Psychology and Aging
2010, Vol. 25, No. 4, 886–897

0882-7974/10/$12.00 DOI: 10.1037/a0019508

Age Differences in Reading With Distraction: Sensory or Inhibitory Deficits?

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Two experiments examined how sensory acuity affects age differences in susceptibility to interference in the reading-with-distraction task. In both experiments, older and younger adults read texts in an italic font and were required to ignore distractor words in an upright font. Experiment 1 examined whether the age-related increase in distractibility can be simulated in younger adults by reducing their visual acuity. Experiment 2 investigated whether the age differences in distractibility disappear if visual acuity is equated across all participants in both age groups. Both experiments showed that an impairment in visual acuity leads to increased interference in the reading-with-distraction task. However, older adults were much more impaired by the distractor material than younger adults with reduced visual acuity (Experiment 1). The age differences in the reading-with-distraction task persisted when visual acuity was equated between older and younger adults (Experiment 2). We conclude that the age-related increase in susceptibility to interference in the reading-with-distraction task is not solely due to perceptual deficits of older adults but arises from a deficit in higher cognitive processes such as inhibitory attention. Nevertheless, sensory acuity has to be taken into account as a potential confounding factor in perceptually demanding visual attention tasks.

Keywords: perceptual deficit hypothesis, sensory deficit hypothesis, inhibitory deficit theory, selective attention, cognitive aging

With increasing age, cognitive performance decreases. Evidence for an age-related decline in many cognitive functions such as attention, memory, speech production, and comprehension can easily be found (Light, 2000; McDaniel, Einstein, & Jacoby, 2008; Zacks, Hasher, & Li, 2000). One of the most important theoretical accounts of the cognitive aging phenomenon is the inhibition deficit theory (Hasher & Zacks, 1988). This theory attributes the age-related decline in cognitive functioning to a deficit in inhibitory attention. According to inhibition deficit theory, this deficit has pronounced effects on cognitive performance because inhibitory attention is essential for efficient information processing. More precisely, it has been proposed (Hasher, Zacks, & May, 1999) that inhibitory control is necessary (a) to prevent irrelevant stimuli from entering working memory where they would disrupt processing of relevant information (*access function*); (b) to delete no longer relevant information from working memory (*deletion function*); and (c) to control dominant but inadequate response tendencies (*restraint function*).

The present study deals with age differences in the access function of inhibitory control. With a deficit in this function, processing of irrelevant extraneous information cannot be avoided. This processing of irrelevant material interferes with the processing of relevant information. As a consequence, cognitive performance declines. Consistent with the assumption of an age-related deficit in the access function, a large amount of evidence suggests that older adults are more susceptible to external distraction than younger adults. For instance, older adults are more impaired by meaningful irrelevant background speech when engaged in demanding working memory tasks (Bell, Buchner, & Mund, 2008; Meijer, de Groot, Van Boxtel, Van Gerven, & Jolles, 2006; Tun, O'Kane, & Wingfield, 2002; Tun & Wingfield, 1999).

One of the most important empirical findings that support the hypothesis of an age-related deficit in the access function of inhibitory control is that older adults are more impaired by distractor words when reading. This finding is frequently cited in cognitive psychology handbooks and textbooks (Hasher, Lustig, & Zacks, 2007; Lustig & Hasher, 2001; Lustig, Hasher, & Zacks, 2007; Zacks & Hasher, 1994; Zacks et al., 2000). The reading-with-distraction task was introduced by Connelly, Hasher, and Zacks (1991). In the original version of this task, participants were required to read aloud short texts. In the distractor words condition, to-be-ignored words in a distinct font style (upright font) were interspersed among the to-be-read text (displayed in an italic font). Connelly et al. (1991) found that the increase in reading time in the distractor words condition relative to the control condition was larger for older adults than for younger adults. These age differences in distractibility were most pronounced when the distractor words were semantically related to the target text. In a subsequent multiple-choice text comprehension test, participants were required to identify previously read target words among new and previously ignored distractor words. Consistent with inhibition deficit theory, older adults made more intrusion errors (i.e., chose the previously to-be-ignored distractor word instead of the target word more often) than younger adults. Age differences in the susceptibility to interference in the reading-with-distraction paradigm have been replicated in several subsequent experiments (Carlson, Hasher, Connelly, & Zacks, 1995; Darowski, Helder, Zacks, Hasher, & Hambrick, 2008; Duchek, Balota, & Thessing, 1998; Dywan & Murphy, 1996; Kim,

This article was published Online First September 20, 2010.
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We thank Martina Bruns and the staff of Die Brille, Krefeld, Germany, for their help.
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Hasher, & Zacks, 2007; Li, Hasher, Jonas, Rahhal, & May, 1998). These results are commonly taken as evidence for a decline in inhibitory efficiency in old age.

However, there might be an alternative explanation for the age differences in the reading-with-distraction task that was neglected in all aforementioned studies. The reading-with-distraction task requires discrimination of subtle perceptual differences between target and distractor font styles. It is plausible that interference in this task increases when target words in an italic font and distractor words in an upright font cannot be discriminated at a perceptual level. Therefore, age differences in the reading-with-distraction task may be caused by a sensory deficit rather than by a deficit in inhibitory attentional control. It is well documented that normal aging is accompanied by a number of changes in the visual system that decrease visual acuity (Fozard, 1990; Schieber, 1992). For instance, aging of the visual system is associated with irregularity of the cornea's surface, opacity of the lenses, senile miosis, thinning of the retinal pigment epithelium, loss of receptor cells, atrophy of retinal ganglion cells, and loss of neurons in the visual cortex. It is important to note that these age-related changes in the visual system cannot be easily compensated by corrective lenses. Thus, a pronounced decrement in the functioning of the visual system can be expected even in samples of older adults with normal cognitive functioning (Schneider & Pichora-Fuller, 2000).

There is ample research showing that sensory and cognitive abilities are correlated (e.g., Clay et al., 2009; Gilmore, Spinks, & Thomas, 2006; Lindenberger, Scherer, & Baltes, 2001). These correlations do not necessarily imply that sensory impairment directly impairs performance in cognitive tests. For instance, both sensory and cognitive deficits may be attributed to common causes, such as age-related biological changes in the brain or health factors, and there is considerable evidence for such indirect links between sensory and cognitive capabilities (e.g., Lindenberger et al., 2001). Nevertheless, a number of researchers argue that impairments in sensory capabilities have direct effects on performance in cognitive tests (e.g., Anstey, Butterworth, Borzycki, & Andrews, 2006; Glass, 2007; Gussekloo, de Craen, Oduber, van Boxtel, & Westendorp, 2005; Valentijn et al., 2005). Most plausibly, sensory impairment may only exert a strong influence on performance in tests that place high demands on sensory processing, such as perceptually demanding selective attention tasks (Schneider & Pichora-Fuller, 2000; Scialfa, 2002). In studies examining auditory selective attention, age differences in auditory distraction disappear when age differences in hearing are controlled for by adjusting the signal-to-noise ratio to the individual hearing threshold (Murphy, Craik, Li, & Schneider, 2000; Murphy, McDowd, & Wilcox, 1999; Schneider, Daneman, Murphy, & See, 2000; Schneider, Daneman, & Pichora-Fuller, 2002).

Schneider and Pichora Fuller (2000) argued that the failure to take age differences in sensory acuity into account may be a problem of studies examining age differences in visual selective-attention tasks. In contrast to studies examining age differences in auditory distraction, studies that have examined age differences in visual attention commonly ignore the problem of age differences in visual acuity possibly amplifying interference effects. The studies using the reading-with-distraction task referred to above are a good example. Given that (a) performance in the reading-with-distraction task most plausibly depends on successful perceptual discrimination of subtly different target and distractor words, and (b) poor visual acuity is prevalent among older adults, one might expect that visual acuity was carefully controlled in studies examining age differences in inhibitory functioning using the reading-with-distraction task. However, none of the published studies we know of (Carlson et al., 1995; Connelly et al., 1991; Darowski et al., 2008; Duchek et al., 1998; Dywan & Murphy, 1996; Feyereisen & Charlot, 2008; Kemper & McDowd, 2006; Kemper, McDowd, Metcalf, & Liu, 2008; Kim et al., 2007; Li et al., 1998; Phillips & Lesperance, 2003) even reported visual acuity for the older and younger samples.

Thus, it is conceivable that visual acuity has a direct influence on age differences in the reading-with-distraction task. Older adults may, at least occasionally, fail to see the difference between italicized target words and upright distractor words and may therefore process the to-be-ignored distractor words with a higher probability than younger adults. This explanation is consistent with several findings showing that the age differences in the reading-with-distraction task decrease when target and distractor words are perceptually more distinct and can therefore be distinguished more easily, even with reduced visual acuity. For instance, several studies have found no age differences in distractibility when target and distractor words were written in a distinct font color, as a result of which target–distractor discrimination may have been greatly facilitated even with reduced visual acuity (Kemper & McDowd, 2006; Phillips & Lesperance, 2003). Furthermore, when distractor words are presented in predictable locations, age differences in distractibility are severely reduced (Li et al., 1998) or even disappear completely (Carlson et al., 1995). These results have been interpreted within the inhibitory deficit theory. It has been suggested that inhibition of locations may be preserved in old age. However, an alternative interpretation of these results would be that age differences are reduced or eliminated because target and distractor words that are presented in different locations can be distinguished more easily at a perceptual level, even with reduced visual acuity. Thus, almost all age differences in the reading-with-distraction task could be attributed either to age differences in inhibitory control or to age differences in visual acuity. Given this, it may be not too surprising that it has been suggested several times that an age-related deficit in inhibitory control does not in fact exist and that the age differences in the reading-with-distraction task can be solely attributed to sensory decline (Bell & Buchner, 2007; Bell et al., 2008; Burke & Osborne, 2007; Burke & Shafto, 2008). We henceforth refer to this hypothesis as the *sensory-deficit* hypothesis.[1] Consistent with the sensory-deficit hypothesis, Gra-

[1] At first glance, the sensory-deficit hypothesis might seem inconsistent with the findings of Kemper and McDowd (2006), who used eye tracking technology to examine age differences in a modified reading-with-distraction task and found no age differences in the probability of fixating distractors. However, this null finding cannot rule out the sensory-deficit hypothesis, because Kemper and McDowd used a modified reading-with-distraction paradigm (e.g., participants read only single sentences, which may have drastically reduced the task's sensitivity to age differences) in which there was no evidence for age differences in interference at all. With no evidence of age-related interference at a performance level, there is also no reason why the probability of distractor fixations should have differed between age groups. An additional problem with this study is that the hypothesis that older adults should fixate distractors more often than younger adults can be derived equally well from the inhibitory-deficit hypothesis and from the sensory-deficit hypothesis. Therefore, no conclusions can be drawn from these findings about whether the age differences in the classical version of the reading-with-distraction task can be attributed to sensory decline.

ham, Osborne, and Burke (2007) reported a significant correlation between visual acuity and distractibility in the reading-with-distraction task. Note, however, that a significant correlation between visual acuity and distractibility could be due to indirect links between sensory and cognitive capabilities. Thus, to examine whether visual functioning has a direct effect on interference in the reading-with-distraction task, it is necessary to manipulate visual acuity experimentally.

In Experiment 1 we examined whether age effects in the reading-with-distraction task can be simulated in younger adults by reducing their visual acuity to that of older adults. To simulate the age-related decline of visual acuity, we used glasses with partial occlusion filters that are commonly used in strabismus monocularis and amblyopia treatment to selectively reduce visual acuity of the better seeing eye (Haase & Gräf, 2003). These partial occlusion filters reduce visual acuity by light scattering. Lindenberger et al. (2001) used this method to examine direct influences of sensory acuity on cognitive functioning. In their study, younger adults with reduced visual acuity and younger control participants completed a cognitive test battery designed to assess working memory, perceptual speed, reasoning, episodic memory, verbal knowledge, and verbal fluency. Visual acuity had no direct effect on any of these functions. Lindenberger et al. concluded that the link between sensory and cognitive decline is most plausibly due to a common biological process that may affect both sensory and cognitive capabilities. However, even though this may be true for the tasks that were used by Lindenberger et al., it is unclear whether visual acuity directly affects distractibility in perceptually demanding visual selective-attention paradigms, such as the reading-with-distraction task (Scialfa, 2002).

To summarize, the sensory-deficit hypothesis (Burke & Osborne, 2007) implies that age differences in the reading-with-distraction task are solely due to a sensory deficit that leads to poor perceptual discrimination between target and distractor words. Therefore, this hypothesis leads to the prediction that age-related deficits in the reading-with-distraction task can be simulated by artificially reducing visual acuity of younger adults. The inhibitory-deficit hypothesis (Hasher et al., 2007), in contrast, implies that age differences in the reading-with-distraction task are solely due to insufficient inhibitory control over the contents of working memory. According to this view, perceptual deficits do not play a role in amplifying age differences in distractibility. Therefore, this hypothesis leads to the prediction that visual acuity reduction does not affect distractibility in the reading-with-distraction task.

Experiment 1

Method

Participants. Participants were 50 community-dwelling older adults and 92 younger adults. Two participants (one older and one younger adult) were excluded on the basis of the results of a dementia screening test. The remaining 49 older adults (34 women) ranged in age from 60 to 83 years (M = 68.10, SD = 5.75). The remaining 91 younger adults (67 women) ranged in age from 19 to 30 years (M = 22.88, SD = 3.35). The latter were randomly assigned to two groups (the visual acuity reduction group and the control group; see below). All participants were native German speakers. Younger adults had more years of education than older adults, $F(1, 138) = 25.20$, $p < .01$, $\eta^2 = .15$. However, older adults performed better on a vocabulary test (Lehrl, 1989) than younger adults, $F(1, 138) = 7.95$, $p < .01$, $\eta^2 = .05$. The scores in the dementia screening test (DemTect; Kalbe et al., 2004) did not differ between age groups, $F(1, 138) = 1.06$, $p = .31$, $\eta^2 = .01$. Participants with a diagnosis of mild cognitive impairment in the dementia screening, those with a history of heart attack, stroke, brain trauma, alcoholism, Parkinson's disease, or pulmonary emphysema, and those who had taken medication that could influence their cognitive functioning were excluded from the study. Older and younger adults did not differ with respect to their self-assessed overall contentment with life, $\chi^2(1, N = 140) = 0.43$, $p = .51$.

Sensory acuity manipulation. To simulate the age-related decline of visual acuity, we required participants in the younger, visual acuity reduction group to wear glasses with thin, self-adhesive partial occlusion filters (Ryser Optik, St. Gallen, Switzerland). There are several types of partial occlusion filters that reduce visual acuity to different degrees. These filters are labeled according to the degree of visual acuity that will result if they are used by an individual with normal or corrected-to-normal visual acuity of 1.0. As in Lindenberger et al.'s (2001) study, partial occlusion filters labeled 0.4 were used in the present study. This means that these filters are expected to reduce visual acuity to values around 0.4 Snellen decimals (Bach, 2007). According to Lindenberger et al., this level of visual acuity most likely corresponds to the age-related sensory decline that is to be expected in a sample of elderly people. Besides, a further advantage of using partial occlusion filters labeled 0.4 is that Lindenberger et al. have shown that this degree of acuity reduction does not result in impairments of higher cognitive functions (including perceptual speed, memory, reasoning and knowledge). Thus, if performance in the reading-with-distraction task would be modulated by the visual acuity reduction, these effects would most likely not be mediated by a depletion of attentional resources but would rather be due to direct sensory effects on the reading-with-distraction task.

Materials. Visual acuity was tested using a Snellen chart (UNI EN ISO 8596/7). The DemTect was applied as a cognitive screening test to detect dementia or mild cognitive impairment (Kalbe et al., 2004). Crystallized intelligence was assessed using the *Mehrfachwahl-Wortschatz-Intelligenztest* (Multiple-Choice Vocabulary Test; Lehrl, 1989).

During the experiment, participants were seated in front of a 20-in. (50.8-cm) computer monitor. Head position was stabilized with a chin rest and a forehead rest at a viewing distance of 40 cm. Thirteen dictation texts were selected from school books used in seventh or eighth grade. On average, the texts consisted of nine sentences (SD = 2) and 120 words (SD = 2). As in previous studies (Connelly et al., 1991; Kim et al., 2007), the to-be-read texts were presented in 15-point black italic Courier font on a white background. At the viewing distance of 40 cm, each character subtended about 0.29° vertically and 0.21° horizontally.

For five nouns of each text, two similar nouns were selected that could replace these nouns without changing the meaning of the text. One of these three alternatives was randomly selected to be used as an italicized target word that appeared at the correct position in the text. The other two alternatives were randomly selected to serve as the distractor word (in the distractor words condition) or as a new foil in the multiple-choice recognition test that followed each reading phase (see the Procedures section, below).

Six of the texts were randomly assigned to the distractor words condition on an individual basis. The other 6 texts were assigned to the gap control condition. In the distractor words condition, 50 distractor words (the five unique distractor words repeated 10 times) written in an upright font were randomly interspersed into the target text with the constraint that the distractor word was never the first or the last word of the text, and no distractor word followed another distractor word directly. In the gap control condition, the distractor words were written in white type on a white background so that the participants could not see them.

Procedure. Participants were tested individually. Their task was to read out loud the texts presented on the computer screen in front of them. Two short sentences—one comprising irrelevant distractor words and one comprising no distractor words—were presented to familiarize the participants with the task. In a practice trial, participants read a complete text without distractor words. The practice trial was followed by the 12 experimental trials. Each trial started with a countdown that alerted the participants that a text was about to be presented. Following the offset of the countdown, the text appeared at the center of the screen. Participants knew that they were to read the italicized text out loud as fast as possible without making pauses and without making errors. They had to ignore all words printed in upright font. The texts were presented in random order. When participants had read the last word of the text, the experimenter pressed a key on the computer keyboard to record reading time.

Each text was followed by a recognition test. The recognition test consisted of five three-alternative forced-choice (3-AFC) questions presented one after another. These questions consisted of segments of the sentences comprising one of the five target words selected for presentation in the reading phase that had been replaced by three question marks. The target word, the distractor word, and the foil were presented below the question, and participants were required to name the target word. When all five questions had been answered, the next reading trial was initiated.

Design. A 3 $\times$ 2 design was used with group (younger control vs. younger, visual acuity reduction vs. older control) as between-subjects factor and distractor condition (gap control vs. distractor words) as within-subject factor. The dependent variables were reading time, the proportion of correctly identified targets, and the proportion of intrusion errors in the 3-AFC recognition test. Given a sample size of 140 (with $N = 47$ younger and $N = 49$ older adults in the control groups and $N = 44$ younger adults in the visual acuity reduction group), an effect of size $f = 0.34$ (i.e., between a medium, $f = 0.25$, and a large, $f = 0.40$, effect as defined by Cohen, 1988) could be detected for the interaction between group and distractor condition with a probability of $1 - \beta = .95$ (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007).

Results

Treatment check of the visual acuity manipulation. As was to be expected, visual acuity was worse for older control participants ($Mdn = 0.60$) than for younger control participants ($Mdn = 0.90$), as revealed by a U test ($z = -6.52$, $p < .01$). This is in line with the literature (Fozard, 1990; Schieber, 1992) suggesting that there are several age-related changes in the visual system that cannot be easily compensated with contact lenses or glasses (Schneider & Pichora-Fuller, 2000). Given that a healthy sample of older adults was examined in the present experiment, there is no reason to suspect that age differences in visual functioning were more pronounced in the present study than in previous studies in which no measurements of visual functioning were reported (Carlson et al., 1995; Connelly et al., 1991; Duchek et al., 1998; Dywan & Murphy, 1996; Kemper & McDowd, 2006; Kemper et al., 2008; Kim et al., 2007; Li et al., 1998). The most important question was whether the age differences in visual acuity would disappear when the older control adults were compared with younger adults with visual acuity reduction. It is important to note that visual acuity was even worse for younger adults with visual acuity reduction ($Mdn = 0.40$) than for older control adults ($Mdn = 0.60$, $z = -5.87$, $p < .01$). Thus, if the age differences in the reading-with-distraction task were solely due to sensory decline (as suggested by Burke & Osborne, 2007), we would expect younger adults with visual acuity reduction to be as susceptible as, or even more susceptible than, the older adults to interference in this task.

Reading times. A 3 $\times$ 2 multivariate analysis of variance (MANOVA) with group (younger control vs. younger, visual acuity reduction vs. older control) and distractor condition (gap control vs. distractor words) as independent variables revealed a significant main effect of group, $F(2, 137) = 50.46$, $p < .01$, $\eta^2 = .42$, on reading time (see Figure 1, left panel). Orthogonal contrasts showed that younger adults with visual acuity reduction read more slowly than younger control adults, $F(1, 138) = 8.81$, $p < .01$, $\eta^2 = .06$, and older adults read more slowly than younger adults, $F(1, 138) = 90.95$, $p < .01$, $\eta^2 = .40$. The main effect of distractor condition was also significant, $F(1, 137) = 651.94$, $p < .01$, $\eta^2 = .83$, due to the fact that reading time was larger in the distractor words condition than in the gap control condition.

Most importantly, there was a significant Group $\times$ Distractor Condition interaction, $F(2, 137) = 26.81$, $p < .01$, $\eta^2 = .28$. To further examine this interaction, three separate 2 $\times$ 2 MANOVAs were conducted. First, we compared the younger control group to the older control group to see whether we could replicate the age-related increase in susceptibility to distraction that was observed in previous studies (e.g., Connelly et al., 1991; Duchek et al., 1998; Dywan & Murphy, 1996; Kim et al., 2007; Li et al., 1998). Indeed, older adults were more prone to distraction than younger adults, $F(1, 94) = 38.97$, $p < .01$, $\eta^2 = .29$.

The most interesting question was whether the age-related increase in susceptibility to distraction could also be replicated if we compared older adults to younger adults with visual acuity reduction or whether this pattern would be abolished or even reversed. The analysis showed that the increase in reading times in the distractor words condition compared with the gap control condition was more pronounced for older adults than for younger adults with visual acuity reduction, $F(1, 91) = 16.49$, $p < .01$, $\eta^2 = .15$, although the effect size for the Age Group $\times$ Distractor Condition interaction was somewhat reduced when compared to the preceding analysis. We therefore conclude that sensory differences cannot fully account for the age-related differences in the reading-with-distraction task.

To see whether the sensory manipulation had any influence on the susceptibility to distraction in the reading-with-distraction task,

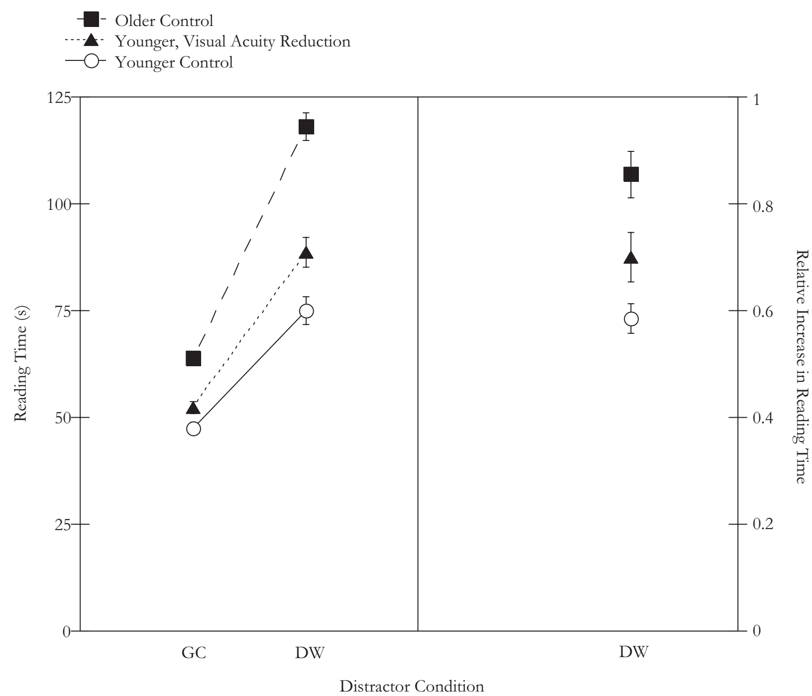

Figure 1. Reading times in Experiment 1. Left panel: Mean reading time as a function of distractor condition (GC = gap control; DW = distractor words) and group. Right panel: Mean proportional increase in reading time in the distractor words condition relative to the gap control condition: $\frac{RT_{\mathrm{DW}} - RT_{\mathrm{GC}}}{RT_{\mathrm{GC}}}$. The error bars represent the standard error of the means.

we compared the younger participants with visual acuity reduction to younger control participants. This analysis revealed a significant interaction between sensory acuity group and distractor condition, $F(1, 89) = 17.78$, $p < .01$, $\eta^2 = .17$. Thus, although sensory decline cannot fully account for the age differences in the susceptibility to interference in the reading-with-distraction task, visual acuity reduction increases distractibility significantly.

To test whether the age differences in reading time were simply due to cognitive slowing, we performed an additional analysis (Duchek et al., 1998; Kim et al., 2007) in which we examined the proportional increase in reading time in the distractor words condition relative to the gap control condition (see Figure 1, right panel), which was calculated by dividing the reading time difference between the distractor words condition ($\mathrm{RT_{DW}}$) and the gap control condition ($\mathrm{RT_{GC}}$) by the reading time in the gap control baseline condition:

$$\frac{RT_{\mathrm{DW}} - RT_{\mathrm{GC}}}{RT_{\mathrm{GC}}}.$$

All conclusions derived from the analysis of the absolute reading times reported above were confirmed. Most important, the relative increase in reading time was larger for older participants than for younger participants in the visual acuity reduction group, $F(1, 91) = 6.03$, $p = .02$, $\eta^2 = .06$, suggesting that cognitive slowing alone cannot fully account for the age-related differences in distractibility (cf. Duchek et al., 1998; Kim et al., 2007).

Recognition test performance. An analysis of the proportion of correctly identified target words in the 3-AFC recognition test (see Table 1) revealed main effects of group, $F(2, 137) = 39.77$, $p < .01$, $\eta^2 = .37$, and of distractor condition, $F(1, 137) = 167.90$, $p < .01$, $\eta^2 = .55$. Orthogonal contrasts showed that older adults correctly identified fewer target words than younger adults, $F(1, 138) = 78.43$, $p < .01$, $\eta^2 = .36$, and that younger adults with visual acuity reduction identified as many target words as younger control participants, $F(1, 138) = 1.52$, $p = .22$, $\eta^2 < .01$. In all three groups, participants correctly identified the target word less often in the distractor words condition than in the gap control condition. Most important, there was no significant interaction between group and distractor condition, $F(2, 137) = 0.67$, $p = .51$, $\eta^2 = .01$.

We also analyzed the error patterns in the distractor words condition. The probability of incorrectly selecting the distractor word was compared to the probability of incorrectly selecting a new foil word that had not been presented in the reading phase (see Table 2). The 3 × 2 MANOVA with group (younger control vs. younger, reduced visual acuity vs. older control) and error type (distractor word vs. new foil word) as independent variables revealed a main effect of group, $F(2, 137) = 20.02$, $p < .01$, $\eta^2 = .23$, suggesting that older adults made more errors than younger adults, $F(1, 138) = 40.03$, $p < .01$, $\eta^2 = .22$, and a main effect of error type (suggesting that participants selected the previously presented distractor word more often than the new foil word), $F(1, 137) = 429.22$, $p < .01$, $\eta^2 = .76$. Most important, there was no interaction between group and error type, $F(2, 137) = 0.83$, $p = .44$, $\eta^2 = .01$, which suggests that intrusions by the distractor material did not differ between the groups. This is consistent with

Table 1
Proportion of Correctly Chosen Target Words (Absolute Number of Correctly Chosen Target Words Divided by Number of Trials) as a Function of Group and Distractor Condition

	Group			
Distractor condition	Younger control	Younger, visual acuity reduction	Older control	Older, visual acuity reduction
Experiment 1				
Gap control	.71 (.01)	.74 (.01)	.61 (.01)	
Distractor words	.58 (.02)	.59 (.02)	.46 (.02)	
Experiment 2				
Continuous control	.82 (.02)	.81 (.02)	.67 (.02)	.67 (.02)
Gap control	.78 (.02)	.82 (.02)	.70 (.02)	.69 (.02)
Random control	.82 (.02)	.85 (.02)	.71 (.02)	.71 (.02)
Distractor words	.58 (.02)	.59 (.02)	.44 (.02)	.40 (.02)

Note. Numbers in parentheses represent the standard error of the mean.

most studies examining age differences in the reading-with-distraction task (Carlson et al., 1995; Connelly et al., 1991; Duchek et al., 1998; Dywan & Murphy, 1996; Kemper & McDowd, 2006; Li et al., 1998; Phillips & Lesperance, 2003).

Discussion

Experiment 1 showed that an artificial decrease of younger adults' visual acuity increased distractibility in the reading-with-distraction task. Thus, age differences in susceptibility to interference may reflect—in part—age differences in sensory capabilities. However, the increase in interference due to the sensory acuity manipulation was much less pronounced than the increase in interference due to cognitive aging. In other words, the age effects in the reading-with-distraction task cannot be fully simulated in younger adults by reducing their visual acuity. This was true even though visual acuity was even worse for younger adults with visual acuity reduction than for older adults. Therefore, we conclude that the sensory-deficit hypothesis is partly correct but cannot fully account for the age differences in the reading-with-distraction task.

In Experiment 1, we examined the sensory-deficit hypothesis by reducing younger adult's visual acuity drastically. This was done to guarantee the comparability between the present study and that of Lindenberger et al. (2001). According to Lindenberger et al., a visual acuity of 0.4 Snellen decimals is commonly observed in a sample of healthy older people. However, using a single value for acuity reduction usually does not result in an exact match for the vision between older and younger adults. In Experiment 2, we thus went one step further and equated visual acuity for two subgroups of younger and older participants by reducing acuity of all of these participants to the same level. In that way, all possible age differences in visual acuity between these two age groups were abolished. The sensory-deficit hypothesis (Burke & Osborne, 2007) leads to the prediction that age differences in distractibility disappear when visual acuity is equal in both age groups. In contrast, the inhibitory-deficit hypothesis (Connelly et al., 1991) again leads to the prediction that the sensory acuity manipulation has no effect on the reading-with-distraction task at all. We also introduced two additional control conditions to allow for a more fine-grained analysis of the age differences in the reading-with-distraction task. First, we used a continuous control condition to assess the "true" baseline in reading speed of the groups involved in this experiment. We also included a random control condition in which random letter strings were interspersed into the text. This condition was designed to assess the extent to which the slowing of the reading speed is caused by lexical and semantic interference. This

Table 2
Proportion of Errors (Absolute Number of Errors Divided by Number of Trials) in the Distractor Words Condition as a Function of Group and Error Type

	Group			
Error type	Younger control	Younger, visual acuity reduction	Older control	Older, visual acuity reduction
Experiment 1				
Distractors	.32 (.02)	.32 (.02)	.40 (.02)	
New foil words	.10 (.01)	.09 (.01)	.14 (.01)	
Experiment 2				
Distractors	.37 (.02)	.37 (.02)	.47 (.02)	.52 (.02)
New foil words	.05 (.01)	.04 (.01)	.09 (.01)	.08 (.01)

Note. Numbers in parentheses represent the standard error of the mean.

is possible because differences between the distractor words and the random control conditions can be assumed to largely reflect the effects of lexical and semantic processes.

Experiment 2

Method

Participants. Seventy-six community-dwelling older adults and 83 younger adults were randomly assigned to two groups. Half of the participants in each age group conducted the experiment with their normal or corrected-to-normal visual acuity. The randomly selected other half of each age group conducted the experiment with their visual acuity artificially reduced to 0.4 to 0.6 Snellen decimals (see the Sensory acuity manipulation section, below). Two participants (one older and one younger adult) were excluded on the basis of the dementia screening. The remaining 75 older adults (55 women) ranged in age from 60 to 85 years ($M = 69.64$, $SD = 4.91$). The remaining 82 younger adults (70 women) ranged in age from 19 to 30 years ($M = 23.04$, $SD = 3.13$).

All participants were native German speakers. The exclusion criteria were the same as in Experiment 1. None of the participants had taken part in the first experiment. As in Experiment 1, younger adults had more years of education than older adults, $F(1, 155) = 27.45$, $p < .01$, $\eta^2 = .15$, but older adults performed better on the vocabulary test, $F(1, 155) = 42.23$, $p < .01$, $\eta^2 = .21$. Older adults had worse scores in the dementia screening test (DemTect) than younger adults, $F(1, 155) = 7.48$, $p = .01$, $\eta^2 = .05$, but the mean score of older adults (16.79 points) was well within the range of age-appropriate functioning (13 to 18 points). Older and younger adults did not differ with respect to their overall contentment with life, $\chi^2(1, N = 157) < 0.01$, $p = .95$.

Sensory acuity manipulation. To equate visual acuity between younger and older adults in the visual acuity reduction groups, partial occlusion filters were used as in Experiment 1. However, to reduce each participant's visual acuity to between 0.4 and 0.6 Snellen decimals, we used different types of partial occlusion filters that reduced visual acuity to different degrees, depending on the participant's sensory capability. To determine which partial occlusion filter would be necessary to reduce the participant's visual acuity to about 0.4 Snellen decimals, participants were required to judge the orientation of the gap in a Landolt C (Bach, 1996) of 2.5 arc min, which is the smallest gap size that can be reliably detected with a visual acuity of 0.4. The Landolt C was presented on the same computer screen that was used for the experiment proper. At the start of the sensory acuity adjustment procedure, participants wore 0.1 partial occlusion filters (which cause the highest possible degree of visual acuity reduction). If they were unable to identify the orientation of the gap six times in a row, the next weakest partial occlusion filter (0.2) was applied. This procedure continued until the orientation of the gap was correctly identified in six successive trials. The occlusion filter the participants were wearing during these six successive trials was used for visual acuity reduction in the experiment proper.

Materials and procedure. Materials and procedure were identical to those of Experiment 1, with the following exceptions. To assess visual acuity, we used the FrACT (Bach, 2007), a computerized visual screening test. The FrACT was applied before and after the visual acuity adjustment as well as at the end of the experiment. The results of the second visual screening (after visual acuity was adjusted in the visual acuity reduction groups) are displayed in Figure 2. Note that the use of a computerized visual screening test allowed us to assess visual acuity using the same computer monitor that was also used for the visual acuity adjustment and the experiment proper. During the entire experiment (including visual acuity adjustment and assessment), participants had a viewing distance of 110 cm to the computer screen. This distance to the screen was necessary to measure visual acuity up to 1.12 Snellen decimals in the FrACT.

For the reading-with-distraction task, 21 dictation texts were selected from school books used in seventh or eighth grade, each containing 60 words. On average, the texts comprised five sentences ($SD = 1$). Font size was 30 point. At the viewing distance of 110 cm, each character subtended about 0.29° vertically and 0.21° horizontally, which corresponds to the angular size of the characters used in Experiment 1.

For three nouns of each text, two similar nouns were selected that could replace those nouns without changing the meaning of the text. One of these three alternatives was randomly selected to be used as an italicized target word that appeared at the correct position in the text. The other two alternatives were randomly selected to be used as distractor words (in the distractor words condition) or as new foil words in the multiple-choice recognition test that followed each reading phase.

Five texts were randomly assigned to one of four conditions (continuous control, gap control, random control, distractor words) on an individual basis. In the distractor words condition, 30 distractor words (the three unique distractor words repeated 10 times) written in an upright font were interspersed into the texts. In the random control condition, the distractor words were replaced by random letter strings written in an upright font that were of the

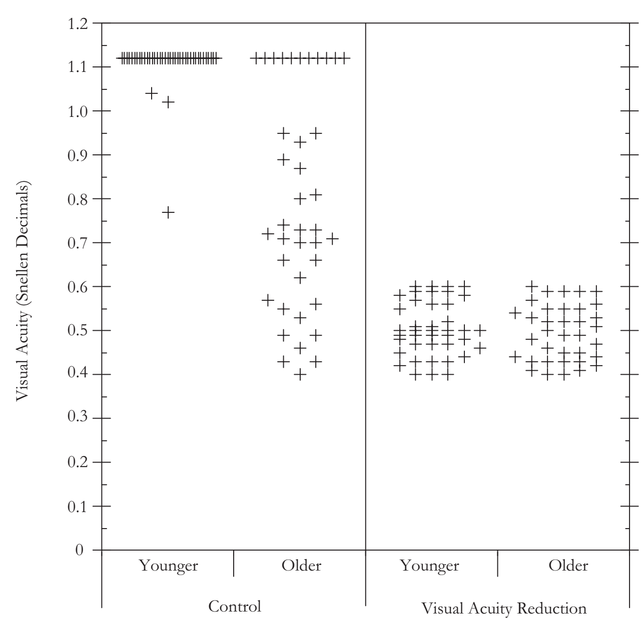

Figure 2. Visual acuity in Snellen decimals for the four groups. Each marker represents the visual acuity of one participant.

same length as the distractor words. The gap control condition corresponded to the gap control condition used in Experiment 1. In the continuous control condition, the to-be-read texts were written continuously without distractor words.

Design. A 2 × 2 × 4 design was used with age group (younger vs. older) and sensory acuity group (control vs. visual acuity reduction) as between-subjects factors and distractor condition (continuous control vs. gap control vs. random control vs. distractor words) as within-subject factor. The dependent variables were reading time, the proportion of correctly identified targets, and the proportion of intrusions in the 3-AFC recognition test. Given a sample size of 157 (with $N = 41$ younger and $N = 39$ older adults in the control groups and $N = 41$ younger and $N = 36$ older adults in the visual acuity reduction groups), an effect size of $f = 0.34$ could be detected for the interaction between sensory acuity group and distractor condition with a probability of $1 - \beta = .95$ (Faul et al., 2007, 2009).

Results

Treatment check of the visual acuity manipulation. In the control groups, visual acuity was worse for older ($Mdn = 0.70$) than for younger adults ($Mdn = 1.12$; $z = -6.32$, $p < .01$). In the visual acuity reduction groups, visual acuity was similarly worse for older adults ($Mdn = 0.77$) than for younger adults ($Mdn = 1.12$) when tested without partial occlusion filters ($z = -6.99$, $p < .01$). When tested with partial occlusion filters, visual acuity was the same for older ($Mdn = 0.50$) and younger adults ($Mdn = 0.50$; $z = -0.61$, $p = .54$; see Figure 2). These results confirm that we succeeded in equating visual acuity between older and younger adults with visual acuity reduction. Thus, any differences in distractibility between these two age groups cannot be attributed to differences in visual acuity.

Reading times. A 2 × 2 × 4 MANOVA with age group (younger vs. older), sensory acuity group (control vs. visual acuity reduction), and distractor condition (continuous control vs. gap control vs. random control vs. distractor words) as independent variables revealed significant main effects of age group, $F(1, 153) = 38.00$, $p < .01$, $\eta^2 = .20$; sensory acuity group, $F(1, 153) = 55.13$, $p < .01$, $\eta^2 = .27$; and distractor condition, $F(3, 151) = 278.34$, $p < .01$, $\eta^2 = .85$ (see Figure 3). The main effects of age group and sensory acuity group can be attributed to older adults reading more slowly than younger adults and participants with visual acuity reduction reading more slowly than control participants. Orthogonal contrasts on the distractor condition variable showed that (a) reading times in the gap control condition were slightly increased in comparison to the continuous control condition, $F(1, 153) = 57.10$, $p < .01$, $\eta^2 = .27$; (b) when random letter strings were interspersed into the text, participants read more slowly than when the text contained no distractors, $F(1, 153) = 626.51$, $p < .01$, $\eta^2 = .80$; and (c) reading times in the distractor words condition were increased compared with the control conditions, $F(1, 153) = 451.31$, $p < .01$, $\eta^2 = .75$.

Replicating previous results, there was a significant Age Group × Distractor Condition interaction, $F(3, 151) = 14.21$, $p < .01$, $\eta^2 = .22$, suggesting that older adults were more susceptible to interference than younger adults. The interaction was primarily due to the fact that the increase in reading times in the distractor words condition compared to the control conditions was more pronounced for older than for younger adults, $F(1, 153) = 35.04$, $p < .01$, $\eta^2 = .19$. Older adults were also slowed down more than younger adults by random letter strings, $F(1, 153) = 15.30$, $p < .01$, $\eta^2 = .09$, and by gaps in the text, $F(1, 153) = 5.23$, $p = .024$, $\eta^2 = .03$. The most interesting question was whether the age differences in distractibility would be moderated by the sensory acuity manipulation. If these age differences were primarily due to age-related sensory decline, we would expect an age difference in the control groups but not in the visual acuity reduction groups. However, there was no significant three-way interaction between age group, sensory acuity, and distractor condition, $F(3, 151) = 0.33$, $p = .81$, $\eta^2 = .01$, suggesting that sensory acuity did not moderate the age differences in distractibility. Does this mean that the sensory acuity manipulation had no effect on distractibility at all? This is also not the case, because there was a significant interaction between sensory acuity group and distractor condition, $F(3, 151) = 21.54$, $p = .01$, $\eta^2 = .30$, suggesting that participants with visual acuity reduction were slowed down more by distractor words, $F(1, 153) = 7.52$, $p = .01$, $\eta^2 = .05$, and random letter strings, $F(1, 153) = 64.34$, $p < .01$, $\eta^2 = .30$, than control participants. We conclude that reducing sensory capability increased interference somewhat but did not moderate the age differences in distractibility.

To further examine the age differences in distractibility, two 2 (age group) × 4 (distractor condition) MANOVAs were conducted for both sensory acuity groups separately. As expected, there was a significant interaction between age group and distractor condition for control participants, $F(3, 76) = 13.42$, $p < .01$, $\eta^2 = .35$. More important, the Age Group × Distractor Condition interaction was also significant when only participants with visual acuity reduction were analyzed, $F(3, 73) = 9.29$, $p < .01$, $\eta^2 = .28$, although effect size was slightly reduced. Thus, the age differences in distractibility can be replicated even when visual acuity is equated across all participants in both age groups. This finding shows that sensory decline cannot be responsible for the age differences in susceptibility to interference in the reading-with-distraction task.

Parallel to Experiment 1, we conducted an additional analysis (Duchek et al., 1998; Kim et al., 2007) in which we examined the proportional increase in reading time relative to the continuous control condition (see Figure 3, right panels). The relative increase in reading time was calculated by dividing the increase in reading time in the gap control, the random control, and the distractor words condition ($RT_{..}$) by the reading time in the continuous control baseline condition (RT_{CC}):

$$\frac{RT_{..} - RT_{CC}}{RT_{CC}}.$$

All conclusions derived from the analysis of the absolute reading times reported above were confirmed. Most important, the interaction between age group and distractor condition remained significant, $F(2, 152) = 6.69$, $p < .01$, $\eta^2 = .08$ (see Figure 3). It is interesting to note that when only participants with visual acuity reduction were examined, there were virtually no age differences in the relative increase in reading times due to gaps in the text, $F(1, 75) = 0.25$, $p = .62$, $\eta^2 < .01$, or random letter strings, $F(1, 75) = 0.60$, $p = .44$, $\eta^2 = .01$. Nevertheless, the age difference in

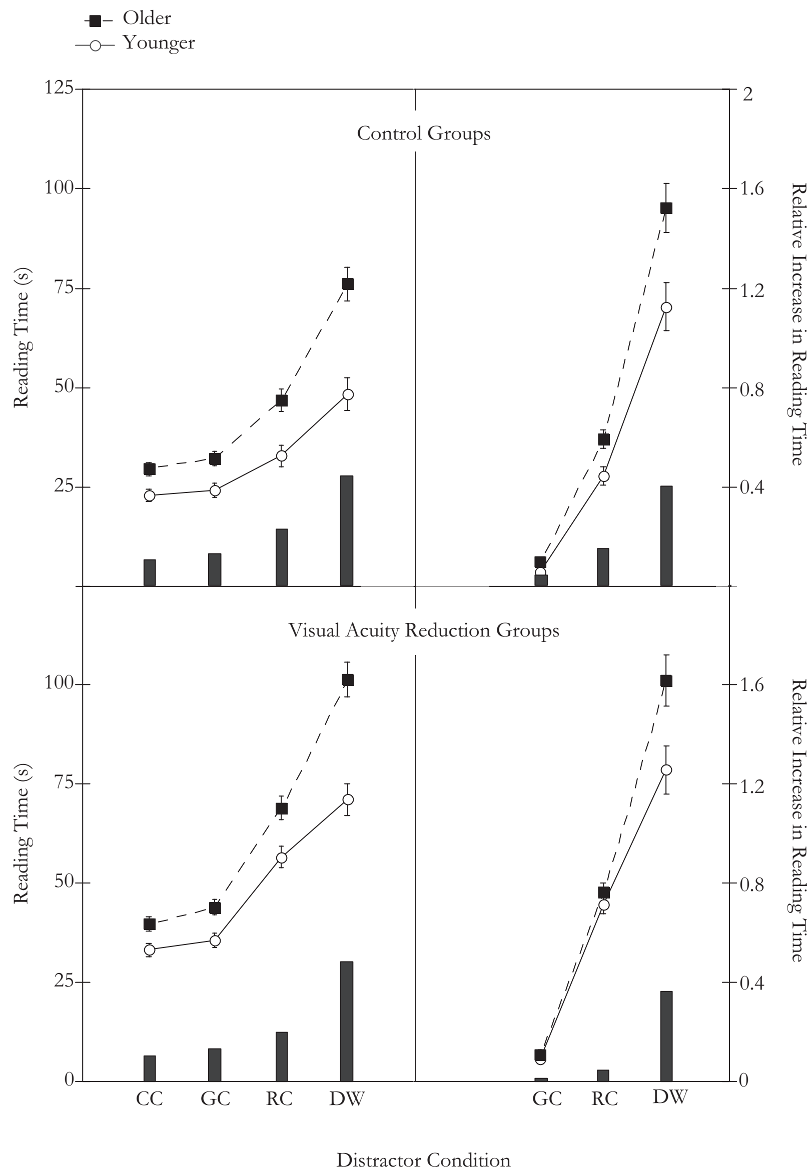

Figure 3. Reading times in Experiment 2. Left panels: Mean reading time as a function of distractor condition (CC = continuous control; GC = gap control; RC = random control; DW = distractor words) in the control groups (upper panel) and the visual acuity reduction groups (lower panel). Right panels: Mean increase in reading time relative to the continuous control condition in the control groups (upper panel) and the visual acuity reduction groups (lower panel): $\frac{RT_{..} - RT_{CC}}{RT_{CC}}$. The error bars represent the standard error of the means. The grey columns show the difference between age groups (older adults – younger adults).

distractibility by distractor words remained significant, $F(1, 75) = 8.11$, $p < .01$, $\eta^2 = .10$.

Recognition test performance. The proportion of correctly identified target words in the 3-AFC recognition test is shown in Table 1. A 2 × 2 × 4 MANOVA with age group, sensory acuity group, and distractor condition as independent variables showed main effects of age group, $F(1, 153) = 123.16$, $p < .01$, $\eta^2 = .45$, and distractor condition, $F(3, 151) = 142.02$, $p < .01$, $\eta^2 = .74$, but no significant main effect of sensory acuity group, $F(1, 153) = 0.17$, $p = .68$, $\eta^2 < .01$. The target words were less often correctly identified in the distractor words condition than in the control conditions, $F(1, 153) = 427.02$, $p < .01$, $\eta^2 = .74$. Older adults correctly identified the target word less often than younger adults. As in Experiment 1, the interaction between age group and distractor condition was not significant, $F(3, 151) = 1.67$, $p = .18$, $\eta^2 = .03$. The interactions between sensory acuity and distractor condition, $F(3, 151) = 0.56$, $p = .64$, $\eta^2 = .01$, and the three-way interaction between age group, sensory acuity, and distractor condition, $F(3, 151) = 0.58$, $p = .63$, $\eta^2 = .01$, were also not significant.

Table 2 displays the proportion of falsely identified distractor words in the distractor words condition and the proportion of falsely identified new foil words (i.e., the absolute number of errors divided by the number of trials in which an error could be made). The errors in the distractor words condition were analyzed using a $2 \times 2 \times 2$ MANOVA with age group (younger vs. older), sensory acuity (control vs. visual acuity reduction) and error type (distractor word vs. new foil word) as independent variables. This analysis revealed significant main effects of age group (older adults made more errors than younger adults), $F(1, 153) = 54.34$, $p < .01$, $\eta^2 = .26$, and error type (participants selected the previously presented distractor word more often than the new foil word), $F(1, 153) = 609.81$, $p < .01$, $\eta^2 = .80$. There was a significant interaction between age group and error type, $F(1, 153) = 9.67$, $p < .01$, $\eta^2 = .06$, in that older adults made more intrusions from the to-be-ignored material than younger adults. This finding stands in contrast to that of Experiment 1, where no age differences in distractibility were found in the 3-AFC recognition test, which may be attributed to the somewhat higher statistical power to detect age differences in this analysis in Experiment 2 relative to that of Experiment 1. It is important to note that there was no main effect of sensory acuity, $F(1, 153) = 0.45$ $p = .50$, $\eta^2 < .01$; no two-way interaction between sensory acuity and distractor condition, $F(1, 153) = 2.05$, $p = .15$, $\eta^2 = .01$; and no three-way interaction between sensory acuity, distractor condition, and age group, $F(1, 153) = 0.59$, $p = .44$, $\eta^2 < .01$. Thus, as in Experiment 1, sensory acuity had no influence on performance in the 3-AFC recognition test at all. Hence, sensory acuity affected reading times only.

Discussion

Experiment 2 shows that older adults are more susceptible to interference in the reading-with-distraction task than younger adults, even when all participants' visual acuity was equated so that there were no differences in visual acuity across both age groups. The visual acuity manipulation did not moderate age differences in the reading-with-distraction task. These findings clearly refute the sensory-deficit hypothesis, which implies that age differences in interference can be solely attributed to sensory decline. Nevertheless, the sensory acuity manipulation led to an increase in distractibility in the reading-with-distraction task. This result replicates the finding of Experiment 1 that sensory deficits may amplify susceptibility to interference in the reading-with-distraction task.

The three different types of control conditions—the continuous control condition, the gap control condition, and the random control condition—allowed for a more fine-grained analysis of the group differences in the reading-with-distraction task. There was only a very small difference in reading time between the continuous control and the gap control conditions. This difference was not affected by visual acuity. The age difference in the increase of reading times due to gaps in the text was small and disappeared when the proportional increase in reading time was analyzed. We may therefore conclude that the gap control condition can indeed be regarded as an adequate baseline condition. Using random letter strings as distractors caused an increase in reading time relative to the other two control conditions, even though interference was much less pronounced than when meaningful distractor words were used. Sensory acuity reduction considerably increased interference by random letter strings. In contrast, the difference between the two age groups in the relative increase in reading time was comparatively small and was abolished when visual acuity was equated. Thus, the small age difference in the increase in reading times due to random letter strings in the control groups may be solely attributed to sensory deficits. The age differences in the increase in reading times due to meaningful distractor words, however, were much larger and persisted even when visual acuity was equated between the age groups. These age differences in the susceptibility to lexical and semantic interference therefore cannot be fully attributed to age-related sensory deficits. Instead, these age differences seem to arise from declines of higher cognitive processes, such as a decline of inhibitory control. The simplest explanation for the pronounced age differences in the distractor words condition is that similarity between targets and distractors increases interference, and the likelihood of finding significant age differences increases with the amount of interference elicited by the distractors. An alternative interpretation of the present results is that older adults are particularly impaired by meaningful irrelevant information. This interpretation of the results would be consistent with studies examining age differences in cross-modal interference (Bell & Buchner, 2007; Bell et al., 2008), which suggest that age differences in susceptibility to cross-modal interference may be restricted to situations in which meaningful information has to be ignored.

General Discussion

The present experiments allow us to derive the following conclusions. First, and most important, the age-related increase in susceptibility to interference in the reading-with-distraction task is clearly not due solely to perceptual deficits of older adults but arises primarily from cognitive deficits at a higher level of processing. This conclusion is mainly based on two findings: (a) Age differences in the reading-with-distraction task cannot be fully simulated by reducing visual acuity (Experiment 1); (b) age differences in the reading-with-distraction task persist even when visual acuity is adjusted to the same level across all participants in both age groups (Experiment 2).

The finding that the age-related increase in distractibility cannot be fully attributed to sensory problems of older adults is consistent with the inhibitory-deficit hypothesis (Hasher et al., 2007), which assumes that older adults have a deficit in controlling the access of to-be-ignored information to working memory. The assumption of age-related deficits in selective attention is highly plausible, given that selective attention seems to rely on frontal lobe functioning, and it is well documented that the frontal lobe is one of the brain structures that degenerates most with increasing age (West, 1996). The finding that age-related differences in sensory capability are not the only cause of age differences in distractibility is also consistent with findings showing older adults to be more susceptible to cross-modal interference than younger adults when engaged in demanding working memory tasks (Bell et al., 2008; Meijer et al., 2006), which cannot easily be attributed to age-related sensory decline.

The second important finding of the present experiments is that sensory impairment had a direct effect on the amount of interference in the reading-with-distraction task. Thus, although sensory decline alone cannot fully explain the age-related differences in distractibility, the influences of sensory capability on measures of visual selective attention should not be ignored. In both experiments, the decrease in visual acuity led to an increase in reading time and—more important—an increase in distractibility, as measured by the difference in reading times between the distractor words condition and the control conditions. Therefore, it is possible that sensory problems may be responsible for some part of the age differences in visual selective attention obtained in previous studies in which older and younger adults differed in sensory capabilities to unknown degrees. In principle, this could have led to an overestimation of attentional decline in older adults. When differences in sensory capabilities are not controlled, distractibility in the reading-with-distraction task must not be viewed as a pure measure of inhibitory capacity. Thus, future studies that examine age differences in perceptually demanding visual selective attention tasks should take sensory capability into account. According to Schneider and Pichora-Fuller (2000), the problem that age differences in sensory acuity may amplify age differences in selective visual attention is generally ignored in cognitive aging studies. Further research is needed to examine whether the finding that sensory capability influences susceptibility to interference is confined to the reading-with-distraction paradigm or whether it is a more general problem that sensory capability affects measures of visual selective attention.

Although sensory capability affected distractibility, this effect was not very large. The visual acuity manipulation influenced reading times only and had no effect on the results of the recognition test at all. This suggests that the present results should not be interpreted as providing evidence for a general reduction of attentional performance due to sensory impairments. Instead, the results suggest that the effects of sensory acuity on cognitive performance may be confined to selective attention tasks, which are perceptually demanding in that targets and distractors are difficult to discriminate at a perceptual level. This interpretation is in line with the results of Lindenberger et al. (2001), who have shown that a sensory acuity manipulation similar to the one used in the present experiments had no influence on various measures of cognitive functioning such as processing speed, reasoning, episodic memory, and verbal fluency.

In summary, age differences in the reading-with-distraction task are affected by but are not solely due to a decline of visual acuity. Instead, these age differences are mainly caused by a decline of cognitive processes, such as a decrease of inhibitory attention. Nevertheless, sensory acuity has to be taken into account as a potential confounding factor in perceptually demanding visual attention tasks and should be carefully controlled in studies examining age differences in selective attention.

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Received December 21, 2009
Revision received March 5, 2010
Accepted March 5, 2010 ■