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The Strong Connection Between Sensory and Cognitive Performance in Old Age: Not Due to Sensory Acuity Reductions Operating During Cognitive Assessment

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Cognitive aging research has documented a strong increase in the covariation between sensory and cognitive functioning with advancing age. In part, this finding may reflect sensory acuity reductions operating during cognitive assessment. To examine this possibility, the authors administered cognitive tasks used in prior studies (e.g., Lindenberger & Baltes, 1994) to middle-aged adults under age-simulation conditions of reduced visual acuity, auditory acuity, or both. Visual acuity was lowered through partial occlusion filters, and auditory acuity through headphone-shaped noise protectors. Acuity manipulations reduced visual acuity and auditory acuity in the speech range to values reaching or approximating old-age acuity levels, respectively, but did not lower cognitive performance relative to control conditions. Results speak against assessment-related sensory acuity accounts of the age-related increase in the connection between sensory and cognitive functioning and underscore the need to explore alternative explanations, including a focus on general aspects of brain aging.

Fluid intellectual abilities as well as many aspects of sensory functioning exhibit linear decrements during adulthood, with signs of accelerated decline in very old age (e.g., Anstey, Stankov, & Lord, 1993; Baltes & Lindenberger, 1997; Baltes, Staudinger, & Lindenberger, 1999; S.-C. Li, Jordanova, & Lindenberger, 1998; Lindenberger & Baltes, 1994; Salthouse, Hancock, Meinz, & Hambrick, 1996; Schaie, 1996; Schaie, Baltes, & Strother, 1964; Stevens, Cruz, Marks, & Lakatos, 1998). These negative age trajectories for sensory acuity and cognitive functioning are accompanied by a pronounced increase in the correlational link between the two domains from adulthood to old age. Thus, several recent studies found that the correlation between sensory acuity and intellectual functioning is much stronger in old and very old age than during earlier periods of adulthood (Anstey, Lord, & Williams, 1997; Anstey, Luszcz, & Sanchez, 2001; Anstey et al., 1993; Baltes & Lindenberger, 1997). For instance, Baltes and Lindenberger (1997) reported that the average proportion of individual differences in five intellectual abilities connected to simple measures of visual and auditory acuity increases from 11% in adulthood (age range = 26–69 years) to 31% in old age (age range = 70–103 years). In the latter study, practically all age differences in intellectual functioning were related to individual differences in auditory or visual acuity.

In the past, four broad classes of explanations have been proposed to explain negative age differences in intellectual and sensory functioning as well as the age-based increments in the correlational link between the two domains (cf. Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Schneider & Pichora-Fuller, 2000). First, negative age changes in sensory and intellectual functioning may reflect an ensemble of common causes that compromise the functional integrity of the brain (common-cause hypothesis; cf. Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). Second, age-based reductions in the quality or quantity of sensory input may accumulate over time and lead to structural (Sekuler & Blake, 1987) or functional (cf. Gilmore, 1995) changes in cognition. Third, sensory and perceptual tasks may become more cognitively loaded with advancing age because effortful or attention-demanding processes are activated with increasing likelihood to attenuate the adverse behavioral consequences of sensory decline (cognitive permeation hypothesis; cf. K. Z. H. Li, Lindenberger, Freund, & Baltes, in press; Lindenberger, Marsiske, & Baltes, 2000; cf. Rabbitt, 1968, 1991).

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A fourth, and perhaps more parsimonious, alternative to these three broad types of explanations for the age-related increase in the sensory–cognitive link refers to cognition-extraneous sensory performance factors operating during standard intellectual-ability or cognitive assessments. Here, the focus is on the direct consequences of degraded sensory input. According to this view, individuals with impaired sensory abilities (such as older adults) are disadvantaged when taking psychometric tests of intellectual abilities or when working on cognitive tasks for reasons that are unrelated to their intellectual competence. Rather, sensory difficulties in stimulus identification and stimulus discrimination result in lower cognitive performance and an increasing covariation between intellectual and sensory functioning. For instance, a person who is unable to identify the critical stimulus dimensions of an analogical reasoning test item because of poor visual acuity is less likely to provide a correct answer to this item than a person who can recognize the critical dimensions, even if the two persons do not differ in "latent" reasoning ability. Thus, according to this view, and given the existence of sizeable sensory decline with age, acuity-related sensory input factors account both for decrements in intellectual performance and for age-based increments in the correlation between sensory and intellectual functioning.

This Study: Experimental Simulation of Age-Associated Sensory Acuity Reductions

In line with the fourth hypothesis, the main purpose of the present study was to test whether sensory acuity reductions operating during the psychometric assessment of intellectual abilities offer a likely explanation for the strong connection between sensory and intellectual performance in old age. Similar to the work of others (Murphy, Craik, Li, & Schneider, 2000; Rabbitt, 1968), we adopted an age-simulation approach (Baltes, Reese, & Nesselroade, 1988; Lindenberger & Baltes, 1995) to test this hypothesis. Specifically, the cognitive test battery used in our correlational explorations of the age-associated link between sensory and cognitive functioning (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994, 1997) was administered to middle-aged adults whose visual or auditory acuity levels were temporarily reduced to old-age levels. To validate the effectiveness of our sensory acuity manipulations, sensory acuity under experimental conditions was compared with acuity levels observed in participants of the Berlin Aging Study (BASE; Baltes & Mayer, 1999; Marsiske et al., 1999).

We made two main predictions. First, if sensory acuity reductions were critical for lowering the intellectual performance of older adults, then midlife adults would show lowered intellectual performance under conditions of simulated acuity loss. Second, any decrements in intellectual performance, if present, should be modality-specific in the sense that performance on cognitive tasks with visual or auditory stimulus presentation is differentially affected by visual and auditory acuity reductions, respectively.

The Scope of This Study

Relations among sensory, perceptual, and cognitive aspects of normal aging are continuous and interactive, and sensory aging itself is a highly complex and multidimensional phenomenon (Schneider & Pichora-Fuller, 2000). For these reasons, the acuity manipulations implemented in this study cannot be portrayed as an exhaustive simulation of sensory age changes. Specifically, our manipulations may fail to mimic peripheral sensory age changes that are relatively independent of changes in acuity. For instance, we do not know to what extent the auditory acuity manipulation used in the present study also induced reductions in the temporal resolution of auditory processing, which, at least in part, appear to be peripheral in origin (Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994). Thus, a possible absence of detrimental effects of our experimentally simulated acuity losses on cognitive performance does not exclude the presence of such effects for other aspects of sensory age changes (cf. Murphy et al., 2000; Rabbitt, 1968).

To reiterate, the relatively narrow but well-specified purpose of this study was to examine whether acuity-related sensory input factors can account for the age-associated increase in the link between sensory and cognitive functioning observed in several correlational studies. To examine this issue, middle-aged adults were administered the cognitive test battery used in past work (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994) under conditions of simulated visual or auditory acuity losses.

Method

Sample and Overview

A total of 218 Berlin residents aged 30 to 50 years were recruited by a national survey research institute for participation in the present study. Individuals participated in two sessions separated by 1 week and were tested in groups of 3 to 5. Individuals within each group were randomly assigned to one of five different acuity conditions: (a) effective reduction of both auditory and visual acuity ($n = 46$), (b) effective reduction of auditory acuity but placebo reduction of visual acuity ($n = 40$), (c) effective reduction of visual acuity but placebo reduction of auditory acuity ($n = 43$), (d) placebo reduction of both visual and auditory acuity ($n = 44$), and (e) no acuity treatment ($n = 45$). About half of the sample ($n = 110$) were men. Ninety-one percent of the research participants reported to be in satisfactory, good, or very good physical health. None of the participants reported the use of hearing aids, and 48% wore their own glasses during the experiment. A detailed description of acuity manipulations is provided below.

Apparatus and Materials

Visual acuity. The visual acuity treatment was accomplished with add-on glasses. Individuals put the add-on glasses on top of regular glasses—that is, their own glasses, if they were wearing glasses, or glasses without correction provided by the experimenter for the duration of the experiment. Under placebo acuity conditions, individuals wore add-on glasses without any optical manipulation. Under effective treatment conditions, the optically neutral properties of the add-on glasses were altered by attaching thin, self-adhesive, partial occlusion filters manufactured by Ryser Optik (St. Gallen, Switzerland) on top of them. In Europe, partial occlusion filters of this kind are often used for the treatment of amblyopia in children (cf. Lang, 1995). Partial occlusion filters reduce visual acuity by light scatter with contrast reduction, rather than by luminance attenuation, lenticular defocus, or other mechanisms. A detailed description of the optical properties of partial occlusion filters is provided by Menozzi and Gessler (1998).[1]

For each filter, the expected degree of visual acuity for standard stimuli presented black on white at high contrast in individuals with 20/20 vision is indicated by the manufacturer in Snellen decimals. Thus, for individuals whose corrected close visual acuity corresponds to 1.0 Snellen decimals, a partial occlusion filter labeled *0.4* is expected to lower visual acuity to values around 0.4 Snellen decimals under conditions of standard optometric testing. Of the 95 individuals with effective visual acuity reductions (i.e., partial occlusion filters), 92 received a 0.4 partial occlusion filter; the other 3 (2 from the visual acuity reduction only group and 1 from the visual-and-auditory acuity reduction group) received a 0.3 partial occlusion filter.[2]

Close visual acuity was measured separately for the left and right eyes at reading distance (e.g., approximately 30 cm) by using standard stimuli (see Geigy, 1977). For each research participant, close visual acuity was measured twice: (a) under one of the five experimental conditions and (b) under control conditions to assess participants' presenting acuity levels. Contrast format was black on white. Measurements were taken with and without their presenting optical correction. The analyses we report in this article are based on the better values, which in all cases referred to corrected vision. For each participant, two kinds of stimuli were used under both experimental and control conditions: (a) a reading table with text in a font of descending size and (b) Landolt rings. In the old-age sample used to validate the acuity-reducing effect of the partial occlusion filters, the identical reading tables but no Landolt rings were used (cf. Marsiske et al., 1999). Therefore, the analyses we report in this article are restricted to values obtained with the reading table to allow for direct comparisons with the BASE sample.

Auditory acuity. Auditory acuity was reduced by means of the headphone-shaped noise protector Contraphon 2000 (Micro Diagnostic GmbH, Dortmund, Germany). On the basis of pilot testing with various noise protectors and the frequency-band descriptions provided by the manufacturers, the Contraphon 2000 noise protector appeared to provide the best approximation to old-age auditory acuity available (i.e., a relatively strong overall reduction of auditory acuity, combined with more pronounced reductions for moderately high than for low frequencies). According to the manufacturer, application of the noise protector leads to threshold increments from 0 to 24.3, 23.8, 26.1, 33.9, 32.8, 39.1, 43.8, and 36.0 dB at 0.063, 0.125, 0.25, 0.5, 1.0, 2.0, 4.0, and 8.0 kHz, respectively. Individuals in groups with effective auditory acuity reductions wore the noise protectors in their original form. Individuals in groups with placebo auditory acuity manipulations wore noise protectors with two circular (diameter = 2.8 cm) and one rectangular (length = 6.5 cm, width = 0.7 cm) holes in each of the two shells and with the inner sound-dampening foam removed.

All auditory measurements were done with a Bosch (Firma Kind-Arbeitssicherheit, Burgwedel, Germany) ST-20-1 pure-tone audiometer at eight different frequencies (i.e., 0.25, 0.50, 1.0, 2.0, 3.0, 4.0, 6.0, and 8.0 kHz). With respect to free-field audiometry, a single sound source (i.e., the loudspeaker provided by the manufacturer for this purpose) was centrally located in front of the research participant at a distance of 1.5 m. In total, three audiometric assessments were taken: (a) binaural free-field audiometry with auditory acuity manipulations, (b) binaural free-field audiometry without auditory acuity manipulations, and (c) standard audiometry without auditory acuity manipulations. Free-field thresholds were obtained binaurally, whereas standard thresholds were obtained separately for the two ears. Throughout this article, the values reported for standard audiometry refer to the better ear.

It was physically impossible to assess the effectiveness of the auditory acuity manipulations through standard audiometry (i.e., with headphones), because most research participants were wearing noise protectors under experimental conditions. Therefore, auditory acuity under experimental conditions had to be assessed with free-field audiometry. The resulting thresholds were not directly comparable to values obtained in the old-age validation sample from the BASE, because measurements in the BASE were obtained with the identical audiometer but under standard conditions (i.e., with headphones; cf. Lindenberger & Baltes, 1994). As a consequence, thresholds for auditory acuity under experimental conditions that used standard audiometric procedures needed to be estimated (see the Results section).

Cognitive test battery. The computerized cognitive test battery used in our original work on the link between sensory and intellectual functioning (Lindenberger, Mayr, & Kliegl, 1993) was adapted for group testing and used in the present study. Macintosh SE30 personal computers equipped with a MicroTouch Systems touch-sensitive screen were positioned at reading distance and used for stimulus presentation and data collection. Test instructions were digitally recorded on an Apple Macintosh computer in good sound quality (i.e., 22 kHz sampling rate, no compression) using the Audio and SoundEdit resources of HyperCard (1994). During the administration of the battery, the experimenter activated the relevant instructions with mouse clicks. Instructions were transmitted in stereo at normal speaking loudness using two Sony SRS-68 active loudspeakers. Loudness was fixed to identical levels under all experimental conditions, and research participants could not influence the level of speech.[3]

The BASE cognitive battery comprises 14 cognitive tests assessing five intellectual abilities: perceptual speed (Digit Letter, Digit Symbol Substitution, Identical Pictures), reasoning (Figural Analogies, Letter Series, Practical Reasoning), and episodic memory (Activity Recall, Memory for Text, Paired Associates) from the mechanic (i.e., broad fluid) domain, and verbal knowledge (Practical Knowledge, Spot-a-Word, Vocabulary) and fluency (Categories, Letter "S") from the pragmatic (i.e., broad crystallized) domain. The materials and procedural details of the cognitive battery have been described elsewhere (i.e., Lindenberger et al., 1993). As in the BASE, written instructions were presented black on white in large fonts on the computer screen (i.e., Times Roman, 36-point type). With respect to cognitive tests based on visual stimuli, relevant detail was always larger than 5 mm in magnitude. Thus, with a reading distance of about 30 cm, relevant information was displayed at angular sizes larger than 50°.

Working memory measures: Listening span and reading span. Measures of working memory were adapted from Salthouse and Babcock (1991; cf. Daneman & Carpenter, 1980). Participants were given a series of *n* sentences and were asked (a) to answer an information question immediately after presentation of each sentence by choosing among three response alternatives, (b) to keep the last word of each sentence in mind, and (c) to recall all last words in their original sequence at the end of the series. Within each task format, we administered two series with two, three, four, five, six, and seven sentences in ascending order. A response to a series was considered correct when all information questions were answered correctly and when all last words were listed in correct order. Given the small number of replications at each level of difficulty (i.e., two), the

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[1] We do not assume that the acuity reduction caused by partial occlusion filters perfectly mimics acuity losses observed with aging. At the same time, partial occlusion filters probably lead to a more realistic simulation of acuity changes associated with aging than alternative devices such as neutral density filters.

[2] The use of 0.3 partial occlusion filters was discontinued because they were found to reduce visual acuity beyond the average levels observed in the old-age validation sample from the BASE.

[3] Compared with testing conditions in the BASE, fixing loudness to a given level most likely introduced a positive bias (e.g., a bias in the direction of finding an effect of experimentally reduced auditory acuity) because experimenters in the BASE tended to raise their voice when research participants were hard of hearing. In the present study, spoken instructions were held constant across experimental conditions to allow for a well-controlled assessment of auditory acuity manipulations.

scoring was based on the total number of correct responses. Therefore, scores could vary between 0 and 12.

In the case of the listening span task, the sentences, the information question, and the three response alternatives were presented auditorily by means of loudspeakers. In the case of the reading span task, the sentences were presented visually black on white on the computer screen, and the information question as well as the response alternatives were presented in the answer booklet, again black on white but with a smaller font (i.e., Times Roman, 18-point type) than the font used in the BASE.

Procedure

Testing site and luminance conditions. Testing took place in three rooms of the psychological laboratory at the Max Planck Institute for Human Development in Berlin, Germany. The first room was used for visual acuity assessment, the second for auditory acuity assessment, and the third for cognitive testing. Light intensity did not differ across the three rooms and varied from about 300 lx to about 400 lx. The luminance of the white areas of the computer screens and of the answer sheets varied from about 76 cd/m^2 to 102 cd/m^2.

First session. At the beginning of the first session, participants completed a short demographic questionnaire. Then they were randomly assigned to one of the five experimental groups, and their auditory and visual acuity under treatment conditions were assessed individually in two separate, quiet rooms. After that, while continuing to be in one of the five acuity conditions, individuals were first given the BASE cognitive battery and then the span measures. During cognitive testing and while answering the questionnaires, research participants worked at separate desks with the computers located in front of them. The desks formed a semicircle, and the experimenter's desk was facing this semicircle. The loudspeakers were placed at the experimenter's desk such that the distance to the loudspeakers was about the same for all research participants.

The 14 tests of the cognitive battery were administered in the same fixed order as in the BASE: Digit Letter Substitution, Spot-a-Word, Memory for Text, Figural Analogies, Fluency: Letter "S", Vocabulary, Practical Reasoning, Digit Symbol Substitution, Activity Recall, Identical Pictures, Paired Associates, Categories, Letter Series, and Practical Knowledge. The psychometric test battery was followed by administration of the two working memory measures. Order of administration of the visual and the auditory versions of the working memory measures was counterbalanced within acuity conditions.

After cognitive testing, research participants were allowed to take off the noise protectors and the add-on glasses and were asked to fill out a questionnaire with a total of 10 questions. The first 2 questions referred to participants' ability to concentrate while working on the cognitive tasks (e.g., "I was able to concentrate well on the tasks"). The remaining 8 questions assessed the degree of distraction experienced by the acuity reduction devices; 4 referred to the noise protectors (e.g., "The noise protectors distracted me from working on the tasks"), and 4 to the add-on glasses. Participants in the no-treatment control condition only received the first 2 questions. Finally, to examine possible confounding treatment effects on mood and emotion, the Positive and Negative Affect Scale (PANAS; Watson, Clark, & Tellegen, 1988) as well as the German adaptation (Laux, Glanzmann, Schaffner, & Spielberger, 1981) of the State–Trait Anxiety Inventory (Spielberger, Gorsuch, & Lushene, 1970) were administered.

Second session. In the second session, all participants were tested under no-treatment control conditions only. First, visual acuity was assessed, followed by free-field as well as standard audiometry with closed headphones. Then the cognitive test battery was administered again, followed by the two measures of working memory span in counterbalanced order.

Results

Research Participants' Visual and Auditory Acuity Under Control Conditions

In the second session, all research participants' visual and auditory acuities were assessed under standard (i.e., no-treatment) conditions to examine whether participants' presenting acuity levels were typical of their age and whether acuity levels accidentally varied across experimental groups. On average, close visual acuity for the better eye and with the best available optical correction was 0.88 Snellen decimals ($SD = 0.23$) and did not vary reliably as a function of experimental group, $F(4, 212) = 1.89$, $MSE = 0.05$, $p > .10$. Average auditory thresholds for pure tones in the speech range (i.e., averaged over 0.50, 1.00, 2.00, 3.00, and 4.00 kHz) using standard procedures (i.e., with headphones) were at 11 dB ($SD = 5$) and did not vary as a function of experimental group either, $F(4, 212) = 1.84$, $MSE = 26.47$, $p > .10$. Thus, both for vision and hearing, acuity levels under no-treatment control conditions were in the normal range and did not vary as a function of assignment of individuals to the five different experimental conditions.

Close visual acuity under control conditions was negatively related to chronological age ($r = -.43$, $p < .01$). In contrast, distance visual acuity ($r = -.04$) and mean auditory thresholds in the speech range ($r = .12$) were unrelated to age in this sample. The negative relation between close visual acuity and age may appear quite strong given the limited age range of the present sample. However, its magnitude is consistent with findings from earlier studies showing a strong linear age trend for corrected close visual acuity across the entire adult life span (e.g., Baltes & Lindenberger, 1997; Salthouse et al., 1996).

Treatment Check (Age-Referenced Validation) of Sensory Acuity Reductions

Table 1 displays close visual and auditory acuity as a function of acuity condition. Again, values for auditory acuity refer to auditory acuity in the speech range. Compared with the groups with placebo visual acuity reductions and the no-treatment control group, close visual acuity was much lower in the two groups with occlusion filters: .85 versus .43, $F(1, 211) = 208.40$, $MSE = 0.05$, $p < .01$. The two groups with effective visual acuity reduction did not differ from each other, and the two groups with placebo visual acuity reductions did not differ from the no-treatment control group ($ps > .10$).

Compared with the groups with placebo noise protectors and the no-treatment control group, auditory free-field thresholds in the speech range were higher in the two groups with intact noise protectors: 35 versus 58, $F(1, 205) = 339.16$, $MSE = 81.59$, $p < .01$. The two groups with effective auditory acuity reduction did not differ from each other ($ps > .10$), but the two groups with placebo auditory acuity reductions had somewhat higher thresholds than the no-treatment control group: 32 versus 36, $F(1, 205) = 6.40$, $MSE = 81.59$, $p = .012$. Apparently, the placebo ear protectors were associated with slight decrements in auditory acuity in the speech range.

Comparisons with the BASE sample. A key question of the present age simulation was whether the acuity manipulations re-

Table 1
Treatment Check (Age-Referenced Validation) of Sensory Acuity Reductions

	Present experiment					
		Experimental group				
Characteristic	Control	Neither	Visual	Auditory	Both	BASE[a]
Age range (years)	30–50					70–84
n	45	44	43	40	46	258
Visual acuity (Snellen)	.84 (.21)	.87 (.24)	.42 (.17)	.84 (.25)	.44 (.18)	.45 (.21)
Auditory acuity in the speech range (dB)						
Estimation Method A				47[b] (4)	47[b] (4)	43 (15)
Estimation Method B	14[c] (9)	20[c] (10)	18[c] (12)	40[c] (7)	40[c] (9)	46 (15)

Note. Close visual acuity refers to values obtained with the better eye using the best available optical correction. Auditory acuity refers to mean pure-tone thresholds in the speech range (i.e., 0.50, 1.00, 2.00, 3.00, and 4.00 kHz). Values in parentheses refer to standard deviations. BASE = Berlin Aging Study.

[a] Values are based on Marsiske et al. (1999).

[b] Estimates are based on 0.50, 1.00, 2.00, and 4.00 kHz and were obtained by adding the sound-reduction norms of the noise protectors provided by the manufacturer to the thresholds obtained with standard assessment.

[c] Estimates are based on 0.50, 1.00, 2.00, 3.00, and 4.00 kHz and were obtained by subtracting differences in thresholds due to assessment method (free-field vs. standard) under control conditions from free-field values obtained under experimental conditions.

duced acuity in the experimental groups down to target age levels. The younger half of the participants in the intensive protocol of the first measurement occasion of the BASE served as the old-age reference sample to address this question ($n = 258$, age range = 70–84 years, *M* age = 77.5 years, $SD = 4.3$; cf. Baltes & Mayer, 1999; Marsiske et al., 1999).

Assessment of close visual acuity did not differ between the present study and the BASE, so that values could be compared directly. In groups with visual acuity reductions, values obtained for close visual acuity with the present midlife sample did not differ significantly from the values naturally observed in the sample of older adults (both $ps > .10$). Thus, with respect to visual acuity, the simulation manipulation had the desired effect (see the upper half of Table 1).

With respect to auditory acuity, comparisons with the BASE sample were more difficult. In the BASE, auditory acuity was assessed using standard procedures (i.e., with headphones). However, in the present study, auditory acuity under experimental conditions was assessed with free-field audiometry because research participants in four of the five experimental groups wore noise protectors (effective or placebo). As a consequence, the two sets of values cannot be compared directly across studies. Therefore, we used two different estimation methods to arrive at estimated values for auditory acuity thresholds under experimental conditions as assessed with standard audiometry.

With the first estimation method (i.e., Method A), we added the increase in thresholds indicated by the manufacturer to research participants' thresholds under standard conditions of auditory acuity assessment. This procedure assumes that the manufacturer's norms are valid and that threshold increments are additive over the range of presenting auditory acuity levels observed in this study. Table 2 summarizes the relevant information for the two groups with effective acuity reductions ($n = 86$), along with relevant data from the old-age comparison sample from the BASE. With a 2 (group) × 6 (frequency) repeated measures analysis of variance, a main effect of frequency was observed, $F(5, 1700) = 305.88$, $MSE = 150{,}628.82$, $p < .01$. This main effect was qualified by a Group × Frequency interaction, $F(5, 1700) = 79.58$, $MSE = 150{,}628.82$, $p < .01$. The main effect of group was not significant ($p > .10$). Post hoc *t* tests for each frequency revealed that thresholds for the two groups did not differ at 0.25 dB, $t(1) = -1.38$; 1.00 dB, $t(1) = 1.83$; 2.00 dB, $t(1) = 1.96$; and 4.00 dB, $t(1) = 0.30$; all $ps > .05$. At 0.50 kHz, mean thresholds for participants with intact noise protectors were actually higher than in the BASE, $t(1) = 4.32$, $p < .01$, but at 8.00 kHz, they were lower, $t(1) = -9.56$, $p < .01$. Thus, according to this estimation procedure, the experimental manipulation successfully reduced auditory acuity in the speech range down to old-age levels.

The second estimation method (Method B) did not rely on the information provided by the manufacturer. According to Method B, we first subtracted, for each participant and each frequency, the threshold obtained with standard audiometry from the corresponding threshold obtained with free-field audiometry under no-treatment conditions. The resulting difference scores can be taken to represent the difference in decibels due to assessment method (i.e., standard vs. free-field). These difference scores were then subtracted from the free-field values obtained under treatment conditions to obtain threshold estimates for standard audiometry under each of the five treatment conditions. The relevant scores are again displayed in Table 2. With a 2 (group) × 8 (frequency) repeated measures analysis of variance, main effects of group, $F(1, 338) = 34.55$, $MSE = 1{,}453.05$, $p < .01$, frequency, $F(7, 2366) = 214.83$, $MSE = 233{,}881.40$, $p < .01$, as well as an Age Group × Frequency interaction were observed, $F(7, 2366) = 50.77$, $MSE = 233{,}881.40$, $p < .01$. Post hoc comparisons revealed that threshold estimates for participants with intact noise protectors did not differ from thresholds in the BASE sample at 0.50 kHz, $t(1) = -1.61$, and 1.00 kHz, $t(1) = 1.12$ (both $ps > .10$); for all other frequencies, thresholds were significantly higher in the BASE sample (all $ts > 3.0$, all $ps < .01$).

In the lower half of Table 1, the aggregate values in the speech range using both estimation methods are shown as a function of

Table 2
Pure-Tone Thresholds (With Standard Deviations) as a Function of Frequency in Research Participants Wearing Intact Noise Protectors Under Experimental Conditions: Comparisons With the Berlin Aging Study (BASE) Sample

	Frequency (kHz)							
Measure	0.25	0.50	1.00	2.00	3.00	4.00	6.00	8.00
Present study								
Free-field, with noise protectors	55 (9)	54 (9)	58 (9)	59 (9)	60 (11)	62 (13)	70 (13)	70 (13)
Free-field, control condition	38 (7)	29 (7)	26 (6)	31 (8)	27 (9)	30 (9)	40 (11)	40 (129)
Standard, control condition	9 (5)	8 (3)	9 (4)	10 (6)	9 (7)	11 (7)	14 (9)	15 (11)
Estimated standard scores: Method A[a]	**35** (5)	42 (3)	**42** (4)	**49** (6)		**55** (7)		51 (11)
Estimated standard scores: Method B[b]	26 (10)	**33** (9)	**41** (10)	38 (10)	42 (12)	43 (13)	44 (13)	45 (14)
BASE sample								
Standard	37 (13)	35 (14)	39 (15)	45 (18)	50 (18)	54 (19)	57 (21)	73 (21)

Note. For the present study, $n = 86$ and age range = 30–50 years; for the BASE, $n = 258$ and age range = 70–84 years. Values regarding the present study refer to the two groups of research participants who wore intact noise protectors under experimental conditions. Estimated scores are printed in bold if they do not differ significantly from values observed with standard audiometry in the BASE sample ($p < .05$).

[a] Estimates obtained by adding the sound-dampening norms of the noise protectors provided by the manufacturer to the thresholds obtained with standard assessment. [b] Estimates obtained by subtracting differences in thresholds due to assessment method (free-field minus standard) under control conditions from free-field values obtained under experimental conditions.

experimental group. Using Method A, thresholds for 3.00 kHz were not included in the mean because norms for this frequency were missing. Here the mean threshold estimate was 47 dB for the group with intact noise protectors but ineffective visual manipulations, compared with 43 dB in the BASE sample; for the difference between the two samples, $F(1, 296) = 2.69$, $MSE = 191.28$, $p > .10$. For the group with intact noise protectors and partial occlusion filters, the average threshold was also 47 dB, and the difference to the BASE sample was again not reliable, $F(1, 302) = 2.16$, $MSE = 187.94$, $p > .10$. With Method B, the mean estimated threshold was 40 dB for the group with effective auditory but ineffective visual manipulations, compared with 45 dB in the BASE sample; for the difference between the two samples, $F(1, 294) = 5.77$, $MSE = 206.52$, $p = .017$. For the group with effective auditory and visual reductions, the mean threshold was also 40 dB, and the difference to the BASE sample was again significant, $F(1, 302) = 5.27$, $MSE = 207.12$, $p = .022$.

Summary. Both the partial occlusion filters and the noise protectors effectively reduced acuity compared with groups with no or placebo treatments. With respect to visual acuity, direct statistical comparisons with the BASE sample indicate that the acuity reductions induced by the partial occlusion filters were sufficient to reach levels of acuity impairment commonly observed in old age. With respect to auditory acuity, differences in assessment methods complicated statistical comparisons with the BASE sample. Two estimation methods were used to overcome this problem, one based on the sound-dampening norms of the noise protectors and the other based on the empirically observed difference between free-field and standard audiometry. Results obtained with the two different estimation methods indicate that threshold increments in the speech range either reached (Method A) or approximated (Method B) old-age levels.

Effects of Sensory Acuity Reductions on Intellectual Performance

An analysis of variance with acuity condition (5) as a between-subjects factor and intellectual ability (5) as a within-subject factor was computed to examine the influence of sensory acuity modification on intellectual performance. Four orthogonal contrasts were defined for the acuity condition factor: (a) the no-treatment control group versus the other four groups receiving some form of experimental treatment, effective or placebo (general treatment effect); (b) the group with placebo auditory acuity and placebo visual acuity reduction versus the three groups with either effective auditory acuity reduction, effective visual acuity reduction, or both (effect of acuity reductions); (c) the two groups with effective visual acuity reductions versus the group with placebo visual acuity but effective auditory acuity reduction (effect of visual acuity reduction); (d) the two groups with effective auditory acuity reductions versus the group with placebo auditory acuity but effective visual acuity reduction (effect of auditory acuity reduction).

None of the four orthogonal main effects regarding sensory acuity was statistically reliable (see Table 3). However, the contrast comparing the control group without any acuity treatment with the remaining four conditions interacted with intellectual ability, $F(4, 852) = 3.70$, $MSE = 52.20$, $p < .01$. Follow-up analyses indicated that this contrast was marginally significant for reasoning, $F(1, 213) = 4.22$, $MSE = 99.31$, $p = .041$; and knowledge, $F(1, 213) = 4.63$, $MSE = 98.92$, $p = .032$; but not for perceptual speed, fluency, and memory. Both for knowledge and reasoning, participants in the no-treatment control condition showed lower levels of performance than did participants in the other four conditions (reasoning: 47.3 vs. 50.7; knowledge: 47.2 vs. 50.7). Thus, individuals experiencing a sensory treatment actually showed slightly higher levels of performance in reasoning and knowledge regardless of whether this treatment actually lowered their sensory acuity.

The main conclusion to be drawn from these analyses is that old-age referenced experimental reductions in visual or auditory acuity did not induce reductions in intellectual performance. Figure 1 illustrates this pattern of results.

Table 3
Effect of Sensory Acuity Reductions on Cognitive Performance

	Acuity condition				
Measure	Control (n = 45)	Neither (n = 44)	Visual (n = 43)	Auditory (n = 40)	Both (n = 46)
		Intellectual abilities			
Memory	51 (10)	51 (11)	49 (10)	50 (11)	49 (9)
Perceptual speed	48 (11)	50 (9)	50 (9)	51 (9)	50 (10)
Reasoning	47 (11)	49 (10)	51 (9)	51 (9)	52 (11)
Fluency	51 (11)	49 (9)	49 (9)	50 (10)	51 (12)
Knowledge	47 (10)	49 (11)	52 (9)	51 (10)	51 (9)
		Working memory task			
Auditory	7.5 (3.5)	7.2 (2.8)	7.8 (2.1)	6.6 (3.2)	6.5 (3.2)
Visual	6.2 (3.2)	6.2 (3.0)	7.1 (2.6)	6.9 (3.2)	6.5 (2.9)

Note. Ability scores are based on unit-weighted composites of multiple tests and are expressed as T scores (M = 50, SD = 10). Working memory performance is expressed in raw scores (maximum value = 12). Values in parentheses refer to standard deviations.

Effects of Sensory Acuity Reductions on Working Memory Performance

One possible reason for the general absence of negative effects of sensory acuity reductions on intellectual performance relates to the relatively high degree of redundancy between visually and auditorily presented information. For instance, in the cognitive battery, all instructions are presented both auditorily as well as visually on the computer screen. The unimodal presentation format of the working memory tasks served to explore this possibility. The relevant data are displayed in the lower portion of Table 3.

With respect to the auditorily administered working memory task, the fourth condition contrast was marginally significant, $F(1, 213) = 5.24$, $MSE = 8.90$, $p = .023$, indicating that the two groups with effective auditory acuity reductions performed less well on this measure than the group with effective visual but placebo auditory acuity reductions. With respect to the visual version, reliable condition effects were absent.

Subjective Measures

The five groups did not differ in positive affect, negative affect, state anxiety, and trait anxiety. In contrast, questions regarding the degree of distraction experienced by the sensory devices showed reliable effects. Participants in the two groups with partial occlusion filters reported more distraction because of the add-on glasses than participants in the groups with placebo add-on glasses: 3.3 versus 2.5, $F(1, 168) = 27.51$, $MSE = 1.08$, $p < .01$. Likewise, participants in the two groups with intact noise protectors reported more distraction because of the noise protectors than participants in the groups with the placebo devices: 3.1 versus 2.3, $F(1, 168) = 27.23$, $MSE = 1.13$, $p < .01$. At the same time, participants in the five groups did not differ in their reported ability to concentrate. Thus, despite the fact that participants with effective sensory acuity reductions reported more distraction than participants with placebos, they did not show a decrease in their reported ability to concentrate on the cognitive tasks.

Absence of Enduring Effects of Acuity Manipulations: Findings at Retest

One week later, participants' cognitive performance was assessed again under control conditions (i.e., all participants were tested without sensory acuity manipulations). In this second session, no reliable effects of acuity condition were observed, neither for the five intellectual abilities nor for the auditorily or visually administered measures of working memory (all $ps > .10$). Thus, it appears that the sensory acuity manipulations used in the present study did not have a lasting effect on cognitive performance.

Discussion

Summary of Findings

The results of the present study are clear. In the presence of simulated aging losses in visual or auditory acuity, middle-aged adults do not deviate negatively in their intellectual performance from middle-aged adults without such simulated losses. If anything, individuals in groups with effective or placebo reductions of sensory acuity showed a tendency to perform above the level of the no-treatment control group. A likely (but post hoc) explanation for this unexpected finding is what Düker (1963) termed a reactive increase in attention and effort (*reaktive Anpassungssteigerung*). According to this interpretation, individuals invest more effort under conditions of reduced sensory acuity to compensate for a supposedly challenging experimental condition.

The only evidence in favor of a detrimental effect of simulated acuity reductions on intellectual performance was observed for the auditorily administered version of the working memory measure, where individuals with reduced auditory acuity performed below the level of the other groups. Relative to the magnitude of age differences commonly observed with measures of working memory span (cf. Salthouse & Babcock, 1991), the size of this effect was quite small (0.32 SD units). Performance on the visually administered working memory measure did not vary at all as a

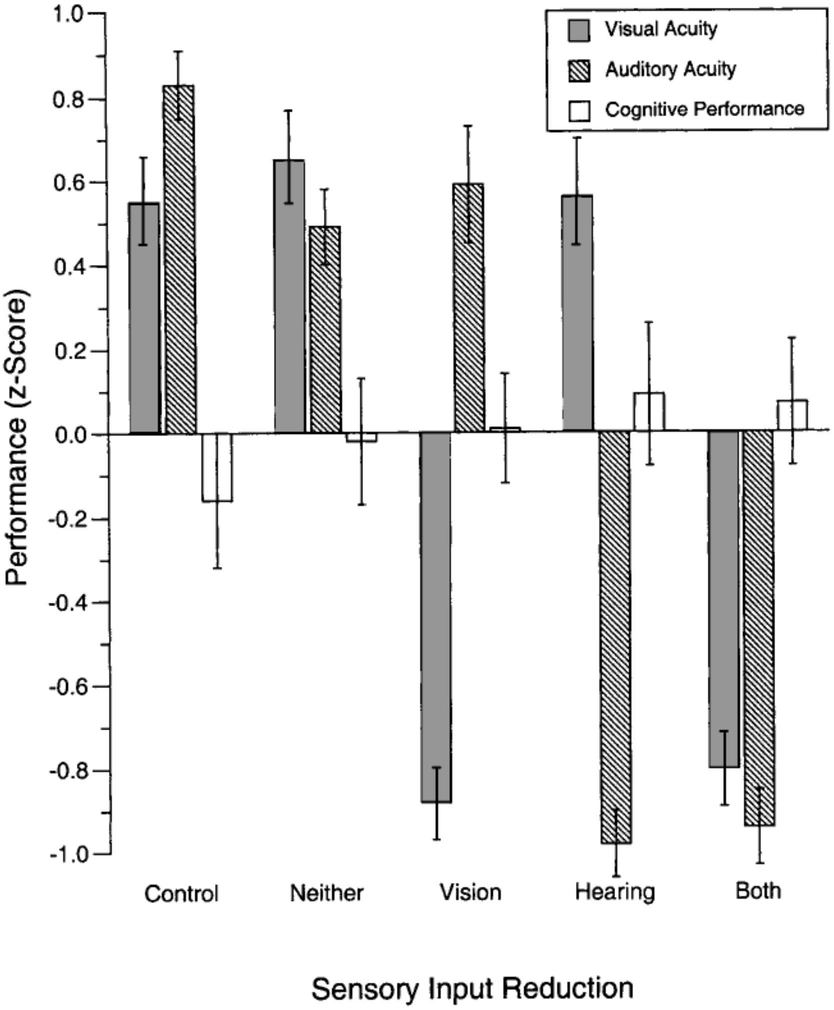

Figure 1. Visual acuity, auditory acuity, and cognitive performance as a function of experimental condition. Pronounced reductions in visual or auditory acuity during cognitive assessment did not induce decrements in cognitive performance. Performance is expressed in standard scores, with higher scores indicating better performance. Error bars refer to standard errors of the mean. Cognitive performance refers to the unit-weighted composite of five intellectual abilities assessed with a standard battery of 14 cognitive tests. $N = 218$.

function of simulated acuity loss. A plausible reason for this difference between auditorily and visually administered span measures is that on-line corrections of perceptual failures (e.g., rechecking) are more easily accomplished in the visual than in the auditory modality.

Finally, the analysis of retest performance under no-treatment control conditions indicates that the observed effects of sensory acuity manipulations, whether positive or negative, were transient in nature because the five experimental groups no longer differed in mean level of performance when they were tested a week later under standard acuity conditions.

Qualifications

As noted in the introduction, the results of this study do not exclude the possibility that other dimensions of sensory aging losses would act as sensory performance factors during cognitive testing or that cognitive performance under different assessment conditions would be influenced by losses in acuity (e.g., Murphy et al., 2000). At the same time, our results strongly suggest that acuity-related sensory performance factors do not contribute in important ways to the close connection between sensory and cognitive aging observed in our earlier work (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). Thus, the relevance of the present findings derives primarily from the fact that the measures and procedures used in this study closely match the ones that were used in the BASE.

In this context, we would like to add three qualifications to the interpretation of our findings. First, it is generally fair to say that conventions of psychometric testing take individuals with sensory deficits into consideration. This is especially true for the cognitive battery of the BASE, which has been designed with the explicit goal to minimize the influence of sensory performance factors.

Specifically, all visual information is presented in large font and with high contrast, all spoken instructions are read loudly, clearly, and slowly; and all task instructions are presented in a bimodal manner (i.e., visually on the computer screen and aurally by the experimenter; cf. Lindenberger et al., 1993). Therefore, it is not surprising that the only acuity-related decrement in cognitive performance was found with the reading span task, which does not allow for rechecking or cross-modal compensation. Note also that this task is not part of the cognitive battery used in the BASE.

Second, it also seems clear that acuity-related sensory performance factors will affect cognitive performance if acuity falls below some threshold. In fact, at the first measurement occasion of the BASE, the visual acuity of about 11% of the participants was impaired to such a degree that a reduced auditory version of the battery had to be administered (cf. Lindenberger & Baltes, 1997). Note, however, that the strong correlation between sensory and cognitive functioning observed in the BASE did not depend on the presence of individuals with very poor hearing or very poor vision in the sample (cf. Lindenberger & Baltes, 1994).

Third, it is likely that attentional and acuity-related interindividual differences interact in various ways, as suggested by the probable increase in attention and effort among individuals assigned to one of the four experimental conditions with effective or placebo acuity manipulations. Specifically, individuals with less attentional resources may be less able to counteract negative effects of sensory impairments than individuals with more attentional resources (see also Schneider & Pichora-Fuller, 2000). To examine this issue more closely, future simulation studies of the kind presented here could be directed at individuals who are low in attentional resources but high in visual and auditory acuity.

Comparison to Findings Obtained by Murphy et al. (2000)

In contrast to the widespread absence of detrimental effects of sensory acuity manipulations on cognitive performance observed in the present study, Murphy et al. (2000) recently reported that the effects of added auditory noise on short-term memory performance resemble the effects of aging on short-term memory performance. Specifically, and similar to aging, noise selectively impaired the retrieval of verbal information stored in secondary memory but did not affect the reproduction of verbal information from primary memory.

At first, the discrepancy in findings between the two studies may seem surprising. However, we would like to argue that it is not, for at least two reasons. First, the BASE cognitive battery used in the present study is probably less sensitive to sensory manipulations than the auditory short-term memory paradigm used by Murphy et al. (2000). Second, the sensory input manipulation used by Murphy et al. (i.e., addition of auditory noise) is probably more powerful than the "passive" reduction of sensory acuity used in the present study.

As noted above, there was one exception to the general absence of effects of sensory acuity reductions on cognitive performance in the present study: Individuals with experimentally reduced auditory acuity performed less well on the auditorily presented version of the working memory task (i.e., listening span) than individuals under control conditions. Presumably, performance on the listening span task involves secondary memory (e.g., Daneman & Carpenter, 1980; Salthouse & Babcock, 1991) and is very sensitive to auditory manipulations at encoding. Thus, the only instance of a detrimental effect of sensory acuity manipulations on cognitive performance in the present study was found for those task conditions that most closely resembled the paradigm used by Murphy et al. (2000; cf. Madigan & McCabe, 1971). Note, however, that the working memory tasks used in the present study are not part of the BASE cognitive battery used in earlier work (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994, 1997). Therefore, this finding does not alter our main conclusion.

Conclusion

During recent years, much attention in cognitive aging research has been directed toward the age-related increase in the link between sensory and cognitive functioning. The next step in this line of research is to sort out and compare alternative explanations for this finding (cf. Anstey, 1999; Bäckman, Small, Wahlin, & Larsson, 2000; Baltes & Lindenberger, 1997; S.-C. Li & Lindenberger, 1999; S.-C. Li, Lindenberger, & Frensch, 2000; Murphy et al., 2000; Rabbitt, 1991; Salthouse & Czaja, 2000; Schneider & Pichora-Fuller, 2000; Stevens et al., 1998; for a discussion of methodological problems, see Bäckman et al., 2000, Hertzog, 1996; Lindenberger & Pötter, 1998). The results of the present study suggest progress in this effort. The experimental reduction of acuity to old-age levels in younger adults has no negative effects on performance on standard measures of cognitive performance that have been shown to be associated with marked negative adult age differences and to be increasingly linked to sensory and sensorimotor functioning with advancing age. Whatever causes either or both of these phenomena, peripheral sensory input factors related to visual or auditory acuity do not seem to play a major role. Future work is needed to discern the relative merit of alternative explanations summarized in the introduction of this article. Experimentation (e.g., K. Z. H. Li et al., in press; Lindenberger et al., 2000) as well as longitudinal data will play a major role in this effort.

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