top-down attentional guidance on search performance is at least as great for older adults as for younger adults.

Older adults' preserved ability to improve performance in this task supports previous investigations of visual search that used variation in the featural composition of the displays to elicit top-down control (Humphrey & Kramer, 1997; Madden et al., 1996). The data for nonsingleton targets are consistent with previous research indicating that under some conditions attentional capture by a singleton is more pronounced for older adults than for younger adults (Kramer et al., 2000; Pratt & Bellomo, 1999). In the present experiment, however, the increased RT represents an attentional shift away from a task-relevant color singleton (one of the nontarget display items) rather than attentional capture by a task-irrelevant onset singleton. It is also important to recognize that, in the present experiment, all of the interactions involving age group were eliminated when the older adults' RT data were transformed by the Brinley plot function (Madden et al., 1992), and thus the task-specific age effects cannot be distinguished from age-related slowing that is pervasive throughout the sequence of information-processing stages.

For both age groups, the decreased RT for singleton targets relative to nonsingleton targets was not limited to the guided condition but also occurred, to a smaller degree, within the baseline condition. This result was unexpected because Jonides and Yantis (1988), using a similar paradigm, reported that when the singleton was not informative, attentional capture was evident for onset singletons but not for either color or luminance singletons. One difference between the present methodology and that of Jonides and Yantis is that they tested the different target types in between-subjects conditions, whereas we varied target type within subjects. Thus, our participants may have used a certain degree of top-down control in the baseline condition, even though they were informed that in this condition there was only a chance probability that the singleton would be the target. The target type effect was significant, however, even in the first block of baseline test trials, for those participants who performed the baseline condition first. Turatto and Galfano (2001) have also reported that a noninformative color singleton can capture attention.

One goal for further research is to define the task demands that lead to an age-related change in top-down attentional control. Two previous studies of visual search reporting an age-related decline in top-down processing involved moving distractors (Folk & Lincourt, 1996; Watson & Maylor, 2002), raising the possibility that motion perception is a critical variable. Investigations reporting an age-related decline in executive control processes typically involve a substantial reliance on working memory or the ability to shift preparatory sets (Kramer et al., 1999; Mayr & Liebscher, 2001). The present task, in contrast, while top-down in nature, allowed observers to adopt a constant preparatory set throughout each block of trials. In addition, top-down effects in visual search include an implicit component resulting from the priming of target features across trials, as well as the explicit preparation for particular target features (Maljkovic & Nakayama, 1994; Wolfe et al., 2003), and it is not clear whether these components of top-down guidance vary as a function of age.

Further information is also needed on age-related changes in the neural systems mediating top-down attentional control. At the behavioral level of analysis, we were not able to distinguish age differences in attentional functioning from generalized slowing. Such a distinction may be possible at the level of functional neuroanatomy. Previous neuroimaging studies have indicated that, during some cognitive tasks, the activation of deep gray matter (e.g., basal ganglia and thalamus) or prefrontal cortical regions is actually greater for older adults than for younger adults (Cabeza, 2002; Madden, Whiting, & Huettel, in press). These effects appear to represent the compensatory recruitment of an attentional network. The age-related increase in activation has been observed in the context of perceptual tasks that are also associated with an age-related decline in activation of occipital cortical regions mediating visual processing (Grady et al., 1994; Madden, Whiting, Provenzale, & Huettel, 2004). If, as suggested by Grady et al. (1994), the recruitment of prefrontal cortical regions compensates accuracy at the expense of speed, then an increased emphasis on top-down attentional guidance and a decrease in the speed of task performance may represent two sides of an aged coin.

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