

Research Article

AGE DIFFERENCES IN THE CONTROL OF LOOKING BEHAVIOR: Do You Know Where Your Eyes Have Been?

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Abstract—Previous research has shown that during visual search young and old adults' eye movements are equivalently influenced by the appearance of task-irrelevant abrupt onsets. The finding of age-equivalent oculomotor capture is quite surprising in light of the abundant research suggesting that older adults exhibit poorer inhibitory control than young adults on a variety of different tasks. In the present study, we examined the hypothesis that oculomotor capture is age invariant when subjects' awareness of the appearance of task-irrelevant onsets is low, but that older adults will have more difficulty than young adults in inhibiting reflexive eye movements to task-irrelevant onsets when awareness of these objects is high. Our results were consistent with the level-of-awareness hypothesis. Young and old adults showed equivalent patterns of oculomotor capture with equi-luminant onsets, but older adults misdirected their eyes to bright onsets more often than young adults did.

Bicyclists spend a considerable amount of time intentionally scanning the environment for other cyclists, automobiles, and pedestrians. However, their attention can also be captured, seemingly independently of their intentions, by salient events in the environment, such as a dog darting out in the road or a tornado warning siren. The phenomenon of attentional capture, defined as the unintentional redirection of attention to some stimulus event, has generated considerable interest in recent years.

One feature of the environment that appears to have a substantial influence on attention is the appearance of a new object, or abrupt onset. Yantis and his colleagues (Yantis & Hillstrom, 1994; Yantis & Jonides, 1984) have found that when a new object appears in a display among old objects, the new object is attended first. This capture of attention by the new object occurs despite the fact that subjects are often unaware that a novel object has been presented in the display (Theeuwes, Kramer, Hahn, & Irwin, 1998; Yantis & Jonides, 1984), and even when the onset never serves as the target in a visual search task (Remington, Johnston, & Yantis, 1992). Thus, these data suggest that abrupt onsets, or new objects, capture attention in an obligatory fashion, perhaps through the generation of an attentional interrupt that directs attention to the location of the onset, at least for a brief period of time (Martin-Emerson & Kramer, 1997; Yantis, 1996; but see Folk & Remington, 1998).

Interestingly, although the phenomenon of attentional capture by abrupt onsets has been extensively examined, there has not, until recently, been any attempt to determine the influence of capture on oculomotor control. In other words, there has been no attempt to distinguish between overt and covert capture of attention.

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We (Kramer, Hahn, Irwin, & Theeuwes, 1999; Theeuwes et al., 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, in press) recently examined the influence of attentional capture on oculomotor control with a paradigm like that illustrated in Figure 1. Subjects were presented with six gray circles, each with a small figure-eight premask inside. After 1,000 ms, the color of five of the circles changed to red, and segments of the figure-eight premasks were removed to reveal letters. Subjects were instructed to move their eyes from the center of the display to the color singleton (i.e., the uniquely colored item) as soon as they detected the color change and to identify the letter inside the gray circle. On a subset of trials, a new red circle (i.e., an abrupt onset) appeared simultaneously with the color change that cued the location of the color singleton target. The abrupt onset never served as the target.

Several interesting results were obtained in these studies. First, on approximately 30% of the trials, the eyes went directly toward the onset distractor, stopped for a brief period of time, and then went directly to the color singleton target. Furthermore, this pattern of results was obtained regardless of whether the onset distractor appeared close to the target or on the opposite side of the visual display. These results suggest that overt as well as covert attention was captured by the appearance of a new but task-irrelevant object in the visual field.

Second, on the trials on which the eyes did initially go to the onset distractor, they stopped for only a brief period of time (i.e., 80% of the fixations were less than 100 ms) before moving directly to the color singleton target. Given that it takes approximately 150 ms to program a saccade (Abrams & Jonides, 1988; Becker, 1991), this finding suggests that multiple saccades may have been programmed in parallel—one saccade to the color singleton target and the other saccade to the task-irrelevant onset. This proposal is compatible with neurophysiological and neuropsychological evidence which suggests that different components of the oculomotor system are responsible for voluntary (goal-directed) and reflexive (stimulus-driven) saccades (Pierrot-Deseilligny, Rivaud, Gaymard, Muri, & Vermersch, 1995; Schall, 1995).

Third, and perhaps most surprisingly, old and young adults showed equivalent patterns of oculomotor capture. That is, young and old adults misdirected their eyes to the task-irrelevant onsets on an equivalent percentage of trials. This finding was quite unexpected given the abundance of research suggesting that older adults exhibit poorer inhibitory control than young adults on a variety of different tasks (Zacks & Hasher, 1997), as well as previous findings that older adults exhibit a much higher percentage of misdirected saccades than young adults on the antisaccade task.

The antisaccade task involves the presentation of an abrupt-onset stimulus to the right or left of fixation in an otherwise empty visual field. The subject's task is to detect the onset using peripheral vision and to rapidly look in the opposite direction. Performance on the

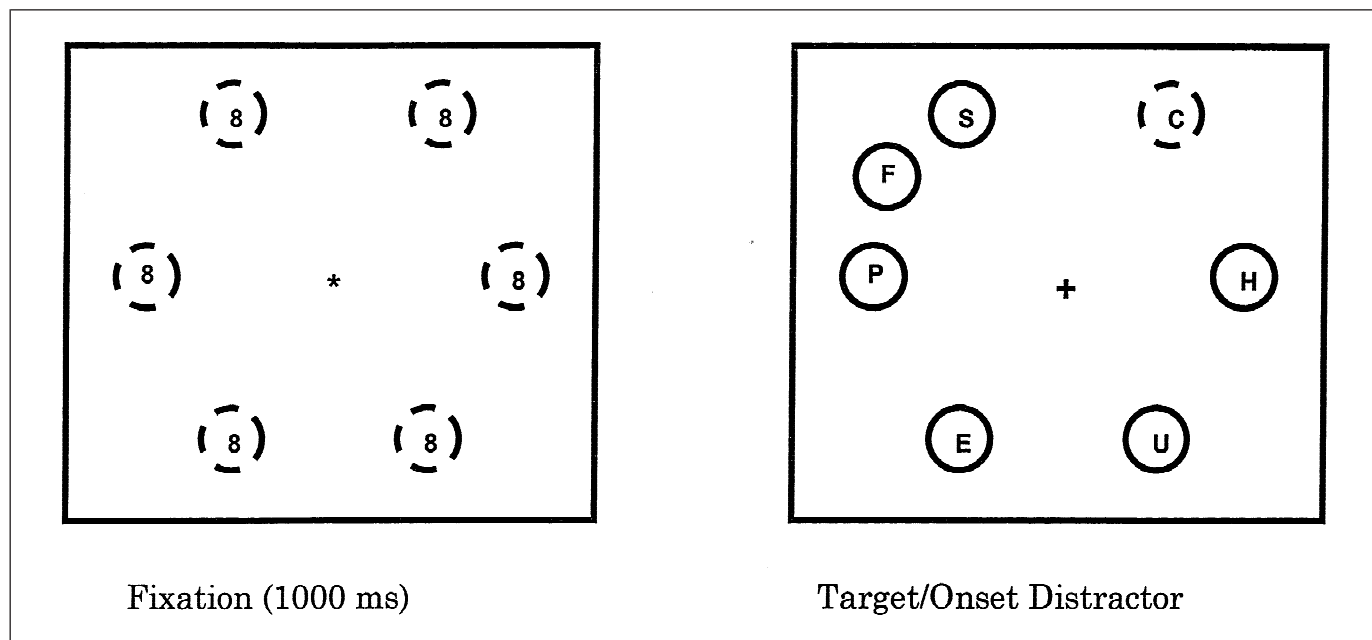


Fig. 1. Graphic illustration of the displays presented on the onset distractor trials in the study. The display in the left panel was presented for 1,000 ms, followed by the display in the right panel, which was presented until the subject responded to the target. The gray circles are represented by dashed lines. The red circles are represented by solid lines.

antisaccade task, which clearly requires that subjects suppress a reflexive eye movement toward the onset stimulus while programming and executing a goal-directed saccade in the opposite direction, is dramatically affected by lesions in the frontal regions of the brain that are involved in the programming of goal-directed saccades (Guitton, Buchtel, & Douglas, 1985; Rivaud, Muri, Gaymard, Vermersch, & Pierrot-Deseilligny, 1994). Frontal lobe patients have great difficulty inhibiting reflexive saccades to the onset stimulus.

Given the often-reported changes in frontal lobe morphology and decreases in metabolism during the course of normal aging (Azari et al., 1992; Coffey et al., 1992; West, 1996), Olincy, Ross, Youngd, and Freedman (1997) examined potential age-related changes in the performance of the antisaccade task. They found that the proportion of misfixations on the onset stimulus increased linearly from approximately 10% for 20-year-olds to 50% for 80-year-olds. The authors concluded that the inhibitory processes necessary for the suppression of eye movements to task-irrelevant events are compromised during the course of normal aging.

The results of the antisaccade study appear to be inconsistent with our results and conclusions with the attentional capture paradigm. Why should older adults show dramatically inferior performance on the antisaccade task yet display performance equivalent to that of young adults in our paradigm? A possible explanation for the age-equivalent performance in our task and the decreased performance exhibited by the older adults in the antisaccade task concerns the subjects' level of awareness of the attention-capturing objects. On the one hand, subjects were generally unaware of the presence of the abrupt-onset distractor in our attentional capture paradigm. On the other hand, in the antisaccade paradigm, subjects must detect the onset before programming and executing an eye movement in the opposite direction. Therefore, subjects must be aware of the potentially attention-capturing abrupt-onset stimulus in the antisaccade task.

Given previous reports of age-related sparing on memory tasks that presumably do not require conscious recollective processes and age-related deficits on memory tasks that do require such processes (Craig & Anderson, 1999; Craig & Jacoby, 1996; Schacter, Kihlstrom, Kaszniak, & Valdiserri, 1993), it appears conceivable that the degree to which age-related differences in attentional capture are observed might be a function of subjects' level of awareness of the attention-capturing stimuli. That is, equivalent performance for young and old adults might have been observed in our paradigm precisely because subjects were unaware of the attention-capturing abrupt-onset stimulus. In such a case, inhibition associated with an implicit representation of the onset distractor might be called upon to suppress eye movements to the abrupt onset. In contrast, subjects' awareness of the abrupt onset in the antisaccade paradigm might result in the utilization of inhibition associated with conscious recollective memory processes such as those employed during working memory tasks. Indeed, an association between working memory and effective inhibition in the antisaccade task has been recently reported. Roberts, Hager, and Heron (1994; see also Walker, Husain, Hodgson, Harrison, & Kenard, 1998) found that the imposition of a mental arithmetic task concurrently with an antisaccade task dramatically increased the number of misfixations on the onset by a group of young adults (i.e., rendered the young adults' eye movements similar to those of frontal lobe patients).

In the present study, we tested this level-of-awareness hypothesis by presenting task-irrelevant abrupt onsets that were either equiluminant with other stimuli in the display or brighter than other stimuli in the display. Our expectation was that subjects would be able to report the presence of the onsets in the latter but not in the former case. We expected that if the level-of-awareness hypothesis is accurate, we would observe a larger proportion of misfixations for older than for younger adults on the bright task-irrelevant onsets and age-equivalent

misfixations with the equiluminant onset distractors. Such a pattern of results would suggest age-related sparing of automatic or implicit inhibitory processes associated with oculomotor control.

METHOD

Subjects

Nineteen old (ages 67–75) and 19 young (ages 18–25) adults participated in the study. All of the young and old adults had near and far visual acuities of at least 20/40 and a perfect score on the Ishihara Color Blindness Test (*Ishihara's Tests for Color Blindness*, 1989). Sixteen individuals (8 young and 8 old adults) served in the equiluminant-onset condition, and 22 individuals (11 young and 11 old adults) served in the bright-onset condition.

Apparatus

A Gateway Pentium 133 MHz computer with a 19-in. SVGA color monitor was used to present the stimuli, control the timing of the experimental events, and record subjects' reaction times (RTs). Eye movements were recorded with an Eyelink tracker with 250-Hz temporal resolution and a 0.2° spatial resolution. The head was stabilized by a chin rest located 53.3 cm from the monitor.

Stimuli

Subjects viewed displays containing six equally spaced gray circles (3.7° in diameter), each containing a small, gray figure-eight premask (0.4° × 0.2°), presented on an imaginary circle with a radius of 12.6°. A star was presented in the center of the display and used for fixation. After 1,000 ms, all circles but one changed to red, and simultaneously line segments were removed from each of the figure-eight premasks to reveal target and distractor letters. At this time, the fixation star also changed to a cross to inform the subjects that they should move their eyes to the color singleton circle. The subjects' task was to determine whether the letter inside the gray circle was a *c* or a reversed *c*. The subjects responded by pressing the "z" or "r" key on the computer keyboard. The distractor letters inside the red circles were randomly sampled from the set of *S*, *H*, *E*, *P*, *F*, and *U*. Because the letters were small, subjects had to make a saccade to the gray circle to identify the target letter.

In the onset condition, an additional red circle (identical to the other five red circles) with a distractor letter inside was added to the display simultaneously with the color change that defined the singleton target. The additional red circle appeared with an abrupt onset at either the 2, 4, 8, or 10 o'clock position. These four possible locations where the onset could appear corresponded to two possible distances from the gray target circle. On the imaginary circle with the fixation point at its center, the abrupt onset was presented three clock positions away from the target, describing an angle of 90°, or five clock positions away from the target, describing an angle of 150° of arc. In Euclidean distances, these figures corresponded to 19.4° and 25.4° of visual angle, respectively. The stimuli remained until a response was made.

On the control trials, an extra circle with a figure-eight premask was presented with the other objects at the beginning of the trial. This

extra object was presented at a location in which an onset could occur on the onset trials, to ensure that any RT or eye movement differences between control and onset trials were due to the appearance of the abrupt onset rather than to a different number of stimuli in the two conditions.

On the equiluminant-onset and equiluminant-control trials, the red and gray circles were matched for luminance (16 cd/m²); on the bright-onset and bright-control trials, the extra object (onset or non-onset control) was brighter (24 cd/m²) than the other objects (16 cd/m²).

Design

Subjects participated in two different conditions that were randomly distributed within each block of trials, an onset condition and a control condition. Age and the nature of the onset or control distractor (equiluminant or bright) served as between-subjects factors.

Subjects performed one practice block of 64 trials and five experimental blocks with 64 trials per block. Each block contained 32 control and 32 onset trials. Targets were presented randomly at each of the six equally spaced positions. Abrupt-onset distractors (and non-onset controls) were presented randomly at each of the two separations from the target.

Procedure

Subjects were instructed that they should initially maintain their eyes on the fixation star. On each trial, the eye position was automatically recalibrated to the center position so that reliable eye movement measurements could be obtained. Following fixation, subjects were instructed to press the space bar on the computer keyboard to initiate the trial. The display of six gray circles (seven gray circles in the nononset control trials) with figure-eight premasks inside was then presented for 1,000 ms. Five of the circles (six in the nononset control trials) then changed to red, and on onset trials an additional red circle was presented in the display. Subjects were instructed to move their eyes to the gray circle as soon as they detected the color change and to make one response if they detected a *c* and another response if they detected a reversed *c*.

RESULTS

Saccade Path

Figures 2 and 3 summarize the effect of the appearance of a new but task-irrelevant object on the scan path of the eyes.¹ The percentages of initial saccades that went toward the onset and control dis-

1. Three thresholds were used for saccade detection: movement distance, velocity, and acceleration. An eye movement was considered a saccade either when the movement distance exceeded 0.2° and velocity exceeded 30°/s or when the movement distance exceeded 0.2° and the acceleration exceeded 8000°/s². Saccade paths to the onset and nononset control distractors were defined as initial eye movements that moved to within 4° of these distractors. Cutoffs for saccade latencies were 100 and 600 ms.

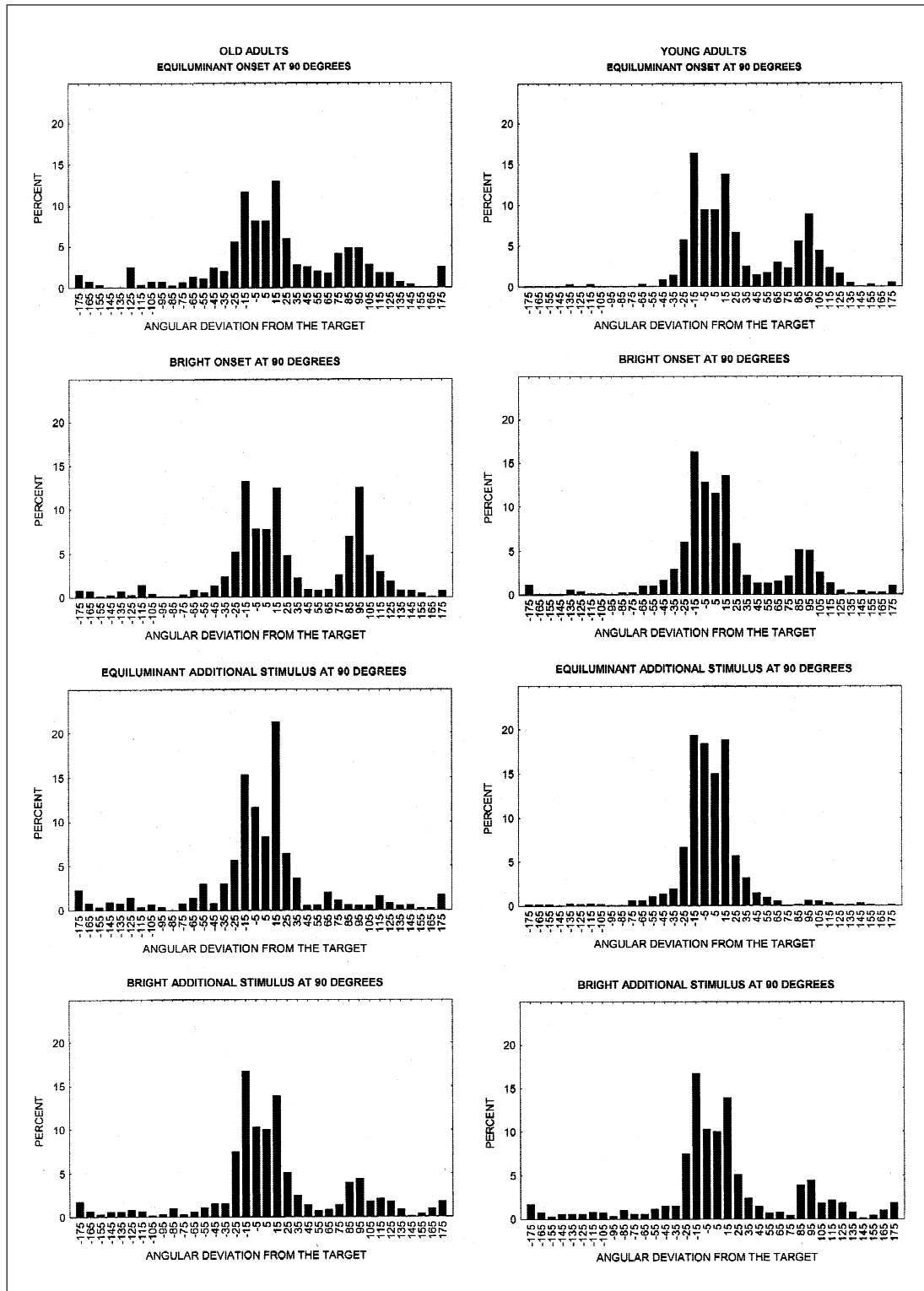


Fig. 2. Histograms for initial saccades in the control and 90° onset distractor conditions. The graphs show the maximal angular deviation from a straight line path from fixation to the position of the target (in degrees of visual angle; positive values indicate that the eye initially moved in the direction of the new object, and negative values indicate that the eye initially moved in the opposite direction). The top four panels present data for the onset distractor conditions, and the bottom four panels present data for the control nononset distractor conditions. Histograms for the older adults are on the left, and histograms for the young adults are on the right.

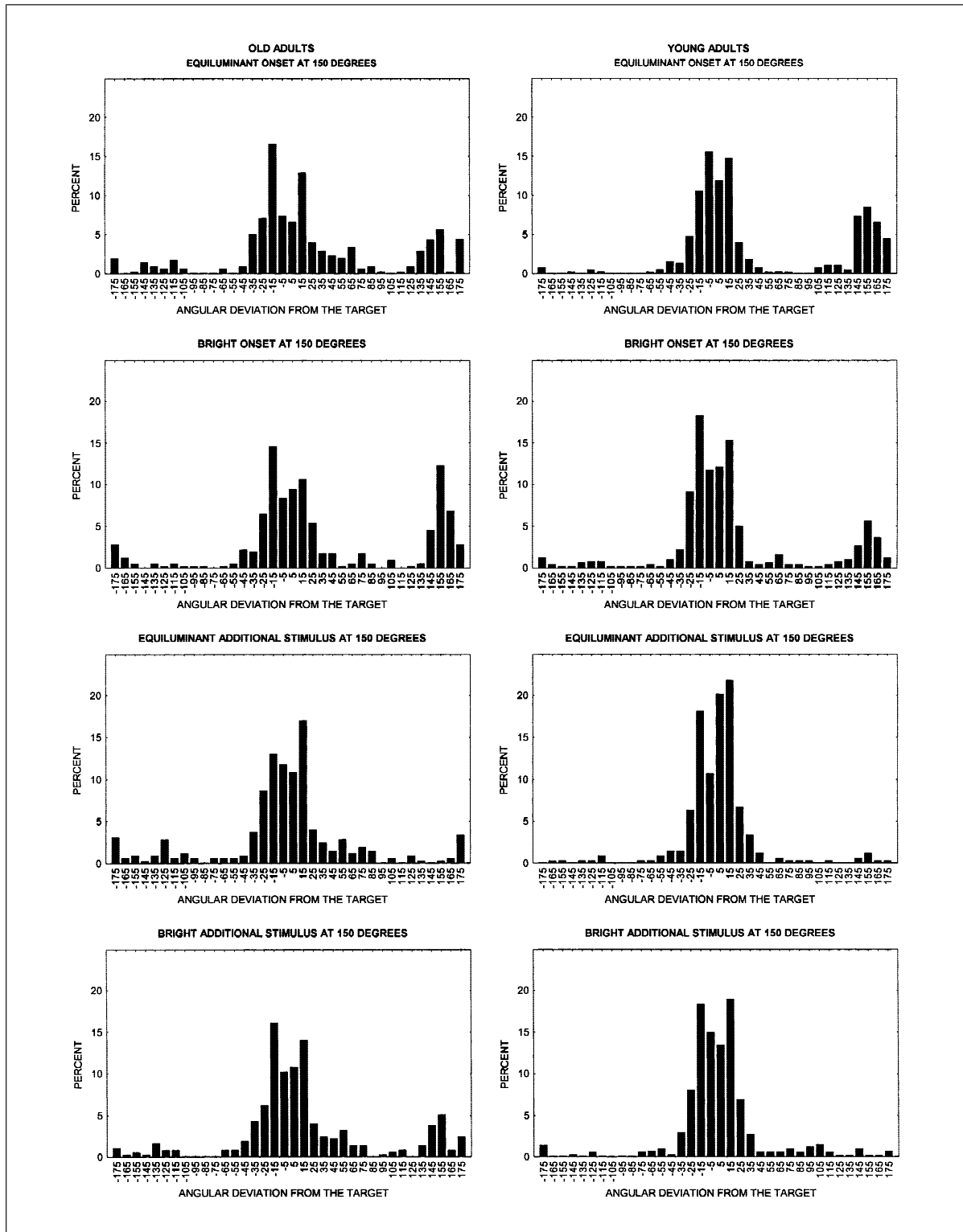


Fig. 3. Histograms for initial saccades in the control and 150° onset distractor conditions. The graphs show the maximal angular deviation from a straight line path from fixation to the position of the target (in degrees of visual angle; positive values indicate that the eye initially moved in the direction of the new object, and negative values indicate that the eye initially moved in the opposite direction). The top four panels present data for the onset distractor conditions, and the bottom four panels present data for the control nononset distractor conditions. Histograms for the older adults are on the left, and histograms for the young adults are on the right.

tractors were calculated for each subject and were submitted to a four-way analysis of variance with age (young vs. old) and distractor luminance (equiluminant vs. bright onset or control distractor) as between-subjects factors and distractor type (onset vs. nononset control) and target-distractor separation (90° vs. 150°) as within-subjects factors.

As can be seen from the figures, subjects' initial saccades in the control condition generally moved directly toward the color singleton target. However, a different pattern of saccades was present when the onset appeared in the display. In this case, a substantial number of saccades initially went toward the onset distractor before stopping briefly and continuing on to the color singleton target, $F(1, 36) = 72.5, p < .01$. These results are consistent with previous studies that reported capture of attention and the eyes by new but task-irrelevant objects (Kramer et al., 1999; Theeuwes et al., 1998).

More important, however, is the finding of a significant three-way interaction among age, distractor luminance, and distractor type, $F(1, 36) = 8.3, p < .01$. As can be seen in the figures, the percentage of initial saccades to the onsets increased from the equiluminant-onset (23.6%) to the bright-onset (35.9%) condition for the old adults, but decreased from the equiluminant-onset (25.2%) to the bright-onset (13.8%) condition for the young adults. The percentage of trials in which the eyes initially went to the nononset control distractor did not significantly differ across conditions.

These data are consistent with our hypothesis that young and old adults would show an equivalent ability to inhibit reflexive saccades when they were unaware of the occurrence of the abrupt onset but that old adults would have more difficulty than younger adults in inhibiting reflexive eye movements when they were aware of the task-irrelevant onset. Further support for this hypothesis is provided by the subjects' reports collected at the conclusion of the study. When asked to describe the display, none of the young or old adults in the equiluminant group reported the appearance of a new object. Indeed, even when told that a new object had appeared on a subset of trials and asked whether they had ever seen it, all of the subjects in the equiluminant group replied negatively. In contrast, all of the young and 10 of the old adults in the bright-onset group described the appearance of a new object in the display on a subset of the trials. Interestingly, when asked whether they occasionally moved their eyes toward this bright new object, all of the subjects replied that they had not because it was not the proper (target) color.

Manual Reaction Time and Saccade Latency

As indicated in Table 1, the appearance of the abrupt onset affected not only eye movements but also RTs to identify the target inside the color singleton target. RTs were significantly slower on onset than on control trials, $F(1, 36) = 9.6, p < .01$ (mean control and onset RTs were 1,072 and 1,128 ms, respectively). However, these RT differences appear to be largely the result of slowed responding on those onset trials on which the eyes first went to the onset before moving to the color singleton target. The mean RT on onset trials on which the eyes first went to the onset was 1,219 ms, whereas the mean RT for onset trials on which the eyes went directly to the target was 1,084 ms. This difference was statistically significant, $F(1, 36) = 52.3, p < .01$.

As expected, older adults were slower to respond than younger adults, $F(1, 36) = 31.9, p < .01$. The difference in RTs between

Table 1. Mean reaction times (in milliseconds) and saccade latencies (in milliseconds; shown in parentheses) for the young and the old adults

Age	Condition		
	Control trials	Onset trials ^a	
		Eyes directly to target	Eyes to onset
Equiluminant onset and control distractors			
Young	937 (310)	945 (308)	1,061 (226)
Old	1,209 (398)	1,228 (402)	1,370 (301)
Bright onset and control distractors			
Young	914 (303)	930 (305)	1,049 (234)
Old	1,212 (411)	1,230 (416)	1,393 (307)

^aResults are shown separately for trials on which the eyes went directly to the target and trials on which the eyes first went to the onset before going to the target.

control and onset trials on which the eyes first went to the onset distractor was larger for the older than for the younger adults, $F(1, 36) = 14.8, p < .01$. This effect appears to be due to the fact that older adults made more saccades, on both onset and control trials, to reach the target than did younger adults (1.86 and 1.51 for older and young adults, respectively).

Accuracies were uniformly high (>97.6%) in all conditions for the young and old adults. There were no significant main effects or interactions for the accuracy data.

As indicated in Table 1, the time it took subjects to move their eyes away from fixation was shorter on the onset than on the control trials, $F(1, 36) = 7.1, p < .01$. However, the difference in saccade latency between the onset and control trials was due largely to the faster saccades on onset trials on which the eyes went initially to the abrupt-onset distractor, as compared with those trials on which the eyes went directly to the target, $F(1, 36) = 14.0, p < .01$. Older adults moved their eyes more slowly than young adults, $F(1, 36) = 6.7, p < .01$. These data are consistent with the notion that it takes some finite amount of time to inhibit attentional capture by the appearance of a task-irrelevant onset. Eye movements that are emitted prior to the imposition of inhibition of the onset are misdirected to the location of the onset before being released and redirected to the target.

DISCUSSION

The present study was conducted to examine the hypothesis that subjects' level of awareness of a task-irrelevant abrupt onset determines whether age-related differences are observed in eye movement control. The results were consistent with the level-of-awareness hypothesis. Young and old adults misdirected their eyes to the task-irrelevant onset on an equivalent percentage of trials when the onset was equiluminant with the other objects. Subjects were unaware of the

presence of the onset under these conditions. However, when the onset was brighter than the other objects and therefore easily detected, young adults were able to more effectively inhibit their reflexive eye movements. In contrast, older subjects made more reflexive saccades to the task-irrelevant object when it was easily detectable than when they were unaware of its appearance in the display.

These data provide a resolution to the apparent paradox posed by previous findings of age-related failures to inhibit inappropriate reflexive saccades in the antisaccade paradigm (Olincy et al., 1997) and age equivalence in the effectiveness of saccade inhibition in the oculomotor task (Kramer et al., 1999). We account for these data by suggesting that age-related differences in saccade inhibition will be observed to the extent that conscious memory processes are required (Craik & Anderson, 1999). However, age equivalence in the inhibition of reflexive saccades will be observed in tasks that depend on automatic memory processes. The research of Roberts et al. (1994) is consistent with this memory-based account of saccadic inhibition. The ability to inhibit reflexive saccades in the antisaccade paradigm, a task in which subjects are clearly aware of the occurrence of an onset, was degraded when performance of a concurrent working memory task was required. Indeed, Roberts et al. wrote that their "explanation for why the arithmetic concurrent load had an adverse effect on performance in the antisaccade task is that performing addition problems taxed limited working memory resources that are required for inhibiting the reflexive response and generating an anti-saccade" (p. 383). On the one hand, the fact that older adults have diminished working memory capacity (Craik & Jacoby, 1996) renders them more susceptible to inhibitory failures in eye movement control when they are aware of the task-irrelevant onset. On the other hand, the age-related invariance in automatic memory processes, and the inhibitory processes that they support, likely aids older adults' eye movement behavior when they are unaware of the occurrence of the onset.

However, there is a potential alternative interpretation for our data. Given the differential salience of the bright and equiluminant onset distractors, it is conceivable that age-related differences in bottom-up processes, that is, operations that register the magnitude of difference between proximal objects (Wolfe, 1994), rather than age-related memory differences, might be responsible for the pattern of oculomotor capture effects that was observed. We examined this alternative bottom-up account of our data in a within-subjects version of our study. In this study, half of our young and old adult subjects began the study in the bright-onset condition, and the other half of the subjects began in the equiluminant-onset condition. All of the young and old adults (5 young and 5 old) who participated in the bright-onset condition in the first session and the equiluminant-onset condition in the second session reported being aware of the onset distractor when it was equiluminant (likely as a result of having detected the bright onset distractor in the first session). Our memory-based hypothesis suggests that given subjects' awareness of the onset distractor in the equiluminant condition, older adults would have substantially more difficulty inhibiting their eye movements to this distractor than younger adults. In contrast, the bottom-up salience hypothesis predicts age-equivalent oculomotor capture under these circumstances, because the (equiluminant) onset is no more physically salient than any of the other stimuli. The results were consistent with the memory-based hypothesis. Older adults who viewed the bright onsets first and the equiluminant onsets second had substantially more difficulty inhibit-

ing reflexive saccades to the equiluminant onset distractor than did young adults (33.4% vs. 14.3% oculomotor capture for the old and young adults, respectively). That is, when subjects were aware of the presence of the equiluminant distractor, their eye movement behavior was equivalent to that observed with the bright distractor. Thus, these data provide strong support for the importance of two different memory-based inhibitory processes in visual search.

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