Psychology and Aging
2000, Vol. 15, No. 4, 635–647

0882-7974/00/$5.00 DOI: 10.1037//0882-7974.15.4.635

Inhibitory Inefficiency and Failures of Intention Activation: Age-Related Decline in the Control of Saccadic Eye Movements

Sander Nieuwenhuis and K. Richard Ridderinkhof
University of Amsterdam

Ritske de Jong
University of Groningen

Albert Kok and Maurits W. van der Molen
University of Amsterdam

Young and older adults' control of saccadic eye movements was compared using an antisaccade task, which requires the inhibition of a reflexive saccade toward a peripheral onset cue followed by an intentional saccade in the opposite direction. In 2 experiments, an age-related decline was found in the suppression of reflexive eye movements, as indicated by an increased proportion of saccades toward the cue, and a longer time needed to initiate correct antisaccades. The results from Experiment 2 suggested that older adults' slower antisaccades may be explained partly in terms of increased failures to maintain the cue-action representation at a sufficient activation level. The results suggest that the notion of selective preservation with age of the ability to inhibit spatial responses does not apply to the active inhibition of prepotent spatial responses.

An increasingly dominant view of the mechanisms responsible for the attentional processing deficits that become apparent with advancing age concerns the decrease in inhibitory efficiency. The inhibitory-deficit hypothesis of aging holds that the well-documented age-related decrease in performance on a range of cognitive tasks can be accounted for by failures to suppress responses to irrelevant information (see, e.g., Hasher & Zacks, 1988; Roberts, Hager, & Heron, 1994; West, 1996). Although the inhibitory-deficit hypothesis can accommodate a large body of data (see, e.g., Zacks & Hasher, 1997), some authors have expressed the need for more precise specification of the inhibition concept (e.g., Burke, 1997; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; McDowd, 1997). There is, for example, a growing amount of evidence of age equivalence on tasks thought to involve inhibitory demands (Kramer et al., 1994; McDowd, 1997). This suggests that instead of one general inhibitory mechanism there may be multiple, distinct inhibitory mechanisms, which are differentially vulnerable to aging.

An important proposal for the selective preservation of inhibitory function during aging refers to the growing body of literature, suggesting that age-related deficits in inhibitory function are limited to tasks requiring the processing of nonspatial information, whereas inhibition mechanisms involved in spatial orienting are spared (e.g., Connelly & Hasher, 1993; Hartley, 1993; Pratt, Abrams, & Chasteen, 1997). For instance, compared with younger adults, older adults exhibit reduced negative priming of the identity of distractor stimuli, as measured by the cost in reaction time if the distractor becomes a target on a following trial. This finding has been taken to suggest that older adults are less efficient in suppressing irrelevant identity information. In contrast, younger and older adults show similar negative priming when required to respond to the location of a stimulus if this location was occupied by a distractor on the previous trial (see, for reviews, Connelly & Hasher, 1993; Kramer et al., 1994). Inhibition of return, the phenomenon that it is more difficult to direct attention to a recently visited location than to an unvisited location, has also been associated with similar or even larger inhibition effects for older adults (see, e.g., Hartley & Kieley, 1995).

In accordance with findings of age-related similarities in the inhibition of covert spatial attention shifts, there is evidence that older and younger adults are equally efficient at inhibiting eye movements (e.g., Kramer, Hahn, Irwin & Theeuwes, 1999; Pratt et al., 1997). There is ample evidence that humans and other organisms have an automatic response tendency to direct both their attention (see for a review, Yantis, 1998) and their eyes (Roberts et al., 1994; Theeuwes, Kramer, Hahn, & Irwin, 1998) toward abrupt visual onsets. Kramer et al. (1999) examined the effect of abrupt onset distractors on goal-directed eye movements in a visual search task. Younger and older adults misdirected their eyes to the distractor onset on an equally large portion of the trials before moving their eyes to the target. Also, compared with a control condition without distractors, search reaction time was lengthened by an equal amount in younger and older adults.

Sander Nieuwenhuis, K. Richard Ridderinkhof, Albert Kok, and Maurits W. van der Molen, Department of Psychology, University of Amsterdam, Amsterdam, the Netherlands; Ritske de Jong, Department of Psychology, University of Groningen, Groningen, the Netherlands.

This research has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences. We thank Jos Blom for his assistance in running participants. Very helpful comments on earlier versions of this article were provided by Nomi Olsthoorn, Eric-Jan Wagenmakers, Jan Theeuwes, and Art Kramer.

Correspondence concerning this article should be addressed to Sander Nieuwenhuis, Department of Psychology, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, the Netherlands. Electronic mail may be sent to stn20@dds.nl.

Kramer and colleagues concluded that the older adults were as efficient inhibiting saccades toward task-irrelevant abrupt onsets as were the younger adults.

In this article, we argue that the absence of age differences in inhibition measures obtained in spatial attention tasks should not be explained in terms of the spatial characteristics of the task. We report the results of two overt spatial attention experiments that demonstrate clear effects of aging on the efficiency of inhibition. We propose that our results and the failure to find age differences in other spatial inhibition tasks can be accommodated by the *inhibition of prepotent responses hypothesis* (IPR) of aging, which will be outlined in the next section.

Aging and the Inhibition of Prepotent Responses

Failures to inhibit prepotent response tendencies, either elicited by task-relevant stimuli or established by practice, have consistently been found to be a major source of disruption in older people's task performance (see, e.g., Hasher, Zacks, & May, 1999; Kramer et al., 1994; for a review, see West, 1996). Examples of tasks probing such prepotent response tendencies are the Wisconsin Card Sorting Task, in which people are required to suppress a sorting rule, which has become prepotent by means of prior experimental practice, and the Stroop task, in which people have to actively inhibit the naturally practiced task of word naming (see Roberts et al., 1994, for more examples). One key aspect that these tasks have in common is that they require the intentionally controlled or active inhibition of an inappropriate response tendency to prevent it from gaining control over action. A second important shared aspect is that the inappropriate response has become highly salient through prior experience. The IPR hypothesis of aging holds that a task will show age deficits to the extent that it embodies these two characteristics.

In our view, most spatial inhibition tasks that are reviewed in the context of the distinction between spatial and nonspatial inhibition do not match these characteristics. Rather, they involve a reflexive form of inhibition, in the sense that the inhibition is not under intentional control, as in the case of negative priming and inhibition of return (see Rafal & Henik, 1994). In other tasks, although it may be evident that spatial distractors hamper performance and may, in principle, be under intentional control, participants are often not explicitly instructed to suppress the evoked covert or overt attention shifts. Moreover, participants may not be aware of the distractors, as has been reported by Kramer et al. (1999). Kramer et al. failed to find age differences in the disrupting effect of a task-irrelevant abrupt onset on overt visual search performance. Reports from their participants, indicating that they were generally unaware of the appearance of the distractor, led Kramer et al. to note that "... it would appear 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" (p. 152). Indeed, this hypothesis has recently been confirmed by Kramer, Hahn, Irwin, and Theeuwes (2000). We argue, therefore, that differences in the spatial nature of task requirements are usually confounded with the need to actively inhibit a prepotent response tendency.

In this article, we advocate a classification of inhibition paradigms according to the need to actively suppress a prepotent response tendency, rather than in terms of the distinction between spatial and nonspatial attention. Strong evidence for this view would be obtained if the IPR hypothesis of aging were found to generalize to prepotent shifts of spatial attention and eye movements. The main goal of the present research was to clarify this issue experimentally. To this end, we investigated age differences in the *antisaccade task*, a spatial inhibition task that requires the regulation of conflict between reflexive eye movements in response to *task-relevant* abrupt onset cues on the one hand, and controlled eye movements toward a target location on the other hand. A major benefit of focusing on eye movements instead of covert attention shifts is that it allows one to distinguish between several performance indices such as the time to initiate eye movements, the number of incorrect prepotent eye movements, and the time needed to correct them.

The Antisaccade Task

In the antisaccade task (Hallet, 1978), participants are required to suppress a reflexive saccade toward a peripherally presented, abrupt onset cue and instead produce a controlled *antisaccade* in the opposite direction. In the version of the task that we used, the cue is subsequently replaced by a briefly presented target in the diametrically opposed location, and the additional instruction is to perform a manual two-choice discrimination response on the basis of the target identity (see, e.g., Guitton, Buchtel, & Douglas, 1985; Roberts et al., 1994). Importantly, the cue serves as a reliable indicator of the target location, prompting participants to produce fast antisaccades to optimize choice performance. The *prosaccade* task, in which the target follows the cue in the same location, has provided an elegant control condition, requiring people to make a simple visually guided saccade. The use of this control condition allows the exclusion of an interpretation of age differences in terms of differences in peripheral acuity, because the cue has equal perceptual qualities in the experimental and control condition.

The basic findings with the prosaccade and the antisaccade task are straightforward. First, the prevalence of reflexive direction errors in the antisaccade task is relatively high, whereas in the prosaccade task participants rarely make errors. Second, the saccadic reaction time (SRT) of correct antisaccades is slower than the SRT of correct prosaccades. These findings are invariant across different participant populations and experimental designs (see, e.g., Everling & Fischer, 1998) and are thought to reflect (a) the difficulty in overcoming the tendency to make a reflexive eye movement toward the abrupt onset (Roberts et al., 1994), and (b) the increased time needed to generate a voluntary saccade (i.e., to an empty location) compared to a visually guided saccade (Guitton et al., 1985). We turn now to a review of the literature on aging and the antisaccade task before describing our experiments.

Aging and the Antisaccade Task

It has been known for a long time that, consistent with performance on other motor tasks, older adults show longer reaction times than younger adults when asked to direct their eyes toward visual signals (e.g., Carter, Obler, Woodward, & Albert, 1983; Fischer, Biscaldi & Gezeck, 1997). However, investigation of age-related performance on antisaccade tasks has started only recently. Surprisingly, these few studies have revealed only modest evidence of age-related differences. Olincy, Ross, Youngd, and

Freedman (1997) reported an age-related decline, specific to antisaccades, in both SRTs and accuracy of saccade direction across the adult life span. However, caution should be taken with the interpretation of these results because the participants in their experiment were tested for only a few minutes without prior practice. In studies in which participants were tested and practiced more extensively, younger and older adults showed comparable performance in terms of the percentage of reflexive direction errors in the antisaccade task (Munoz, Broughton, Goldring, & Armstrong, 1998) and the extra time needed to initiate correct antisaccades compared to prosaccades (Fischer et al., 1997; Munoz et al., 1998).

Arguing that cognitive limitations arise most clearly when the system is put to the test, Butler, Zacks, and Henderson (1999) included a secondary target identification task in order to force participants to generate rapid saccades and compared a group of young adults with a group of older adults aged 65–80. The secondary task consisted of a briefly presented target stimulus, presented 400 ms after cue onset at the cue location (prosaccade task) or the opposite location (antisaccade task), requiring a non-speeded manual response to its identity. With this version of the task, Butler et al. obtained evidence for an age-related deficit in suppressing reflexive eye movements, as measured by the percentage of eye movements in the direction of the cue. However, as in the studies of Fischer et al. (1997) and Munoz et al. (1998), the delay in initiating antisaccades compared to prosaccades did not differ between age groups. Thus, Butler et al. concluded that the mechanisms needed to generate a correct antisaccade may be preserved in older age.[1]

However, this account leaves unanswered the question why the increased difficulty in suppressing a reflexive saccade was not expressed in an increased reaction time on trials where the tendency was successfully suppressed. The observed age equivalence in the additional time needed to produce an antisaccade may, however, be an outcome specific to the procedure used by Butler et al. (1999). The target stimulus itself may have elicited a fast reflexive saccade, thus reducing the overall average latency of antisaccades. If older adults are more sensitive to reflexive eye movements (in this case, toward the target stimulus), then they may have benefitted more than younger adults from this feature. This would have led to an underestimation of older adults' antisaccade SRTs and consequently to an underestimation of age differences in antisaccade speed. Importantly, an increased dependency of antisaccade initiation on the exogenous support of the target, has been reported by Guitton et al. (1985) in frontal patients, and by Roberts et al. (1994) in young adults under conditions of high cognitive load. We propose that a more accurate estimate of antisaccade SRT may be obtained through the use of long intervals between cue and target, which prevents visual guidance of the target stimulus. Thus, if older adults' initiation of antisaccades is somehow dependent on the exogenous support of the target, then a delayed presentation of the target should result in delayed antisaccades. Therefore, we expect that possible age differences in antisaccade speed—crucial to the controversy between the IPR hypothesis and the spatial–nonspatial hypothesis—will become most apparent under conditions of little exogenous support of the target, that is, at long cue-targets intervals.

The Present Paradigm

In our experiments, we studied horizontal and vertical pro- and antisaccades in a group of university students and in a group of healthy older adults. The paradigm is illustrated in Figure 1. Participants were instructed to maintain fixation until a salient cue (a procue or anticue) briefly flashed in one of four locations. At cue onset, participants were to move their eyes as fast as possible either to the cued location or to the opposite location, depending on the instruction. After a variable stimulus onset asynchrony (SOA), a target was presented in the target location for a very brief time, and participants were required to give a nonspeeded manual two-choice response with respect to the identity of the target.

SOA was varied between 100 and 1,500 ms for two reasons. First, we intended to extend the study of Butler et al. (1999), by examining the speed of older adults' antisaccades in both the presence and absence of support of the exogenous qualities of the target. If the older adults would be dependent on the exogenous triggering of the target in a similar fashion as the frontal patients reported by Guitton et al., then their antisaccade performance should be found to decrease with increasing time between the cue and the target. Short SOAs were also included in order to provide a motivation for participants to optimize their saccade speed (cf. Fischer et al., 1997; Munoz et al., 1998).

The second reason for varying SOA was to obtain an index of the speed of shifting attention to the target location in response to procues and anticues. The rationale of this approach was that the time needed to direct attention to a certain location can be inferred from the accuracy of identifying targets at that location at various points in time (e.g., Gottlob & Madden, 1998). For example, fast shifts of attention should be evident in relatively high levels of target identification accuracy at short SOAs. Likewise, the time needed to overcome the tendency to attend to anticues should manifest itself in relatively low accuracy levels at the short SOAs. Following a method introduced by Zacks and Zacks (1993; Gottlob & Madden, 1998), we ensured that baseline accuracy of target detection in an additional, neutral cue condition (i.e., in which the cue was not predictive of the target location) was equalized across groups. This was accomplished by adjusting the target duration on an individual level in the practice phase and taking the resulting duration as initial duration in the experimental cue conditions. Under the assumption that the neutral and experimental cue conditions differed only in the possibility to shift attention in advance of the target, this method enabled us to investigate age differences in the speed of attention shifts and the time course of inhibition thereof, while controlling for sensory and motor differences that usually contribute to main effects of age.

If we were able to demonstrate that potential age-related difficulties in inhibiting the tendency to attend to abrupt onsets are not confined to a specific effector system (i.e., the oculomotor system), but do also apply to shifts of attention, this would promote the generalization of our results to other output modalities. This demonstration may seem trivial since studies that have examined the relationship between visuospatial attention and eye movements

[1] Although it may be that older adults sacrificed direction accuracy in order to produce faster antisaccades, such a speed-accuracy trade-off was deemed unlikely on the basis of the prosaccade data, which showed equal error rates for younger and older adults.

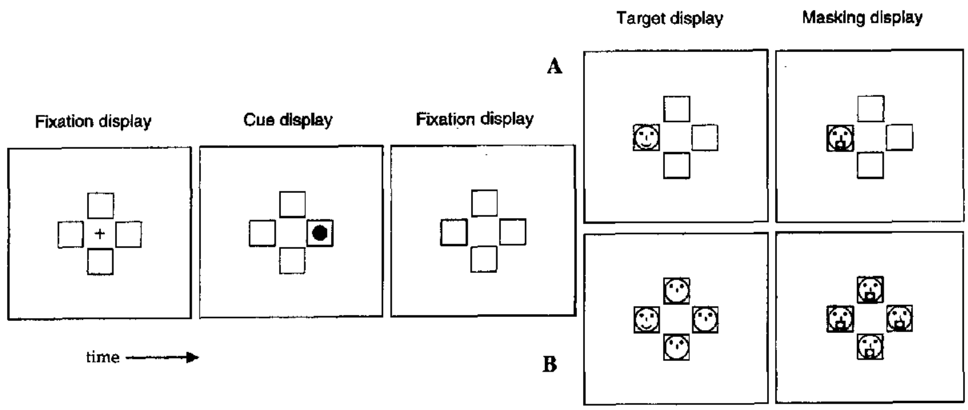

Figure 1. Example of sequence of events for an anticue trial in Experiment 1 (A) and Experiment 2 (B). See text for actual size. Participants fixated on the central cross. A cue then appeared for 67 ms. After a variable stimulus onset asynchrony, starting at cue onset, the target appeared for a variable duration before being masked.

have often found an intimate coupling between the programming of saccades and shifts of visual attention (e.g., Hoffman & Subramaniam, 1995; Rizzolatti, Riggio, & Sheliga, 1994). However, recent research with the antisaccade task suggests that attention may often move in the intended direction even though concurrently a reflexive eye movement is being made in the wrong direction (Mokler & Fischer, 1999; Deubel, Mokler, Fischer, & Schneider, 1999).

Experiment 1

Method

Participants. Eighteen young (10 women and 8 men) and 18 older (10 women and 8 men) adults participated in this experiment. The young participants, ranging in age from 18 to 25 years (M age = 20.3, SD = 1.8), were undergraduate students at the University of Amsterdam and received course credits for their participation. The older participants ranged in age from 59 to 80 years (M age = 68.9, SD = 6.2) and were paid for their participation. A standard health questionnaire revealed that none of the older participants had serious health problems or were using psychoactive medication. Also, all older participants were relatively healthy and alert according to self-report and were living independently in their own homes. Their mean years of education was 10.7.

Apparatus and stimuli. Stimuli were presented on a black computer screen. The fixation display consisted of a central fixation cross, subtending 0.7°, surrounded by four boxes that were symmetrically positioned above, below, to the left and right of the cross. The boxes each subtended 4.3°, both horizontally and vertically, and the visual angle between fixation and the center of each box was 9.0°. Cues were yellow circles, subtending 1.5°, and were presented in the center of a box. The target consisted of a schematic face in the shape of a circle with a diameter equal to the length of the side of a box. The mouth, which differentiated between a happy and a sad face, subtended 1.5° × 0.5°. Eye movements were recorded with an infrared-based iView eye tracker (SMI, Berlin, Germany) with 50-Hz temporal resolution and a <0.1° spatial resolution. The head was stabilized by means of a chin rest, which was located 40 cm from the monitor.

Design. There were two experimental cue conditions: (a) the procue condition in which the face appeared in the cued box, and (b) the anticue condition in which the face appeared in the box opposite from the cued box. In addition, there was a neutral control condition in which each of the boxes was cued at the same time, and accordingly, participants received no information about the location of the target. After having received practice with each of the conditions, participants entered the experimental phase, which consisted of four sets of four blocks. Cue condition (procue or anticue) was held constant within each set and was varied across sets according to an *ABBA* design with half of the participants starting in the procue condition. One third of the trials in each block was in the neutral condition. These trials were randomly intermixed with the experimental trials. The first of every four blocks consisted of 24 trials, all of which were discarded because of carry-over effects from the other cue condition. The other three blocks consisted of 60 experimental trials each. Five SOAs (100, 300, 600, 1000, or 1500 ms) were used. On the basis of pilot work, these were thought sufficient to capture the dynamics of the visual attention shifts. SOA was randomly varied within blocks, but the percentage of trials with each SOA was controlled to yield approximately 27% trials with each of the two shortest SOAs, 20% with the intermediate SOA, and 13% with each of the two longest SOAs.[2] Cue location was randomly determined on each trial.

Procedure. The experiment involved one session, which lasted approximately 2 hr. Before the start of each experimental set, participants fixated three series of five calibration targets that were presented on the screen, one at a time and in the shape of a plus symbol. The iView system was calibrated by computing the linear regression of target location on the average eye-position signal. Following calibration, participants received a practice set of 4 blocks, each of 90 trials, before entering the experimental phase. In the second and third block, they received practice with the procue and anticue condition, respectively. The first and the fourth block consisted of only neutral condition trials.

Before the experiment, participants received written instructions to direct their eyes at fixation at the start of each trial. After a fixed duration of 1300 ms, the fixation point disappeared and, after a gap period of 200 ms, the cue was briefly presented for 67 ms. This gap between fixation point and cue allows for faster prosaccadic reaction times (which is generally referred to as the *gap effect*) and results in more reflexive direction errors in the antisaccade task (Fischer & Weber, 1993). Participants were instructed to move their eyes to the target location as soon as possible in order to improve their accuracy scores. After a variable SOA, starting at

[2] The estimated variance of the proportion of correct manual responses for each SOA was $p \times (1 - p)/n$, where p is the probability of a correct response, and n is the number of trials. Because p increased with SOA, we needed fewer trials at the long SOAs than at the short SOAs in order to obtain a similarly reliable estimate of the percentage of correct responses.

cue onset, the face was displayed until a (nonspeeded) response was registered by the computer keyboard. Response keys, "v" for happy and "n" for sad, were operated by the left and right index fingers. Importantly, the discriminative feature of the face—the mouth—was masked after an individually calibrated duration. The practice phase was used to determine the time that the mouth should be displayed, before being masked, in order to yield 67% correct responses with the neutral cue for that particular participant. This was done by means of a staircase tracking algorithm. The resulting target duration was used as initial duration in the experimental phase, but, if necessary, target duration was adjusted at the start of a new experimental set with the aim of maintaining participants at a 67% accuracy level in the neutral cue condition. Mean target duration differed between age groups [123 ms for the young and 213 ms for the older adults, $F(1, 34) = 18.3$, $p < .001$]. Before the start of each block, participants were informed about the upcoming cue condition. At the end of each block, feedback about manual response accuracy was presented on the computer screen. Finally, a rest break of 10 min was allowed after the training phase and after the second experimental set for young adults. Older adults had a rest break after each experimental set.

Results

In both experiments, p values were corrected using the Greenhouse–Geisser adjustment of degrees of freedom when necessary.

Manual response accuracy. The analysis of the manual response data included all experimental trials. Table 1 shows the response accuracy data for both groups as a function of cue condition and SOA. For young adults, accuracy in both cue conditions quickly approached a high asymptotic level, although the cuing effect, the difference between prosaccade and antisaccade accuracy, appeared to persist for about half a second. A comparison with the two functions of the older adults revealed clear age deficits, both in the steepness and in the asymptotic level of the functions. This was especially evident for the anticue condition, causing the cuing effect of older adults to persist for more than 1 s. Indeed, unlike for young adults, the anticue function for older adults remained at the neutral control level for at least 300 ms, suggesting a much stronger tendency for the cue to pull attention to the wrong location.

Table 1
Manual Accuracy (in Percentages) for Younger and Older Adults as a Function of Cue Condition and SOA (in ms) in Experiment 1

	% correct							
	Young				Old			
SOA	Neu	Pro	Anti	Effect	Neu	Pro	Anti	Effect
100	58	69	60	9	61	74	60	14
300	68	89	78	11	65	83	65	18
600	68	97	95	2	68	91	81	10
1000	61	96	97	−1	66	94	88	6
1500	68	97	97	0	66	92	91	1

Note. SOA = stimulus onset asynchrony; Neu = neutral cue condition; Pro = procue condition; Anti = anticue condition; Effect = cuing effect (pro–anti). Standard errors in the experimental cue conditions ranged between 0.6–2.0 (*Mdn* = 1.1) for younger adults and between 1.2–2.4 (*Mdn* = 1.9) for older adults.

Trials from the neutral cue condition were analyzed separately using a two-way ANOVA with age as between-subjects factor and SOA as within-subjects factor. The staircase tracking procedure was successful in equating both age groups in the neutral condition, as indicated by a nonsignificant main effect of age, $F(1, 34) < 1$. The main effect of SOA was significant, $F(4, 136) = 9.6$, $MSE = 45.89$, $p < .001$, but the performance pattern across SOA was similar for both age groups, $F(4, 136) = 2.1$, $MSE = 45.89$, $p > .05$. The effect of SOA was due mainly to the relatively low accuracy at the shortest SOA. We believe that this is an instance of forward masking by light (see, e.g., Kahneman, 1968), in this case of the highly illuminant cue. Note that this masking effect might have caused an underestimation of the cuing effect for both age groups at the shortest SOA, because it hampers target detection in the procue condition where the target replaces the cue but not in the anticue condition where cue and target appear in different locations.

For the main analysis of manual response accuracy, the data were submitted to a three-way ANOVA with age as between-subjects factor and SOA and cue condition as within-subjects factors. All three main effects and all three two-way interactions were highly significant, $p < .001$. Taken across the two cue conditions, the young adults ($M = 87\%$) were more accurate than the older adults ($M = 82\%$), $F(1, 34) = 20.7$, $MSE = 128.97$, indicating that the former group shifted their attention more efficiently in response to informative cues. As expected, accuracy was significantly lower in the anticue condition ($M = 81\%$) than in the procue condition ($M = 87\%$), $F(1, 34) = 95.3$, $MSE = 45.22$, and, importantly, this cuing effect was more pronounced for the older adults (*Ms* = 77% vs. 87%) than for the young adults (*Ms* = 85% vs. 89%), $F(1, 34) = 14.8$, $MSE = 45.22$. The factor SOA showed a significant main effect, $F(4, 136) = 290.5$, $MSE = 38.37$, $p < .001$, and entered in a reliable interaction with cue condition, $F(4, 136) = 21.0$, $MSE = 30.74$, reflecting a slower rise in accuracy in the anticue condition. The three-way interaction, indicating how the development of the cuing effect over time differs between age groups, failed to confirm the impression that older adults needed longer SOAs than younger adults to attain asymptote accuracy in the anticue condition, $F(4, 136) = 1.2$, $MSE = 30.74$, $p = .3$, observed power = .30.

Eye movement indices. From the eye movement data, several dependent measures were determined offline. *Saccadic reaction times* (SRTs) were defined as the time, relative to the onset of the cue, at which the velocity signal exceeded 25°/s, and the position signal exceeded 2.5°. The definition of direction errors was limited to those trials in which the first saccade was in the opposite direction from the target stimulus. Corrective saccades were defined as those saccades that followed a direction error and were opposite in sign from the erratic saccade. Finally, *saccadic correction time* (SCT) was defined as the time between the onset of the direction error and the onset of the corrective saccade. Initial analyses showed that horizontal saccades were faster and more error prone than vertical saccades. However, unless explicitly mentioned, saccade dimension (i.e., horizontal or vertical) did not interact with any of the main independent variables and was therefore excluded as factor in follow-up ANOVAs.

Discarded data. Trials from the neutral cue condition were not included in the eye movement analyses. Further, for various reasons, some trials from the experimental cue conditions were discarded. First, trials were discarded if no saccade was made after cue onset. This led to a data loss of 1.5% and 1.9% for the young and older adults, respectively. Second, trials with SRTs less than 80 ms were classified as anticipations (e.g., Fischer et al., 1997) and were also excluded. This resulted in a loss of 2.9% and 7.1% for the young and older adults, respectively. Third, trials were discarded in which the primary or secondary saccade moved along the irrelevant dimension. This led to a data loss of 5.6% and 14.7% for the young and older adults, respectively. An ANOVA revealed that the remaining subset of the experimental trials showed no systematic differences in behavioral measures with the overall dataset. One older and one younger participant were excluded from the analysis of error SRTs and SCTs because they made too few errors to obtain reliable averages.

Saccadic reaction times. The upper left panel of Figure 2 presents mean correct SRT for the two age groups in both cue conditions. Two findings seem especially noteworthy. First, the age-related slowing of SRTs manifest in prosaccades was more pronounced in antisaccades. Second, the antisaccades of the older group exhibited a marked increase in SRT with SOA, suggesting that older adults' antisaccade performance was somehow supported by the onset of the target.

An ANOVA produced significant main effects of age (young, M = 277 ms; older, M = 478 ms), $F(1, 34) = 43.6$, MSE = 83,330.95; cue condition (pro, M = 301 ms; anti, M = 455 ms), $F(1, 34) = 169.7$, MSE = 12,632.66; and SOA, $F(4, 136) = 23.7$, MSE = 9,571,23, all $ps < .001$. The main effect of SOA was qualified by the interaction with age, $F(4, 136) = 10.6$, MSE = 9,571.23, $p < .001$, and cue condition, $F(4, 136) = 7.9$,

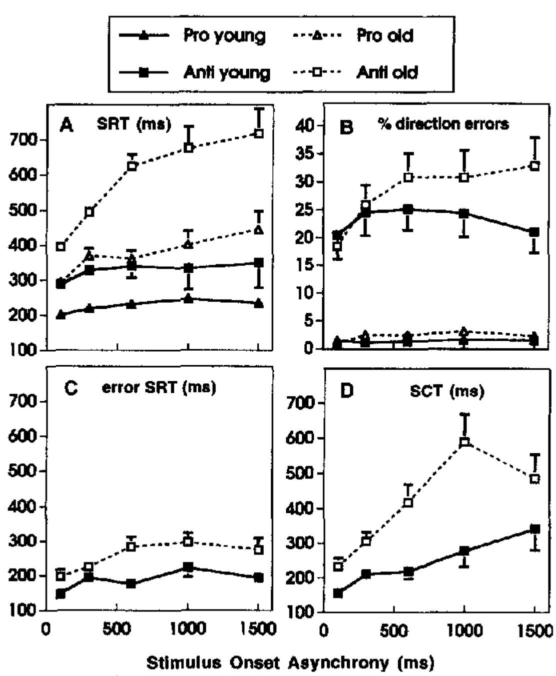

Figure 2. Eye movement indices for younger and older adults as a function of cue condition and stimulus onset asynchrony in Experiment 1. (A) Correct saccadic reaction times (SRTs). (B) Percentage of direction errors. (C) SRTs of direction errors. (D) Saccadic correction times (SCTs).

MSE = 4,669.99, $p < .001$. These interactions and the significant three-way interaction, $F(4, 136) = 6.9$, MSE = 4,669.99, $p < .001$, support the view that the SOA effect was due mainly to the slowing with SOA of older adults' antisaccades. Finally, there was a reliable interaction between age and cue condition, $F(1, 34) = 20.1$, MSE = 12,632.66, $p < .001$, confirming the impression that the amount of age-related slowing was more evident for antisaccades (Ms = 328 ms vs. 582 ms) than for prosaccades (Ms = 227 ms vs. 375 ms).

An important question refers to the extent to which age-related effects on antisaccade performance are unique to the speed of antisaccades. There is an impressive literature suggesting that age-related differences in a variety of cognitive measures are mediated by age differences in such general factors as working-memory capacity or simple processing speed (see, e.g., Salthouse, 1996). To investigate to what extent the slowing of antisaccades in the older age group could be explained by an age-related decline in simple processing speed, we took the following steps. The additional time consumed by the control processes engaged in the generation of antisaccades vis-à-vis prosaccades is reflected most directly in the difference between antisaccade SRT and prosaccade SRT, because this difference measure does not include overhead factors such as saccade initiation and movement time. If age has a deteriorating effect on the speed of these control processes that exceeds the global effect of age on the speed of all cognitive operations, then an age effect on the difference measure should remain present after partialing out the age effects on basic processing speed. The most direct measure of basic processing speed in the present context is prosaccade SRT. Thus, we computed the total variance in the difference measure as explained by age, and then determined what proportion of this total age-related variance was explained uniquely by age after partialing out the age-related variance in basic processing speed (following the statistical control procedures suggested by Salthouse, 1996). In this experiment, this proportion (.67) was considerably greater than zero, thus justifying an interpretation of the observed age effects in terms of the control processes of interest, rather than in terms of global slowing.

Direction errors. The upper right panel of Figure 2 shows the percentage of direction errors for both age groups as a function of age group. As expected, participants made virtually no direction errors in the procue condition. We analyzed only the trials from the anticue condition. The main effect of SOA was significant, $F(4, 136) = 5.3$, MSE = 161.33, $p < .005$, as was the interaction among SOA and age, $F(4, 136) = 2.6$, MSE = 161.33, $p = .05$, indicating a steady rise with SOA of the percentage of direction errors for older adults. Similar to the increase in correct antisaccade RT with SOA, this seems to suggest that the initiation of some potential errors was cancelled in time by the onset of the stimulus in the target location. Together, this resulted in a nonsignificant main effect of age, $F(1, 34) = .7$, $p > .4$. As already mentioned, horizontal saccades were more error prone than vertical saccades, $F(1, 34) = 13.9$, MSE = 206.89, $p < .001$. To our surprise, the dimension factor showed an interaction with age group, $F(1, 34) = 26.2$, MSE = 206.89, $p < .001$: whereas compared with the young group, the older adults made far more horizontal direction errors, the vertical errors showed virtually no trace of such an age effect.

The lower left panel of Figure 2 presents SRTs of direction errors, which, as expected, were much faster than the SRTs of correct saccades, as confirmed by a separate t test, $t(1, 35) = 6.7$, $p < .001$. An ANOVA showed that the main effect of age was again significant, $F(1, 32) = 10.9$, $MSE = 18{,}677.00$, $p < .005$, indicating slower error SRTs for the older group. The main effect of SOA was also highly significant, $F(4, 128) = 6.5$, $MSE = 5{,}626.89$, $p < .001$, and although, again, the older adults showed a more notable effect of target onset time, the interaction with age was not significant, $F(4, 128) = 1.3$, $p = .28$.

Finally, mean saccadic correction times are depicted in the lower right panel of Figure 2. Most notably, the older group showed a dramatic increase in SCT with SOA. We found main effects of both age, $F(1, 32) = 18.2$, $MSE = 64{,}489.34$, $p < .001$, and SOA, $F(4, 128) = 11.9$, $MSE = 29{,}459.96$, $p < .001$, the latter effect suggesting that the correction of direction errors was quickened by the appearance of the target stimulus. Indeed, as was the case with most of the dependent measures, the effect of SOA was qualified by a marginal interaction with age, $F(4, 128) = 2.6$, $MSE = 29{,}459.96$, $p = .07$, indicating that older adults benefited the most from the exogenous triggering qualities of the target. To investigate whether older adults' sizeable SCTs at the longer SOAs were a mixture of relatively fast, voluntary corrections and slow corrections triggered by the onset of the target, we computed for both groups the percentage of voluntary corrective saccades at each SOA. Assuming that onsets faster than 80 ms after target onset could be considered voluntary, we found percentages of 0%, 81%, 97%, 96% and 95% with increasing SOA for the young adults, and percentages of 0%, 38%, 77%, 92% and 100% for the older adults. Clearly, these percentages reject the mixture hypothesis raised above. Moreover, although older adults produced more visually guided corrections at the intermediate SOAs than younger adults, this may be explained at least in part by their increased error SRT.

Discussion

The results of Experiment 1 confirm the basic findings usually obtained in the antisaccade paradigm. First, anticues were effective at inducing a prepotent response tendency, as indicated by a substantial amount of direction errors for both younger and older adults. In contrast, performance in the procue condition posed no problems for either group of participants. Second, it took participants longer to initiate antisaccades than prosaccades and corrective saccades. This result is consistent with the idea that it takes some time to override the reflexive pull of the cue. Finally, latencies of direction errors in the antisaccade task were faster than latencies of correct prosaccades, suggesting that at least some portion of these eye movements were emitted in a purely reflexive fashion.

The main purpose of Experiment 1 was to examine age-related differences in antisaccade task performance in order to investigate whether the IPR hypothesis of aging extends to tasks requiring the active suppression of a spatial response. We found that, at least in the absence of immediate support of the exogenous qualities of the target (i.e., at longer SOAs), older adults appeared to have more difficulties than younger adults suppressing saccades toward the abrupt onset cue. This was evident in the percentage of direction errors, which was higher for older adults than for younger adults. In addition, and in contrast to previous research (e.g., Butler et al., 1999), we found that the control processes specific to antisaccade task performance were prolonged in older age. Importantly, only a minor part of the age-related variance in the duration of these processes could be explained in terms of generalized slowing. We argue that the slowing of antisaccades reflects in part the increased problems that older people experience at inhibiting the prepotent response. Note, however, that the requirement to inhibit the reflexive eye movement in the antisaccade task is confounded with the necessity to generate a voluntary eye movement, which may also show an impairment with age. Indeed, this is suggested by our finding that older participants showed dramatically increased saccadic correction times at the longer SOAs, almost all of which were voluntary, that is, in advance of the target.

The present results provide a demonstration that the notion of selective age-related sparing of spatial inhibition is not generally valid. Rather, it appears that the well-documented age deficit in the inhibition of prepotent responses also applies to the active inhibition of spatial responses. Importantly, this finding does not seem to be restricted to the inhibition of the oculomotor system. In general, the eye movement results paralleled age differences in the speed of spatial attention shifts, as measured by the accuracy of target detection. The cuing effect, defined as the difference between manual response accuracy in the antisaccade task and the prosaccade task, was larger for older than for younger adults. Presumably, older adults were less capable of overriding the automatic orienting response with a voluntary attention shift away from the cue.

One remaining issue that we discuss concerns the finding that antisaccade performance of older adults became progressively worse with increasing intervals between cue and target. If the target appeared almost immediately after the cue, then older adults displayed faster antisaccades and fewer direction errors than if the SOA were relatively long. Apparently, their antisaccade performance was dependent on the support of the target, which by definition indicated the destination of the required eye movement. Only when given ample time (i.e., at the longest SOAs) did older adults manage to initiate many of their antisaccades before target onset. Importantly, our finding supports the notion that the reported age equivalence in antisaccade SRT in Butler et al.'s (1999) study may be due to the use of a relatively short and fixed SOA. Moreover, a related finding was reported by Guitton et al. (1985), who studied the performance of frontal lobe patients in the antisaccade task. Compared with age-matched controls, these patients' direct antisaccades as well as their corrective saccades after direction errors were more often triggered by the appearance of the target, suggesting that they experienced problems at initiating saccades toward an empty location. Indeed, the need for strong retrieval cues to guide behavior has been associated with both healthy aging and frontal lobe pathology (e.g., Duncan, Emslie, Williams, Johnson, & Freer, 1996; Maylor, 1996). It could be argued, then, that the true age deficit in antisaccade performance—thought to reflect older adults' inherent limitations in the ability to reconcile the conflict between a prepotent response and a desired, voluntary response—is only visible at long SOAs (cf. Butler et al., 1999).

There is, however, an alternative interpretation of the SOA pattern obtained for the older adults in our experiment. It is possible that even if older adults were, in principle, capable of using the cue to produce fast and accurate antisaccades, they might not always use this ability. For reasons discussed below, we label this possibility the *intention-activation hypothesis* (cf. De Jong, Berendsen, & Cools, 1999). Note that effective use of the opportunity to shift the eyes in advance of the target was optional, because the present design allowed saccades to be visually guided by the target, which in most instances appeared very soon after the cue. Such a passive performance mode would explain the strong correlation between older adults' antisaccade speed and SOA. If, by neutralizing the triggering effect of the target, older adults were forced to move their eyes on the basis of the cue, they might become faster in the anticue condition. Assuming that the intention-activation hypothesis does not apply to younger adults, such a speed-up of older adults' performance in the anticue condition would be apparent in reduced age differences in the speed of direct antisaccades, corrective saccades, and in the size of the cuing effect. This is what we set out to investigate in Experiment 2.

Experiment 2

The primary objective of Experiment 2 was to evaluate the above raised intention-activation hypothesis of the results of the older adults in Experiment 1. To attain this goal, we chose a design that was identical to Experiment 1 with one exception. To neutralize the unique exogenous qualities of the target, we presented three distractors in the target display. These distractors were similar to the target, except that they lacked a distinguishing feature (i.e., the mouth), and they were presented at the same time as the target in the three remaining possible target locations. The manipulation of the target display necessitated the use of the cue in order to produce task-relevant eye movements and thus to perform above chance level in the target detection task. This allowed us to examine age differences in the initiation of purely voluntary antisaccades. The general prediction derived from the intention-activation hypothesis was that in Experiment 2 older adults would choose a different performance mode and would more often use the cue, compared with the older adults in Experiment 1. The performance benefit associated with this change in performance mode should be apparent in smaller age differences in the speed of voluntary eye movements (i.e., direct antisaccades and corrective saccades) and attention shifts (i.e., the cuing effect).

Method

Participants. Sixteen young (12 women and 4 men) and 16 older (12 women and 4 men) adults participated in this experiment. None of them had participated in Experiment 1. The young participants, ranging in age from 18 to 25 years (M age = 21.1, SD = 1.9), were undergraduate students at the University of Amsterdam and received course credits for their participation. The older participants ranged in age from 61 to 79 years (M age = 68.6, SD = 5.3) and were paid for their participation. The data from one older participant were discarded because she was not able to fixate at the start of a trial. The data from another old participant were discarded because he was unable to respond above chance level in the experimental conditions. Both participants were replaced. A standard health questionnaire revealed that none of the older participants had serious health problems or were using psychoactive medication. Also, all older participants were relatively healthy and alert according to self-report and were living independently in their own homes. Their mean years of education was 12.1. All of the young and older participants had far and near visual acuities of at least 0.5 as measured by Snellen charts.

Apparatus and stimuli. Apparatus and stimuli were the same as in Experiment 1. The distractors were faces, identical to the target, but without a mouth (see Figure 1).

Design and procedure. Design and procedure were the same as in Experiment 1 with the following exceptions. The distractors were presented and masked at the same time as the target face. No distractors were presented on neutral cue trials. Participants received the same amount of practice as in Experiment 1, initially without distractors in order to gradually build up task complexity. Mean target duration was 133 ms for the young and 215 ms for the older adults, $F(1, 30) = 15.2, p < .001$.

Results

Manual response accuracy. The analysis of the manual response data included all experimental trials. Table 2 shows the response accuracy data for both groups as a function of cue condition and SOA.

The data from the neutral cue condition were analyzed separately. The staircase tracking procedure was successful at equating both age groups in the neutral condition, as indicated by the lack of an effect of age, $F(1, 30) < 1$. The main effect of SOA was significant, $F(4, 120) = 7.4$, $MSE = 52.57$, $p < .001$. This was again due to the low accuracy at the shortest SOA, probably reflecting forward masking of the cue. As in Experiment 1, this performance pattern across SOA was similar for both age groups, $F(4, 120) = 2.1$, $MSE = 52.57$, $p > .1$.

The data from the experimental cue conditions showed two important departures from Experiment 1. First, in the absence of support from the exogenous qualities of the target, both age groups showed decreased manual accuracy levels at the two shortest SOAs compared to Experiment 1. Second, in contrast to the younger adults who showed similar cuing effects as in Experiment 1, the older adults revealed a marked reduction in the size of the cuing effect. This finding was supported by the absence of an interaction between age group and cue condition, $F(1, 30) = .01$, $MSE = 124.50$, $p > .9$. The other main effects and interactions were similar to Experiment 1. We will suffice here with a list of the statistics of these effects: age group (young, M = 83%; older, M = 79%), $F(1, 30) = 7.0$, $MSE = 244.53$, $p < .05$; cue condition (pro, M = 83%; anti, M = 79%), $F(1, 30) = 13.0$, $MSE = 124.50$, $p < .005$; SOA, $F(4, 120) = 229.0$, $MSE = 67.54$, $p < .001$; Cue Condition × SOA, $F(4, 120) = 14.2$, $MSE = 29.26$, $p < .001$;

Table 2
Manual Accuracy (in Percentages) for Younger and Older Adults as a Function of Cue Condition and SOA (in ms) in Experiment 2

	% correct							
	Young				Old			
SOA	Neu	Pro	Anti	Effect	Neu	Pro	Anti	Effect
100	57	61	55	6	64	61	54	7
300	66	82	68	14	68	75	63	12
600	70	93	91	2	68	87	82	5
1000	69	95	95	0	67	89	91	−2
1500	68	96	95	1	69	92	91	1

Note. SOA = stimulus onset asynchrony; Neu = neutral cue condition; Pro = procue condition; Anti = anticue condition; Effect = cuing effect (pro–anti). Standard errors in the experimental cue conditions ranged between 1.1–2.4 (Mdn = 1.6) for younger adults and between 1.3–3.5 (Mdn = 2.5) for older adults.

three-way interaction, $F(4, 120) = .5$, $MSE = 29.26$, $p = .7$. The effect of the target-display manipulation on the age difference in the size of the cuing effect was further confirmed by an additional between-experiments analysis, which showed a significant Experiment × Age Group × Cue Condition interaction, $F(1, 64) = 4.1$, $MSE = 82.38$, $p < .05$.

Discarded data. For various reasons, some trials from the experimental cue conditions were discarded. First, trials were discarded if no saccade was made after cue onset. This led to a data loss of 0.2% and 0.8% for the young and older adults, respectively. Second, trials with SRTs less than 80 ms were classified as anticipations and were also excluded. This resulted in a loss of 2.9% and 4.8% for the young and older adults, respectively. Third, trials were discarded in which the primary or secondary saccade moved along the irrelevant dimension. This led to a data loss of 9.7% and 16.6% for the young and older adults, respectively. An ANOVA revealed that the remaining subset of the experimental trials showed no systematic differences in behavioral measures with the overall dataset. Finally, one older and one younger participant were excluded from the analysis of error SRTs and SCTs because they made too few errors to obtain reliable averages.

Saccadic reaction times. The presentation of distractors in the target display in Experiment 2 noticeably reduced the SOA effect on older adults' antisaccade reaction times (see upper left panel of Figure 3). This supports our notion that the older group in Experiment 1 made heavy use of the triggering qualities of the target onset. In the present experiment, the main effect of SOA was still significant, $F(4, 120) = 2.2$, $MSE = 67.54$, $p < .001$. This probably reflects an aspecific alerting effect of the onset of the

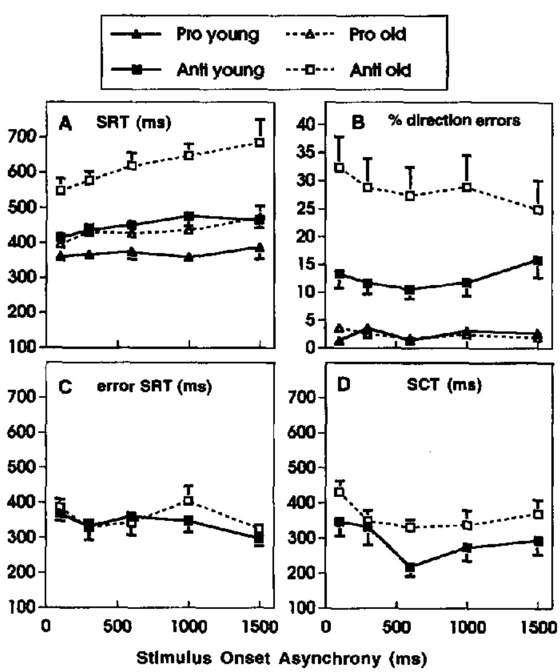

Figure 3. Eye movement indices for younger and older adults as a function of cue condition and stimulus onset asynchrony in Experiment 2. (A) Correct saccadic reaction times (SRTs). (B) Percentage of direction errors. (C) SRTs of direction errors. (D) Saccadic correction times (SCTs).

target display. In contrast to Experiment 1, however, the two age groups did not statistically differ in the effect of SOA, $F(4, 120) = 2.2$, $MSE = 4797.73$, $p = .13$, observed power = .38; or the interaction between cue condition and SOA, $F(4, 120) = .9$, $MSE = 2156.12$, $p = .45$, observed power = .24.

Interestingly, the manipulation of the target display also seemed to have a disrupting effect on the time to initiate saccades. This was especially evident for the younger adults whose SRTs were slowed substantially compared with the young participants in Experiment 1. The effect of age group on SRTs (young, $M = 409$ ms; older, $M = 523$ ms) was nevertheless reliable, $F(1, 30) = 13.1$, $MSE = 244.53$, $p < .005$. Also, and most important, the effect of cue condition, $F(1, 30) = 64.2$, $MSE = 21255.83$, $p < .001$, was more manifest for the older (*M*s = 432 ms vs. 615 ms) than for the younger adults (*M*s = 370 ms vs. 448 ms), $F(1, 30) = 10.1$, $MSE = 21255.83$, $p < .005$, thereby replicating Experiment 1. Interpretation of this age difference in terms of global slowing was not possible, because there was virtually no correlation between basic processing speed and effect size (.08). A between-experiments test yielded a nonsignificant interaction of Experiment × Age Group × Cue Condition, $F(1, 64) < 1$, indicating that the decrease in age effects on correct SRTs, as observed in Experiment 2 (Experiment × Age, $F(1, 64) = 3.8$, $MSE = 81808.72$, $p = .05$), was similar for prosaccades and antisaccades.

Direction errors. The upper right panel of Figure 3 shows the percentage of direction errors for both age groups as a function of SOA. As expected, participants made virtually no direction errors in the procue condition. We analyzed only the trials from the anticue condition. In contrast to the previous experiment, there was no reliable difference between the percentage of horizontal and vertical direction errors, $F < 1$, $p > .3$. Nor was there a reliable interaction between age group and dimension, $F < 1$, $p > .4$. As Figure 3 illustrates, Experiment 2 succeeded in preventing visually guided support of the target at the short SOAs. This was reflected by the lack of a main effect of SOA, $F(4, 120) = 1.3$, $p > .2$ and the absence of an interaction of age group and SOA, $F(4, 120) = 1.9$, $p > .1$. Most importantly, this resulted in a significant main effect of age group, $F(1, 30) = 7.9$, $MSE = 2363.46$, $p < .01$, indicating that older adults were impaired at suppressing reflexive eye movements toward the cue.

The lower left panel of Figure 3 presents SRTs of direction errors in the antisaccade task. Interestingly, SRTs of these direction errors were approximately twice as slow as those observed in Experiment 1. Also, there was age equivalence in the SRTs of reflexive errors, as confirmed by the lack of a main effect of age group, $F(1, 28) = .4$, $p > .5$. In line with other eye movement indices, the effect of SOA was not significant, $F(4, 112) = 2.0$, $p > .1$.

The lower right panel of Figure 3 shows saccadic correction times after direction errors in the antisaccade task. Note that the SCTs of older adults exhibit an entirely different pattern than in the previous experiment. Although the SCTs of the older group were significantly slower than those of the young group, $F(1, 28) = 13.1$, $MSE = 34559.51$, $p < .05$, this relatively small age difference did not grow larger with increasing SOA as in Experiment 1. This observation, supported by the lack of an interaction between age group and SOA, $F(4, 112) = .5$, $p > .6$, is compatible with the intention-activation hypothesis of the results of older adults in Experiment 1. A significant main effect of SOA, $F(4,$

112) = 2.2, MSE = 16974.42, $p < .05$, indicated that SRTs were somewhat slower at the shortest SOAs. Finally, in line with the observed reduction of older adults' SCTs in Experiment 2, a between-experiments analysis revealed a marginally significant interaction effect of experiment and age group, $F(1, 64) = 3.2$, MSE = 52569.71, $p = .08$, observed power = .42.

Discussion

The results of Experiment 2 are consistent with the notion that older adults are less capable than younger adults of actively suppressing an unintended saccade toward a highly salient abrupt onset. As in the previous experiment, older adults misdirected their eyes to the abrupt onset more often and were slower at initiating correct antisaccades than younger adults. Unlike in Experiment 1, age differences in the percentage of direction errors were also present at short SOAs, reflecting the effect of the target display manipulation, which neutralized the exogenous quality of the target, and for saccades in the vertical dimension, emphasizing the central nature of the inhibitory age deficit. Like in Experiment 1, older adults also displayed elevated SCTs, suggesting that they were impaired at the initiation of voluntary antisaccades after an error. These results emphasize the robustness of our findings in Experiment 1 and thus provide evidence in favor of the IPR hypothesis and against the generality of the spatial–nonspatial hypothesis of inhibitory decline in older age.

The principal aim of Experiment 2 was to evaluate the intention-activation hypothesis by means of a between-experiments comparison of the target display manipulation. Although one should be aware of sampling error in comparing different groups of participants, it seems unlikely that this caused the notable differences between Experiment 1 and 2. Note that the intention-activation hypothesis predicted smaller age differences in the present experiment compared to Experiment 1. Two performance indices in particular supported this prediction. First, in Experiment 2, the age difference in the speed of generation of corrective saccades was substantially smaller than in Experiment 1. A similar trend was present for direct antisaccades, but the interpretation of this finding was complicated by the finding of an equivalent decrease in age differences in prosaccade speed. Second, in contrast with Experiment 1, both age groups showed similar attention cuing effects in Experiment 2, suggesting age equivalence in the extra amount of time needed to overcome the pull of an anticue and shift attention to the other side.

In contrast with these speed measures, the display manipulation seemed, if anything, to increase the age difference in the number of direction errors in the antisaccade task. Apparently, forced use of the cue speeded up older people's voluntary eye movements and attention shifts, but did not reduce their susceptibility to move their eyes toward it. The notion that aging affects the time needed to activate relevant cue-action schemas but not the sensitivity to the cue (as measured by a change in performance elicited by the cue) gains support by analogy to recent research on age differences in prospective memory. Prospective memory is defined as the memory of future intentions and the ability to retrieve them and carry them out at the proper time. In laboratory studies of prospective memory, the appropriate time is usually indicated by a cue signal prompting people to allocate attention from an ongoing primary task to the carrying out of the memorized intention. In a typical prospective memory task, West and Craik (1999) found preserved cue sensitivity in older age, as defined by the difference in primary task performance between trials on which the cue failed to elicit the execution of a cue-action schema, and trials on which no cue was presented at all. In contrast, while being only minimally slowed in primary task performance, older adults were much slower than younger adults in the initiation of prospective responses.

The broader implication of these results would seem to be that older adults more frequently fail to maintain an intention to react to discrete imperative signals. In the antisaccade task this means that increasing age results in less efficient use of the opportuny to optimize task performance by means of a voluntary eye movement in response to the cue. Indeed, the importance of intention activation in the antisaccade task has been stressed by Roberts et al. (1994) who noted that "... successful [antisaccade] performance seems dependent on maintaining a high enough level of activation of the relevant self-instructions to make an eye movement to the opposite side at the moment the cue is presented" (p. 391). Interestingly, our results show that failures in intention activation can be overcome under conditions when cue use is mandatory.

General Discussion

The present study focused on the influence of normal aging on the ability to suppress automatic eye movements toward task-relevant, highly salient visual onsets. According to the IPR hypothesis, this ability, as measured in the antisaccade task, should be vulnerable to aging because it involves the active inhibition of an inappropriate, prepotent response tendency in favor of a task-relevant action (Roberts et al., 1994; West, 1996). Given that in the antisaccade task the cue is completely predictable and never primes the target location, participants in this task are required to actively control their looking behavior and avoid shifting their eyes toward the cue. Furthermore, abrupt onset cues, as used in our study, are known to capture covert and overt attention in an automatic way (Theeuwes, Atchley, & Kramer, in press; Yantis, 1998), thus evoking a prepotent response tendency. The tendency to foveate the cue is even more augmented by the relevance of cue location for proper task performance.

The results were consistent with the IPR hypothesis of aging. Older adults were impaired at actively suppressing prepotent eye movements toward task-relevant abrupt onsets, as indicated by an increased percentage of inappropriate, reflexive saccades, and by a task-specific slowing of antisaccade generation. Furthermore, the target-detection accuracy results, reflecting the degree to which attention was focused on the target, were nicely in line with these eye movement findings. The age difference in the size of the cuing effect indicated that older adults were less successful at preventing or overcoming the reflexive pulling of attention by the peripheral cue. This suggests that the inhibitory problems of older adults were not confined to eye movements but also applied to shifts of attention, which is in agreement with the notion that spatial attention usually accompanies eye movements (e.g., Hoffman & Subramaniam, 1995; Rizzolatti et al., 1994). It should be noted, however, that in our experiments attention shifts were always made in the presence of oculomotor activation. It remains an empirical question to what extent these findings generalize to a setting where the deliberate control of strictly covert attention shifts is required. Importantly, our results regarding eye movements and the associated attention shifts are in clear contrast with previous studies suggesting age equivalence in the inhibition of spatial orienting, and thus they provide evidence against the distinction between inhibition of spatial and nonspatial orienting as the crucial determinant of age-related differences in inhibitory function (Connelly & Hasher, 1993; Hartley, 1993; Pratt et al., 1997). Instead, they are consistent with the distinction between reflexively and actively controlled inhibition as important predictor of age-related decline.

There is some neurophysiological evidence for the existence of separate neural pathways supporting reflexively and actively controlled inhibition of spatial responses (see, e.g., Rafal & Henik, 1994). Reflexive inhibition of spatial orienting is dependent on a primarily subcortical pathway through the superior colliculus. For instance, the superior colliculus is well known to be intimately involved in generating inhibition of return (Posner, Rafal, Choate, & Vaughan, 1985), inhibition of spatial location in covert (Posner & Petersen, 1990) and overt (see Rizzolatti et al., 1994) orienting toward peripheral stimuli, and the maintenance of fixation (Munoz & Wurtz, 1992; Pratt et al., 1997), all of which have been found to be resistant to normal aging. It may well be possible, then, that the subcortical brain structures involved in these reflexively controlled forms of inhibition are relatively less affected by the neuronal degeneration usually associated with older age. Indeed, in contrast to most other brain structures the volume of the tectum (i.e., the part of the midbrain that includes the superior colliculus) has been reported to shrink only slightly with increasing age (for review see Raz, 1996; Raz, 2000).

Active inhibition of responses, in general, is thought to be mediated by prefrontal structures exerting control over subcortical reflexes (Roberts et al., 1994; West, 1996). Given that the neurological changes that accompany aging are known to occur earlier and to be more pronounced in the frontal lobes than in other regions of the brain (see, e.g., Van der Molen & Ridderinkhof, 1998; West, 1996), it should perhaps not be surprising that older adults perform more poorly on frontal tasks than do younger adults (Kramer et al., 1994; West, 1996). Conversely, although there is abundant evidence for the existence in the brain of two separate attention systems, an occipital-temporal pathway for the processing of identity information and an occipital-parietal pathway for the processing of or acting on spatial information (see, for review, Milner & Goodale, 1995), we know of no neuroanatomical or neurophysiological studies indicating that these systems are differentially susceptible to aging.

The distinction between two neural pathways, one for active and one for reflexive control, is particularly relevant to eye movement tasks as those used in the present study. Replicating previous studies (Fischer et al., 1997; Munoz et al., 1998), we found relatively similar reaction times of direction errors in the antisaccade task. Other researchers (Pratt et al., 1997) have reported age equivalence in the size of the gap effect, which is probably indicative of an intact fixation system in older adults. Importantly, both the maintenance of fixation and the control of rapid, reflexive eye movements, are known to be mediated by a subcortical pathway involving the superior colliculus (e.g., Schiller, 1998). In contrast, cortical regions, including the frontal eye fields, supplementary eye fields, and dorsolateral prefrontal cortex, subserve the generation of voluntary eye movements and the active inhibition of reflexive eye movements, presumably by controlling the superior colliculus through the basal ganglia (see, for review, Everling & Fischer, 1998). Clearly, both of these purportedly frontal functions were found to be affected in our older adults.

In sum, in line with other eye movement studies our results support the notion of two parallel oculomotor pathways in the brain: One pathway that is responsible for the cortically exerted top-down control of the superior colliculus and the initiation of voluntary eye movements, which loses efficiency in older age. And another, primarily subcortical pathway for the control of rapid, reflexive eye movements, which appears age insensitive (see Fischer et al., 1997, for a similar view).

Contrary to the expectation, on the basis of generalized slowing theory (e.g., Salthouse, 1996), that the increased task complexity of Experiment 2 would add to the already existing age differences in Experiment 1, we found that when forced to use the cue (Experiment 2), older adults' antisaccades and associated attention shifts were less slowed relative to younger adults than when use of the cue was not mandatory (Experiment 1). The combined results from the two experiments are consistent with the hypothesis that the older adults in Experiment 1 had problems maintaining a sufficiently high level of intention activation during the experiment. Experiment 2 indicated that these problems can, in principle, be overcome. This intention-activation account is consistent with the growing body of literature reporting age-related decline in a variety of prospective memory tasks (e.g., Duncan et al., 1996, Experiment 2; West & Craik, 1999), indicating that older adults have a harder time keeping intentions sufficiently activated over time. Importantly, several authors have emphasized the role of the frontal lobes in tasks requiring the active maintenance of future goals (Duncan, 1995; see also West, 1996). Hence, the reported age deficit in intention activation appears to provide additional support for frontal lobe theories of aging (West, 1996).

Duncan and associates (Duncan, 1995; Duncan et al., 1996) have functionally interpreted this frontal deficit in terms of goal neglect, which they defined as a disregard of a task requirement even though it has been fully understood (see also De Jong et al., 1999). Duncan (1995) specified a number of conditions under which goal neglect is likely to occur. One condition is the need to satisfy multiple task requirements at the same time. Interestingly, this might be an explanation for the absence of a specific slowing of antisaccades in older adults in two previous aging studies (Fischer et al., 1997; Munoz et al., 1998). In these studies, the cue was not followed by a target stimulus. Hence, because the generation of fast antisaccades in response to the cue was the sole objective for participants, older adults could focus entirely on this task. In contrast, in the present study the task of producing fast saccades was instrumental with respect to optimal performance in the target detection task. Weak environmental support is another important condition that can give rise to goal neglect. Accordingly, we argued that in this study the more stringent task environment of Experiment 2 served as a form of external support to overcome problems of intention activation in older adults. Other researchers have also emphasized the importance of external support in the form of verbal prompts (Duncan et al.) and explicit task instructions (Eenshuistra, Wagenmakers & De Jong, 1999) in intention activation in older adults and frontal patients (see also Maylor, 1996).

It remains an open question whether problems with the active maintenance of intentions and a reduced ability to suppress prepotent responses are the result of separable frontal functions or do both reflect the decrement of a more general frontal function such as working memory (Roberts et al., 1994). An important message of the present study and the other studies mentioned in this section is that age effects in executive control tasks might reflect real limitations in inhibitory capabilities, failures to fully or consistently utilize such capabilities, or some combination of these factors (De Jong et al., 1999). Therefore, future research should focus on both structural, cognitive limitations and failures in intention activation as determinants of age-related decline in inhibition tasks.

References

Burke, D. M. (1997). Language, aging, and inhibitory deficits: Evaluation of a theory. *Journals of Gerontology: Psychological Sciences, 52B,* P254–P264.

Butler, K. M., Zacks, R. T., & Henderson, J. M. (1999). Suppression of reflexive saccades in younger and older adults: Age comparisons on an antisaccade task. *Journal of Memory and Cognition, 27,* 584–591.

Carter, J. E., Obler, L., Woodward, S., & Albert M. L. (1983). The effect of increasing age on the latency of saccadic eye movements. *Journal of Gerontology, 38,* 318–320.

Connelly, S. L., & Hasher, L. (1993). Aging and the inhibition of spatial location. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1238–1250.

De Jong, R., Berendsen, E., & Cools, R. (1999). Goal neglect and inhibitory limitations: Dissociable causes of interference effects in conflict situations. *Acta Psychologica, 101,* 379–394.

Deubel, H., Mokler, A., Fischer, B., & Schneider, W. X. (1999, September). *Reflexive saccades are not preceded by shifts of visual attention: Evidence from an antisaccade task.* Paper presented at the meeting of the 10th European Conference on Eye Movements, Utrecht, the Netherlands.

Duncan, J. (1995). Attention, intelligence and the frontal lobes. In M. S. Gazzaniga (Ed.), *The Cognitive Neurosciences* (pp. 721–733). Cambridge, MA: MIT Press.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology, 30,* 257–303.

Eenshuistra, R. M., Wagenmakers, E. J. M., & De Jong, R. (1999, September). *Age-related strategy differences in task-switching.* Poster presented at the meeting of the XIth conference of the European Society for Cognitive Psychology, Ghent, Belgium.

Everling, S., & Fischer, B. (1998). The antisaccade: A review of basic research and clinical studies. *Neuropsychologia, 36,* 885–899.

Fischer, B., Biscaldi, M., & Gezeck, S. (1997). On the development of voluntary and reflexive components in human saccade generation. *Brain Research, 754,* 285–297.

Fischer, B., & Weber, H. (1993). Express saccades and visual attention. *Behavioral and Brain Sciences, 16,* 553–610.

Gottlob, L. R., & Madden, D. J. (1998). Time course of allocation of visual attention after equating for sensory differences: An age-related perspective. *Psychology and Aging, 13,* 138–149.

Guitton, D., Buchtel, H. A., & Douglas, R. M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research, 58,* 455–472.

Hallet, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research, 18,* 1279–1296.

Hartley, A. A. (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychology and Aging, 8,* 371–379.

Hartley, A. A., & Kieley, J. M. (1995). Adult age differences in the inhibition of return of visual attention. *Psychology and Aging, 10,* 670–683.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension and aging: A review and a new view. In G. G. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and Performance XVII, Cognitive Regulation of Performance: Interaction of Theory and Application* (pp. 653–675). Cambridge, MA: MIT Press.

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception and Psychophysics, 57,* 787–795.

Kahneman, D. (1968). Method, findings, and theory in studies of visual masking. *Psychological Bulletin, 70,* 404–425.

Kramer, A. F., Hahn, S., Irwin, D. E., & Theeuwes, J. (1999). Attentional capture and aging: Implications for visual search performance and oculomotor control. *Psychology and Aging, 14,* 135–154.

Kramer, A. F., Hahn, S., Irwin, D. E., & Theeuwes, J. (2000). Age differences in the control of looking behavior: Do you know where your eyes have been? *Psychological Science, 11,* 210–217.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9,* 491–512.

Maylor, E. A. (1996). Does prospective memory decline with age? In M. Brandimonte, G. O. Einstein, & M. A. McDaniel (Eds.), *Prospective memory: Theory and applications* (pp. 173–197). Hillsdale, NJ: Erlbaum.

McDowd, J. M. (1997). Inhibition in attention and aging. *Journals of Gerontology: Psychological Sciences, 52B,* P265–P273.

Milner, A., & Goodale, M. A. (1995). *The visual brain in action.* Oxford, England: Oxford University Press.

Mokler, A., & Fischer, B. (1999). The recognition and correction of involuntary prosaccades in an antisaccade task. *Experimental Brain Research, 125,* 511–516.

Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research, 121,* 391–400.

Munoz, D. P., & Wurtz, R. H. (1992). Role of the rostral superior colliculus in active visual fixation and execution of express saccades. *Journal of Neurophysiology, 70,* 576–589.

Olincy, A., Ross, R. G., Youngd, D. A., & Freedman, R. (1997). Age diminishes performance on an antisaccade eye movement task. *Neurobiology of Aging, 18,* 483–489.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13,* 25–42.

Posner, M. I., Rafal, R. D., Choate, L., & Vaughan, J. (1985). Inhibition of return: Neural basis and function. *Cognitive Neuropsychology, 2,* 211–228.

Pratt, J., Abrams, R. A., & Chasteen, A. L. (1997). Initiation and inhibition of saccadic eye movements in younger and older adults: An analysis of the gap effect. *Journals of Gerontology: Psychological Sciences, 52B,* P103–P107.

Rafal, R. D., & Henik, A. (1994). The neurology of inhibition: Integrating controlled and automatic processes. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory, and language* (pp. 1–51). Academic Press.

Raz, N. (1996). Neuroanatomy of aging brain: Evidence from structural MRI. In E. D. Bigler (Ed.), *Neuromimaging II: Clinical applications* (pp. 153–182). New York: Academic Press.

Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik & T. A. Salthouse (Eds.), *Handbook of Aging and Cognition II* (pp. 1–90). Mahwah, NJ: Erlbaum.

Rizzolatti, G., Riggio, L., & Sheliga, B. M. (1994). Space and selective attention. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing. Attention and performance series* (pp. 232–265). Cambridge, MA: MIT Press.
Roberts, R. J., Hager, L. D., & Heron, C. (1994). Prefrontal cognitive processes: Working memory and inhibition in the antisaccade task. *Journal of Experimental Psychology: General, 123,* 374–393.
Salthouse, T. A. (1996). The processing speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428.
Schiller, P. H. (1998). The neural control of visually guided eye movements. In J. E. Richards (Ed.), *Cognitive neuroscience of attention. A developmental perspective* (pp. 3–50). Mahwah, NJ: Erlbaum.
Theeuwes, J., Atchley, P., & Kramer, A. F. (in press). On the time course of top-down and bottom-up control of visual attention. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII.*
Theeuwes, J., Kramer, A. F., Hahn, S., & Irwin, D. E. (1998). Our eyes do not always go where we want them to go: Capture of the eyes by new objects. *Psychological Science, 9,* 379–385.
Van der Molen, M. W., & Ridderinkhof, K. R. (1998). The growing and aging brain: Life-span changes in brain and cognitive functioning. In A. Demetriou, W. Doise, & C. F. M. van Lieshout (Eds.), *Life-span developmental psychology: A European perspective* (pp. 35–99). London: Wiley.
West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120,* 272–292.
West, R., & Craik, F. I. M. (1999). Age-related decline in prospective memory: The roles of cue accesibility and cue sensitivity. *Psychology and Aging, 14,* 264–272.
Yantis, S. (1998). Control of visual attention. In H. Pashler (Ed.), *Attention* (pp. 223–256). Psychology Press.
Zacks, R. T., & Hasher, L. (1997). Cognitive gerontology and attentional inhibition: A reply to Burke and McDowd. *Journals of Gerontology: Psychological Sciences, 52B,* P274–P283.
Zacks, J. L., & Zacks, R. T. (1993). Visual search times without reaction times: A new method and an application to aging. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 798–813.

Received November 17, 1999
Revision received March 22, 2000
Accepted March 23, 2000 ■