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Sensory Functioning and Intelligence in Old Age: A Strong Connection

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Relations among age, sensory functioning (i.e., visual and auditory acuity), and intelligence were examined in a heterogeneous, age-stratified sample of old and very old individuals (N = 156, M age = 84.9 years, age range = 70–103). Intelligence was assessed with 14 tests measuring 5 cognitive abilities (speed, reasoning, memory, knowledge, and fluency). Together, visual and auditory acuity accounted for 49.2% of the total and 93.1% of the age-related reliable variance in intelligence. The data were consistent with structural models in which age differences in intelligence, including speed, are completely mediated by differences in vision and hearing. Results suggest that sensory functioning is a strong late-life predictor of individual differences in intellectual functioning. Explanations are discussed, including the possibility that visual and sensory acuity are indicators of the physiological integrity of the aging brain (common cause hypothesis).

The purpose of this study is to explore the general role of auditory and visual functioning in cognitive aging. The focus is on the very old, that is, on the age range from 70 to 100 years and above covered in the Berlin Aging Study (BASE; cf. P. B. Baltes, Mayer, Helmchen, & Steinhagen-Thiessen, 1993). BASE offers the opportunity to examine the relationship between sensory and cognitive functioning because its interdisciplinary assessment protocol includes overall measures of auditory and visual functioning in addition to an elaborate assessment of psychometric intelligence and cognition (Lindenberger, Mayr, & Kliegl, 1993).

The theoretical rationale for this study derives from several considerations. A first general question is associated with the issue of "explanatory continuity versus discontinuity" in cognitive aging (P. B. Baltes, 1973; Lindenberger & Baltes, in press). For the most part, age-related differences in intellectual functioning in old age are conceptualized as the cumulative outcome of a life history of cultural–environmental–educational conditions interacting with genetic factors. This constitutes the "explanatory life-span developmental continuity" point of view because we expect high stability of interindividual differences in cognitive functioning from middle adulthood into old age. In general, for the period of middle adulthood and early old age, longitudinal data are supportive of such a stability–continuity view of interindividual differences in intellectual functioning (Hertzog & Schaie, 1986, 1988). However, life-span developmental models of aging (P. B. Baltes, 1987) posit that the process of aging is regulated also by factors that may emerge during later phases of the life course. To the extent that these late-life sources or determinants of development are powerful and uncorrelated with earlier ontogenetic sources of individual differences, a case for "explanatory life-span developmental discontinuity" might exist.

One illustration of such explanatory or causal discontinuities is the late-life onset of brain-related pathology suggestive of a distinction between "normal" and "pathological" cognitive aging (Fozard, Metter, & Brant, 1990; Gerok & Brandtstädter, 1992). Another possibility is the late-life emergence of new correlates or determinants of cognitive functioning such as auditory or visual functioning (cf. Rabbitt, 1990). Sensory functioning does not seem to be among the important determinants of individual differences in cognitive performance during earlier phases of the life span including middle and late adulthood (cf. Horn, 1980; Schaie, Baltes, & Strother, 1964; but see Raz, Moberg, & Millman, 1990). However, the situation may be different in old and very old age for at least two reasons. First, negative age changes in cognition may correlate with sensory functioning because they reflect the accumulated effects of reduced sensory stimulation. Protracted *sensory underload* (Sekuler & Blake, 1987) may reduce opportunities for intellectually stimulating exchanges with the environment, eventually reducing the general level of cognitive ability. This view can be labeled as the *sensory deprivation* hypothesis. Second, correlations between measures of sensory functioning and intellectual ability may increase in old age because both sets of measures are an expression of the physiological architecture, or the "mechanics" (P. B. Baltes, 1987), of the brain. Such a perspective can be identified as a kind of "common cause" hypothesis. For either or both

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reasons, we would expect that, with increasing age, measures of intellectual functioning share increasingly large portions of their variance with sensory measures.

Both the sensory deprivation and the common cause hypotheses predict an increasing correlation between sensory functioning and intellectual abilities with advancing age. In addition, the common cause hypothesis is consistent with recent findings about the source of age differences in vision, hearing, and intellectual functioning. Researchers in the fields of visual and auditory aging have repeatedly argued that a considerable portion of age-associated changes in sensory functioning is neuronal in origin and may include both peripheral and central sources. With respect to vision, for instance, recent evidence suggests that a large portion of negative age differences in visual acuity is due to neural deterioration beyond the level of the eye (Balazsi, Rootman, Drance, Schulze, & Douglas, 1984; Devaney & Johnson, 1980; Owsley, Sekuler, & Siemsen, 1983; Weale, 1987; Werner, Peterzell, & Scheetz, 1990). Similarly, the importance of neurological changes has been stressed for age changes in hearing (Bergman, 1983; Fozard, 1990). Thus, "the big story on age differences in vision and audition is that the nervous system at and beyond the level of the end organ is implicated in age differences in seeing and hearing" (Fozard, 1990, p. 165). In a similar vein, researchers in the field of cognitive aging generally agree that negative age differences are more pronounced for central than for peripheral aspects of information processing (Cerella, 1990; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; Salthouse, 1985). If sensory measures provide a more reliable and direct measure of age-associated changes in the brain than measures of cognitive functioning, then the former should mediate a large proportion of the age-related variance in the latter.

The common cause hypothesis is primarily concerned with the *aging-related* variance in sensory and intellectual functioning. Thus, we do not assume that low levels of sensory functioning are always linked to low levels of intellectual functioning. In fact, evidence from earlier periods of the life span suggests that sensory impairments often have rather small and circumscribed effects on cognitive functioning (Braden, 1985; Craig & Gordon, 1988; DeBeni & Cornoldi, 1988; Groenveld & Jan, 1992; Vernon, 1968). However, if changes associated with aging simultaneously reduce the functional efficacy of many brain systems, sensory and cognitive functions that are known to be dissociable in the neuropsychological sense (Shallice, 1988) may evince aging-induced covariation.

A related rationale of this study was to examine the role of sensory systems in the determination of cognitive assessment (Shindell, 1989; Vernon, 1989). In the cognitive aging literature, there is a lack of relevant work on this issue. Most research does not report on the auditory and visual status of their subjects. The absence of such work is probably due to the fact that much cognitive aging research has been conducted with the young–old (Neugarten, 1974) and with samples screened for health-related dysfunctions. The BASE, with its strong focus on a heterogeneous and age-stratified sample representative of a city population of the old and very old, forces a more explicit concern with the interface between cognition and sensory functioning.

Sensory Functioning and Cognitive Ability: Prior Studies

The following overview is restricted to the relationship of visual and auditory acuity measures to intellectual functioning in middle and later adulthood. (For consistency, auditory threshold scores were inverted so that higher scores imply better sensory functioning.) There are not many studies on this issue. In part, this may reflect the relatively weak connection between intellectual and sensory functioning that exists during this part of life. With respect to hearing, findings have been quite inconsistent across studies, ranging from moderate correlations (Birren, Botwinick, Weiss, & Morrison, 1963; Granick, Kleban, & Weiss, 1976; O'Neil & Calhoun, 1975; Schaie et al., 1964, Sample 1) to smaller and sometimes insignificant effects (Colsher & Wallace, 1990; Era, Jokela, Qvarnberg, & Heikkinen, 1986; Gilhome Herbst & Humphrey, 1980; Jones, Victor, & Vetter, 1984; Ohta, Carlin, & Harmon, 1981; Schaie et al., 1964, Sample 2; Thomas et al., 1983).

Granick et al. (1976) reported high correlations between auditory thresholds at various frequencies and measures of cognitive functioning in two samples with a mean age above 70 years. The average correlation with the Wechsler Adult Intelligence Score (WAIS; Wechsler, 1955) Vocabulary score was above .44, and the average correlation with the WAIS Digit Symbol score was above .36. Similarly, Schaie et al. (1964) reported moderately high correlations between auditory thresholds and a composite of Thurstone's primary marker abilities (PMA; Thurstone & Thurstone, 1949) in a small select sample of older men (Kendall's $\tau = .41$). In a sample of older women, the same authors found a significantly lower correlation with the PMA composite (Kendall's $\tau = .18$) coupled with better auditory acuity.

In a large, population-based Finnish study on men of different ages (31–35, 51–55, and 71–75 years), Era et al. (1986) obtained an average correlation of .13 between auditory thresholds and three subtests of the WAIS. There was no clear evidence of an increase in correlations across the three age groups in their data. In another large-scale study, Thomas et al. (1983) reported a small but significant correlation ($r = .19$) between auditory thresholds (i.e., the mean of pure-tone thresholds at 0.50, 1.00, and 2.00 kHz) and cognitive functioning as measured with a cognitive screening instrument in a select sample of 259 individuals between the ages of 60 and 89 years.

Only few studies have reported correlations between cognitive functioning and visual acuity among adults without serious visual impairments. In a sample of 53 older drivers with a mean age of 70 years, Owsley, Ball, Sloane, Roenker, and Bruni (1991) found a close-to-zero correlation between visual acuity and a cognitive screening measure. At present, we do not know whether higher correlations between visual acuity and cognitive functioning would emerge in an age-heterogeneous sample of over 70-year-old adults (cf. O'Neil & Calhoun, 1975). However, there is some evidence that Alzheimer's disease is associated with a degeneration of the optic nerve (Hinton, Sadun, Blanks, & Miller, 1986) and low visual acuity (Cogan, 1985; Sadun, Borchert, DeVita, Hinton, & Bassi, 1987).

This Study

Because of the lack of relevant precursor research, this study is largely exploratory. For a heterogeneous sample of 70 to 103-year-old adults, we examined the magnitude of the correlational relationships between cognitive performance and measures of sensory visual and auditory acuity, and we tested a structural model in which age differences in intelligence are fully mediated by individual differences in visual and auditory acuity. Then, we determined the extent to which the variance in intellectual functioning predicted by auditory and visual acuity was correlated with balance–gait, general somatic health, and years of education. If large portions of the predictive variance in visual and auditory acuity were orthogonal to life-history variables such as education but shared with balance–gait, this would strengthen the conclusion that concurrent sensory status emerges as a powerful predictor of individual differences in intellectual functioning in advanced old age.

Method

Sample

The data were drawn from the BASE, an ongoing multidisciplinary project on old age and aging (P. B. Baltes et al., 1993). The BASE sample is designed (a) to be representative of the western part of the city of Berlin and (b) to oversample the very old and the male population. Specifically, it is a stratified probability sample of community-dwelling and institutionalized individuals aged 70–103 years. Stratification variables were age (i.e., 70–74, 75–79, 80–84, 85–89, 90–94, and 95+ years) and gender. The sample was randomly drawn from the city registration office (in Germany, every citizen is registered). The data reported here belong to the intensive data collection protocol of BASE, which comprises a total of 14 sessions covering four different disciplines (i.e., internal medicine, psychiatry, psychology, and sociology).

The present sample is from the first wave of the BASE, comprising subjects contacted before August 24, 1991, and is identical with the sample reported in Lindenberger et al. (1993). Of the subjects completing the intensive data collection protocol (N = 276), 13 individuals were selected at random for each of the 12 cells of the intended design, that is, Gender (2) × Age Group (6). In Table 1, we summarize the characteristics of the resulting sample (N = 156) separately for old (70–84 years) and very old (85–103) individuals. In comparison to convenience samples typically used in cognitive aging research, the present sample was older, more heterogeneous, and less educated (P. B. Baltes et al., 1993).

Because only 28% of the parent sample completed the entire 14-session protocol, drop-out effects were investigated for more than 20 different variables such as age, gender, marital status, subjective health, and mortality risk (P. B. Baltes et al., 1993; Lindenberger, Gilberg, Little, & Baltes, 1994). In general, drop-out effects were small. The major exception was 12-month mortality following the contact to participate in the BASE. Individuals completing the intensive data collection protocol, which extended on average over 4 months, were less likely to die within 1 year after first contact than individuals who did not complete the protocol (16.8% vs. 4.7%). We interpret the outcome of these analyses as suggesting that the BASE sample maintains much of its intended heterogeneity. There is evidence that the sample is more educated and healthier than the parent population. For the present study, this sample bias in education and health is likely to produce a conservative test of the hypothesized relationships.

Visual Acuity

Visual acuity was measured in Snellen decimal units at two different distances using two different standard reading tables (Geigy, 1977). Distance visual acuity was assessed binocularly during the multidisciplinary first-contact session using a reading table presented at a minimum distance of 2.5 m to the subject (Borchelt & Steinhagen-Thiessen, 1992). Close visual acuity was assessed during one of the three internal medicine sessions of the BASE intensive protocol and was measured separately for the left and the right eye using a reading table presented at reading distance. All three measurements were taken with and without the best optical correction available to the subject. Ninety-two percent of the subjects had at least one pair of glasses.

The analyses reported in this article are based on the better values, which in most cases referred to corrected vision. The decision to use corrected rather than uncorrected vision is in agreement with both the sensory deprivation and the common cause hypotheses. According to the sensory deprivation hypothesis, the actual amount of sensory input is the critical variable; therefore, corrected vision is more appropriate than uncorrected vision (assuming that subjects actually wear their glasses in their daily living). The common cause hypothesis refers to aging-induced sensory impairments that are neuronal in origin and not easily remediable at the level of the end organ. Corrective devices allow for a more direct assessment of this portion of sensory loss.

Auditory Acuity

Measures related to auditory acuity were assessed with a Bosch ST-20-1 pure-tone audiometer using headphones during one of the internal medicine sessions of the BASE protocol at the subject's residence or in the clinic of a university medical school. Thresholds were measured

Table 1
Sample Characteristics

	Age group					
	70–84 (N = 78)		85–103 (N = 78)		Total (N = 156)	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	77.3	4.6	92.6	4.7	84.9	9.0
Digit Symbol Substitution	29.8	9.6	19.3	11.4	24.6	11.8
Education (years)	11.6	3.1	10.4	2.6	11.0	3.0
Subjective physical health[a]	2.9	1.1	3.0	1.1	2.9	1.1
Objective physical health[b]	8.1	3.3	9.1	2.9	8.6	3.1
Visual acuity[c]	.42	.16	.25	.16	.33	.19
Auditory acuity[d]	41.2	15.2	51.4	13.6	46.3	15.3

[a] On a Likert scale ranging from 1 (*excellent*) to 5 (*very poor*). [b] Number of medical diagnoses according to the International Classification of Diseases (ICD 9, 1988). [c] Based on the average of close and distance visual acuity with the best available correction and scored in Snellen decimal units. [d] Pure-tone auditory thresholds (dB) based on the average threshold at 0.5, 1.0, and 2.0 kHz for the better ear.

separately for the right and left ears at eight different frequencies. The portion of the sample with hearing aids was 16.7%. For technical reasons, thresholds were assessed without hearing aids only. Testing started with the better ear; for subjects who did not know which ear was the better one, it started with the right ear. Within ears, frequencies were tested in the following order: 1.00, 2.00, 3.00, 4.00, 6.00, 8.00, 0.50, and 0.25 kHz.

Cognitive Tests

A total of 14 tests were administered, measuring five different intellectual abilities: speed (Digit Letter Test, Digit Symbol Substitution, and Identical Pictures), reasoning (Figural Analogies, Letter Series, and Practical Problems), knowledge (Practical Knowledge, Spot-a-Word, and Vocabulary), memory (Activity Recall, Memory for Text, and Paired Associates), and fluency (Animals and Letter *S*). Stimulus presentation and data collection was supported by a Macintosh SE30 personal computer equipped with a MicroTouch Systems touch-sensitive screen.

A detailed description of the tests as well as of their psychometric and structural properties is given in Lindenberger et al. (1993). The 14 measures were found to have satisfactory internal consistencies, high interrater reliabilities, and substantial loadings on their respective latent factors (i.e., ability constructs; see Figure 1). The intercorrelation matrix of the 14 tests formed a highly positive manifold. Nevertheless, structural differentiation into the five latent ability factors could be demonstrated.

Results

Overview of Results

In the following, we first provide separate information on vision, hearing, and cognitive ability and their relationship to age and gender. Then, we present a structural model that relates age differences in sensory functioning to age differences in cognitive performance and determine the extent to which age-related variance in intellectual functioning is related to individual differences in sensory functioning. These analyses are extended to include balance–gait, general somatic health, and years of education as additional predictors of intellectual functioning. Next, we examine whether results vary as a function of age group (i.e., 70–84 vs. 85–103 years), gender, dementia diagnosis, or severity of sensory impairment and compare our results to an earlier analysis regarding the relationship between speed and intelligence (Lindenberger et al., 1993). Finally, we investigate in more detail to what extent sensory performance factors operating in association with the administration of the cognitive tests might have contributed to the relationship between sensory functioning and cognitive performance.

Structural modeling analyses were based on the Persons × Variables matrix using Bentler's Structural Equations Program (EQS; Bentler, 1989). Throughout this article, we report the Comparative Fit Index (CFI) and the Non-Normed Fit Index (NNFI) as indexes of incremental fit (Bentler, 1989; Marsh, Balla, & McDonald, 1988). As a rule of thumb, values larger than .90 on these indexes are desirable (Bentler, 1989). In addition, we report chi-square values, degrees of freedom, and corresponding p values for all models that we examined.

Visual Acuity

Figure 2 displays means and standard deviations for the three measures of visual acuity as a function of age group and gender in Snellen decimal units. An Age Group (2) × Gender (2) × Type of Measure (3) repeated measures analysis of variance (ANOVA) with Type of Measure as a within-subjects factor revealed a significant effect of Age Group, $F(1, 152) = 41.32$, $MS_e = 0.09$, $p < .001$, and a nonsignificant effect of Gender, $F(1, 152) = 0.78$, $MS_e = 0.09$, $p > .10$. The Age × Gender interaction was also not significant, $F(1, 152) = 0.76$, $MS_e = 0.09$, $p > .10$. Moreover, no mean differences among the three measures were observed, $F(2, 304) = 1.22$, $MS_e = 0.03$, $p > .10$, and the three measures did not interact with age or gender (all $ps > .10$). For structural modeling analyses, the three visual acuity variables were rescaled to a mean of 5 and a standard deviation of 2.

Auditory Acuity

Figure 3 displays auditory thresholds for the better ear as a function of age group, gender, and frequency. An Age Group (2) × Gender (2) × Frequency (8) repeated measures ANOVA with Frequency as a within-subjects factor revealed a significant main effect of Age Group, $F(1, 152) = 29.72$, $MS_e = 1{,}418.34$, $p < .001$, and Gender, $F(1, 152) = 3.90$, $MS_e = 1{,}418.34$, $p = .050$. The Age × Gender interaction did not reach significance, $F(1, 152) = 2.60$, $MS_e = 1{,}418.34$, $p > .10$. Hearing thresholds increased as a function of frequency: linear trend, $F(1, 152) = 741.74$, $MS_e = 287.52$, $p < .001$; quadratic trend, $F(1, 152) = 64.43$, $MS_e = 101.83$, $p < .001$. Moreover, the linear, quadratic, and cubic trends of frequency interacted with Gender: linear trend, $F(1, 152) = 28.12$, $MS_e = 287.52$, $p < .001$; quadratic trend, $F(1, 152) = 7.30$, $MS_e = 101.83$, $p < .01$; cubic trend, $F(1, 152) = 24.22$, $MS_e = 84.54$, $p < .001$. None of the three-way interactions reached significance (all $ps > .08$). Post hoc comparisons showed that gender differences were significant at 3.00 kHz, $F(1, 154) = 8.59$, $MS_e = 295.33$, $p < .01$; 4.00 kHz, $F(1, 154) = 16.43$, $MS_e = 301.18$, $p < .001$; and 6.00 kHz, $F(1, 154) = 18.27$, $MS_e = 365.40$, $p < .001$, but not at 0.25, 0.5, 1.00, 2.00, and 8.00 kHz (all $ps > .05$). Thus, hearing thresholds increased substantially with age, women were somewhat less hard of hearing than men, and the average shape of the frequency threshold curve varied as a function of gender.

Table 2 displays the correlations among thresholds separately for the two ears. Correlations across ears for equal frequencies are reported in the main diagonal. Within ears, the data clearly followed a simplex pattern (cf. Schaie et al., 1964). To obtain a stable, single-factor construct for auditory acuity, we decided to remove the simplex structures by aggregating across frequencies and ears, thereby avoiding the factor indeterminacy problem associated with simplex structures. Specifically, three indicator variables of hearing were constructed. The first two variables were unit-weighted composites of the six lower frequencies within ears (i.e., one variable for the right ear and another variable for the left ear). The third indicator variable was computed across ears and was based on hearing threshold scores obtained for 6.00 and 8.00 kHz. In contrast to the other two variables, the high-frequency variable was computed as a unit-weighted composite of the log-transformed raw scores to reduce skewness and kurtosis. Finally, the three resulting variables of auditory acuity were inverted so that higher values imply better hearing and were rescaled to a mean of 5 and a standard deviation of 2.[1]

[1] The aggregation of auditory threshold scores into three indicator variables was guided by the goal to obtain a stable factor of auditory

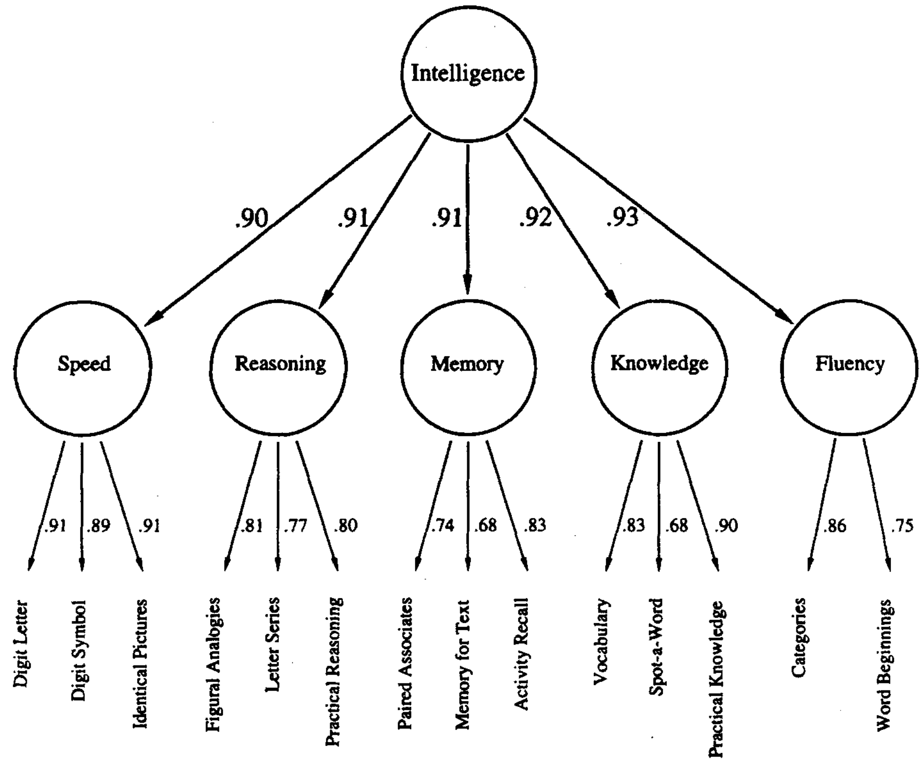

Figure 1. The hierarchical structure of the cognitive test battery.

Intellectual Functioning

The 14 cognitive tests were assumed to measure five different cognitive abilities, three from the fluid domain (Reasoning, Memory, and Speed) and two from the crystallized domain (Knowledge and Fluency). To examine the factor structure of the battery, a hierarchical model of intelligence with five first-order factors and one second-order general ability factor was specified using a confirmatory factor (Bentler, 1989). This model reproduced the data quite well, $\chi^2(69, N = 156) = 118.27, p < .01$, CFI = 0.970, NNFI = 0.961 (see Figure 1). Thus, in contrast to the analyses reported in Lindenberger et al. (1993), Speed was subsumed under the second-order factor of general intellectual ability. A comparison to the analyses reported by Lindenberger et al. is provided later in this article.

Alternative models were computed by (a) collapsing the two crystallized factors into a single factor, (b) collapsing the three fluid factors into a single factor, and (c) collapsing all five factors into a single factor (i.e., a one-factor model). Direct comparisons with the five-factor model displayed in Figure 1 were possible because these three alternative models were nested within the five-factor model. All three alternative models were associated with a significant loss in fit.[2] Thus, although the factors of the five-factor solution were highly intercorrelated, each of them contained a significant amount of reliable, ability-specific variance.

acuity. Analyses reported below did not lead to different results when two (i.e., one for each ear) rather than three indicator variables were used to define auditory acuity.

In the analyses that follow, the five different cognitive abilities were represented as unit-weighted composites of their indicators. The main reason for doing this was to reduce the number of variables used in structural modeling to achieve a more defendable ratio of persons over variables. The five composites were rescaled to a mean of 5 and a standard deviation of 2. Table 3 displays the correlations among the unit-weighted ability composites and age. As reported elsewhere (Lindenberger et al., 1993), substantial negative age correlations were observed for all five abilities. Mean ability levels and correlations among abilities did not vary significantly as a function of gender.

Measurement Model

The Person × Variables input data matrix was inspected for the contribution of individual variables and subjects to devia-

[2] The following differences in fit between the model with five first-order factors and the three alternative models were found: For the model that collapses Fluency and Knowledge into a single factor, $\Delta\chi^2(1, N = 156) = 15.18, p < .01$; for the model that collapses Speed, Reasoning, and Memory into a single factor, $\Delta\chi^2(2, N = 156) = 56.07, p < .01$; for the model that collapses all five first-order factors into one factor, $\Delta\chi^2(4, N = 156) = 83.30, p < .01$. One of the reviewers advocated a more differentiated factor solution with three interrelated factors at the second-order level: Reasoning–Memory, Knowledge–Fluency, and Speed (the latter being identical to the corresponding first-order factor). The general factor model nested within this model was not associated with a significant decrement in fit, $\Delta\chi^2(2, N = 156) = 0.01, p > .10$. These comparisons suggest the hierarchical model depicted in Figure 1 was an appropriate representation of the ability factor space of this data set.

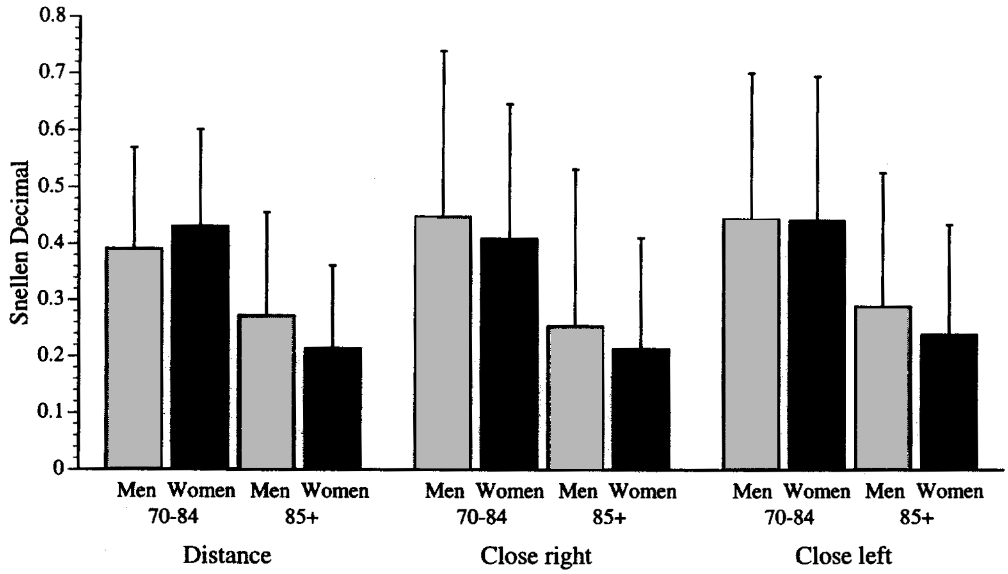

Figure 2. Visual acuity as a function of age group and gender. Error bars refer to standard deviations.

tions from normality following Bentler's (1989) recommendations. Except for the high-frequency hearing variable with a skewness estimate of 1.09, univariate kurtosis and skewness estimates did not exceed | 1 | for any of the variables. Two subjects with very high contributions to multivariate kurtosis were excluded from further analysis. An inspection of the data revealed that 1 of these 2 subjects was nearly blind in one eye but had above average vision in the other eye and that the other subject was nearly deaf in one ear but had normal hearing in the other ear. Results were practically identical when the 2 subjects were not removed from the sample.

The measurement model specified four latent factors: Intelligence, Vision, Hearing, and Close Vision. Furthermore, both linear and quadratic trends of age were included as independent, error-free variables. Quadratic trends were computed outside of EQS by regressing age squared on age and saving the residuals (i.e., the quadratic component that is orthogonal to the linear component of age). Intelligence (i.e., general cognitive ability) was represented by reasoning, speed, memory, knowledge, and fluency. Hearing was represented by the three hearing variables. Vision was represented by distance visual acuity and by a Close Vision subfactor defined by right-eye close visual acuity and left-eye close visual acuity. Age, Vision, Hearing, and Intelligence were allowed to freely covary.

This model (measurement model 1 [MM1] in Table 4) reproduced the variances and covariances of the data very well, $\chi^2(57, N = 154) = 71.31, p = .10$, CFI = 0.987, NNFI = 0.983. Quadratic age trends for Vision, Hearing, and Intelligence did not differ from zero and could be set to zero without a significant decrement in fit, $\Delta\chi^2(3, N = 154) = 2.17, p > .10$ (see MM2 in Table 4). Therefore, quadratic age trends were removed from the model. This resulted in MM3 of Table 4, $\chi^2(48, N = 154) = 62.42, p = .08$, CFI = 0.987, NNFI = 0.982.

Despite the nonsignificant p value and the magnitude of the fit indexes, we examined whether allowing for a direct path from one of the three sensory factors—Vision, Hearing, and Close Vision—to any of the five indicator variables of Intelligence—speed, reasoning, memory, knowledge, and fluency—would result in a significant increment in fit. We found a significant effect of Close Visual Acuity on speed ($\beta = .20, z = 3.48, p < .01$). Thus, Close Visual Acuity and speed shared a significant amount of variance that was not explained by the correlation between Vision and Intelligence.

Given that the three speed tests all required the fast identification of visual material, the residual effect of Close Visual Acuity on speed possibly reflected a visual performance factor on the side of the speed tests. Not controlling for this effect may artificially increase the effect of Vision on Intelligence. For this reason, we decided to include the path from Close Visual Acuity to speed in the final measurement model (i.e., MM4 in Table 4), $\chi^2(47, N = 154) = 50.82, p = .33$, CFI = 0.997, NNFI = 0.995. Correspondingly, a nested comparison with MM3 indicated that the addition of the path was associated with a sig-

Table 2
Correlations Among Pure-Tone Thresholds at Different Frequencies

Frequencies (kHz)	1	2	3	4	5	6	7	8
1. 0.25	**.63**	.90	.81	.68	.57	.48	.43	.74
2. 0.50	.89	**.72**	.90	.74	.61	.53	.48	.50
3. 1.00	.80	.88	**.72**	.84	.71	.63	.60	.57
4. 2.00	.68	.72	.82	**.68**	.89	.79	.73	.66
5. 3.00	.58	.61	.71	.88	**.71**	.90	.84	.71
6. 4.00	.51	.51	.60	.77	.91	**.73**	.90	.77
7. 6.00	.42	.44	.55	.71	.84	.89	**.74**	.82
8. 8.00	.39	.41	.51	.64	.72	.74	.80	**.77**

Note. $N = 156$. Values above the main diagonal refer to the right ear, and values below the main diagonal refer to the left ear. Values in boldface on the main diagonal refer to correlations between the left and right ear for the same frequency.

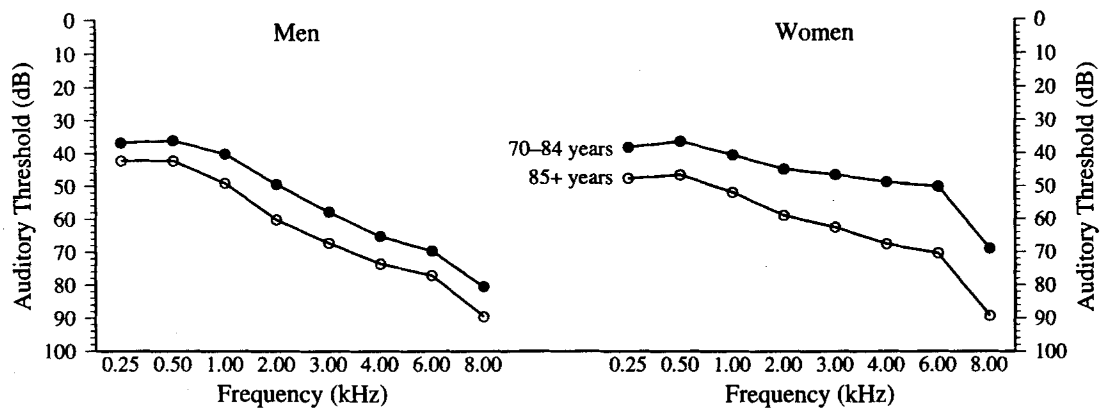

Figure 3. Auditory acuity for the better ear as a function of age group, gender, and frequency.

nificant increment in the overall fit of the model, $\Delta\chi^2(1, N = 154) = 11.60, p < .01$. Table 5 displays the correlations among the latent constructs of the final measurement model.

The Structural Model: Sensory Functioning Mediates the Effect of Age on Intelligence

Figure 4 shows the hypothesized structural model: Age affects Vision and Hearing, which in turn together affect Intelligence. This model (structural model 1 [SENS1] in Table 4) reproduced the variances and covariances very well, $\chi^2(48, N = 154) = 52.81, p = .29$, CFI = 0.996, NNFI = 0.994. A nested comparison with the final measurement model (i.e., MM4 in Table 4) revealed that the constraint inherent in the structural model did not lead to a significant decrement in fit, $\Delta\chi^2(1, N = 154) = 1.99, p > .10$. Accordingly, allowing for a direct effect of age on Intelligence did not result in a significant increment in the fit of the model, $\Delta\chi^2(1, N = 154) = 2.03, p > .10$.

Next, we imposed constraints on the parameters of the structural model to further explore the relations among latent factors. First, we were interested to know whether the age effect on Vision and the age effect on Hearing could be constrained to be equal without a significant loss in fit. This was not the case, $\Delta\chi^2(1, N = 154) = 25.97, p < .001$ (see SENS2 in Table 4), which means that age had a greater effect on Vision than it had on Hearing. Second, an inspection of the path coefficients of SENS1 revealed that the covariance between Vision and Hearing did not differ significantly from zero ($z = 1.61, p > .05$). The corresponding residual covariance estimate could be set to zero without a significant decrement in the overall fit of the model, $\Delta\chi^2(1, N = 154) = 2.62, p > .10$ (see SENS3 in Table 4). In contrast, in the final measurement model (i.e., MM4 of Table 4), we had observed a correlation of .53 between Vision and Hearing. This drop in the magnitude of the standardized parameter estimate reflects the fact that the bidirectional paths from age to Vision and Hearing in the measurement model were converted into unidirectional paths in the structural model and implies that practically all of the variance shared between Vision and Hearing was also related to age. Finally, the path from Vision to Intelligence and the path from Hearing to Intelligence could be constrained to be equal without a significant loss in fit, $\Delta\chi^2(1, N = 154) = 2.76, p > .10$ (see SENS4 in Table 4).[3]

In summary, the results of these analyses are extremely clear-cut with two noteworthy findings. First, a structural model that represents age differences in intellectual functioning as an indirect (mediated) consequence of age differences in sensory functioning was completely consistent with the data. Second, the interrelation between factors of visual and auditory acuity could be fully explained by the fact that the two constructs share a sizable portion of their variance with age. Moreover, age had a greater effect on visual than on auditory acuity; in contrast, the difference between the effect of visual acuity on intellectual functioning and of auditory acuity on intellectual functioning was not significant.

Commonality Analysis in Latent Space

To determine the shared and unique variance components of the main effects of age, Vision, and Hearing as predictors of intellectual functioning in a more comprehensive manner, we regressed Intelligence on all seven possible predictor combinations in the latent space (i.e., age alone, Vision alone, Hearing alone; age and Vision, age and Hearing, Vision and Hearing; and age, Vision, and Hearing). Following procedures described

Table 3
Intercorrelations Among Cognitive Abilities and Age

Cognitive ability	Reasoning	Memory	Knowledge	Fluency	Age
Speed	.72	.70	.74	.72	−.61
Reasoning	—	.66	.72	.65	−.54
Memory		—	.64	.70	−.53
Knowledge			—	.70	−.51
Fluency				—	−.48

Note. $N = 156$. Correlations are based on unit-weighted composites of z-transformed test scores. All values were significant at the .01 level.

[3] Note that equality constraints were imposed on standardized parameter estimates. Results did not differ significantly when constraints were imposed on the unstandardized solution, which is not surprising because the vision and hearing indicators had been scaled to the same metric (i.e., $M = 5, SD = 2$).

Table 4
Summary of Model-Fitting Procedure

Model	Commentary	χ^2	*df*	*p*	CFI[a]	NNFI[b]
Measurement models (MM)						
MM1	Free covariation among linear age, quadratic age, vision, hearing, and intelligence	71.31	57	.10	0.987	0.983
MM2	Same as MM1, but with quadratic age trends set to zero	73.48	60	.11	0.988	0.984
	Comparison between MM2 and MM1	2.17	3	>.10		
MM3	Same as MM2 but with quadratic age trends removed from the model	62.42	48	.08	0.987	0.982
MM4	Same as MM3 but adding a path from close visual acuity to speed; final measurement model	50.82	47	.33	0.997	0.995
	Comparison between MM4 and MM3	11.60	1	<.01		
Structural models (SENS)						
SENS1	The basic sensory model: Age affects vision and hearing, which affect intelligence (see Figure 4)	52.81	48	.29	0.996	0.994
SENS2	Same as SENS1 but with correlation between vision and hearing set to zero	55.43	49	.25	0.994	0.992
	Comparison between SENS2 and SENS1	2.62	1	>.10		
SENS3	Same as SENS1 but with paths from age to vision and from age to hearing constrained to be equal	78.78	49	<.01	0.974	0.964
	Comparison between SENS3 and SENS1	25.97	1	<.01		
SENS4	Same as SENS1 but with paths from vision and hearing to intelligence constrained to be equal	55.57	49	.24	0.994	0.992
	Comparison between SENS4 and SENS1	2.76	1	>.10		

Note. $N = 154$.
[a] Comparative Fit Index (cf. Bentler, 1989). [b] Non-Normed Fit Index or Tucker Lewis Index (cf. Bentler, 1989; Marsh et al., 1988).

by Hertzog (1989), we then used the amount of variance explained by each of the seven different regression equations in conjunction to determine unique and shared variance components in the prediction of interindividual differences in Intelligence. Note that the estimates of shared and unique variance portions reported here are not biased by differences in reliabilities between the constructs because the analyses were done in latent space.

Table 6 displays the results of these analyses. They reiterate the message of the structural model. Age accounted for 40.8% of the variance in Intelligence, Vision for 41.3%, and Hearing for 34.5%. Taken together, age, Vision, and Hearing accounted for 52.0% of the variance in Intelligence. About 24% of the total variance in Intelligence (i.e., 45.8% of the explained variance) was shared by all three predictors. Only 2.8% of the total variance in Intelligence (i.e., 5.4% of the explained variance and 6.9% of the age-related variance) was uniquely related to age. This amount did not differ significantly from zero, $\Delta\chi^2(1, N = 154) = 2.03, p > .10$. The same amount of total variance (i.e., 2.8%) was uniquely related to Vision; because of a smaller confidence interval for the maximum likelihood estimate, however, this value was significant at the .05 level, $\Delta\chi^2(1, N = 154) = 5.17, p < .05$. Finally, Hearing also had a significant unique effect (5.4% of the total or 10.4% of the explained variance), $\Delta\chi^2(1, N = 154) = 8.33, p < .01$.[4]

[4] The significance of unique effects was tested using the full model (i.e., the model with all three predictors). In three separate analyses, one of the three paths (i.e., age → Intelligence, age → Vision, age → Hearing) was set to zero, and the Lagrange Multiplier test provided in EQS (Bentler, 1989) was used to examine whether freeing up this constraint was associated with a significant increment in fit.

Table 5
Correlations Among Age, Vision, Hearing, and Intelligence

Variable	1	2	3	4
1. Age	—	−.75	−.54	−.62
2. Vision	−.61	—	.53	.65
3. Hearing	−.50	.40	—	.58
4. Intelligence	−.61	.53	.53	—

Note. $N = 154$. Standardized covariance estimates (i.e., latent correlations) of measurement model 4 (MM4) in Table 4 are shown above the main diagonal. Pearson correlations are shown below the main diagonal. All values were significant at the .01 level. Pearson correlations for vision and hearing were based on the unit-weighted composites of the indicators (i.e., vision: distance visual acuity, close visual acuity; hearing: left ear [0.25–4 kHz], right ear [0.25–4 kHz], both ears [6 kHz and 8 kHz]).

Adding Balance–Gait, General Somatic Health, and Education as Predictors of Intellectual Functioning

In this section, we consider the predictive power of three additional constructs: balance–gait, general somatic health, and education. It was assumed that the three constructs differ in the degree to which they predict intellectual functioning and in the degree to which their predictive variance is shared with visual and auditory acuity. As a measure of sensorimotor functioning, balance–gait was expected to be the most powerful of the three predictors, and most closely related to visual and auditory acuity. In contrast, general health, an unspecific indicator of somatic morbidity, was expected to be less closely related to intelligence than visual acuity, auditory acuity, and balance–gait. Finally, the prediction regarding education was ambiguous. On the one hand, based on a life-span continuity perspective, educational level (especially in this heterogeneous sample) should continue to display a fair degree of predictive power. On the other hand, the life-span discontinuity view would suggest that the effect of education may be on the wane in very old age.

Balance–gait. Balance–gait was defined as a latent construct and was assessed by three measures of balance and gait (cf. Tinetti, 1986): (a) the "Romberg," (b) the 360-degree turn task, and (c) the "Unterberger." A detailed description of these tasks is provided elsewhere (M. M. Baltes, Mayr, Borchelt, Maas, & Wilms, 1993). In the Romberg task, subjects stood upright for about 1 min, with legs as close together as possible, arms extended in front of the body, palms turned up, and eyes closed. Performance was scored by a physician on a 6-point scale ranging from *no swaying* to *not able to stand upright at all.* In the 360-degree turn task, subjects were asked to perform a full turn around their body axis as fast as they could without risking a fall. The score corresponded to the number of steps needed to finish the circle. In the Unterberger task, subjects were asked to lift their feet alternately without changing their position and orientation. The score on this task corresponded to the angle that subjects deviated from their original orientation. Raw correlations among the three scores ranged from $r = .67$ to $r = .71$, and confirmatory factor loadings on the Balance–Gait factor were high and significant (Romberg, $\beta = .84$; 360-degree turn, $\beta = .86$; Unterberger, $\beta = .78$).

When Balance–Gait was the only predictor, it accounted for 41.2% of the variance in Intelligence ($\beta = .64$, $z = 7.53$, $p < .001$). When Balance–Gait was added as a predictor of Intelligence after Vision, Hearing, and age, the proportion of total variance explained increased by 3.6% from 52.0% to 55.6%, $\Delta\chi^2(1, N = 154) = 4.73, p < .05$. When Balance–Gait was added as a predictor after Vision and Hearing (i.e., leaving out age), the proportion of total variance explained increased by 4.7% from 49.2% to 53.9%, $\Delta\chi^2(1, N = 154) = 5.33, p < .05$. Thus, as a predictor of Intelligence, Balance–Gait was in the same order of magnitude as Vision or Hearing and shared 88.6% of its predictive variance with these two constructs, that is, $(1 - [53.9 - 49.2]/41.2) \times 100$.

General somatic health. The internal medicine research unit of the BASE (Steinhagen-Thiessen & Borchelt, 1993) collected detailed clinical information using standardized instruments and diagnostic tests to assess subjects' physical health status. Diagnoses were based on the International Classification of Diseases (ICD 9, 1988). An overall index of somatic health was computed by summing all diagnoses across all organ systems excluding questionable and uncertain codings (for a more detailed description of the procedure, cf. Steinhagen-Thiessen & Borchelt, 1993).

When this index of somatic health was the only predictor, it explained 6.1% of the variance in Intelligence ($\beta = .25$, $z = 3.00, p < .01$). When somatic health was added as a predictor of Intelligence in a model with Vision, Hearing, and age as intercorrelated predictors, the amount of variance explained did not increase at all, $\Delta\chi^2(1, N = 154) = 0.05, p > .10$. The same result was obtained when only Vision and Hearing but not age were considered as predictors before entering the somatic health variable into the equation. Thus, general somatic health was a significant predictor of intellectual functioning. However, it had much less predictive power than age, Vision, and Hearing and shared all of its predictive variance with these three constructs.

Education. With respect to education, the original variable (i.e., years of education) was log transformed because it showed high values for skewness (1.15) and kurtosis (2.23). After the log transformation, skewness was reduced to 0.34 and kurtosis to −0.24.

When education was the only predictor, it explained 12.4% of the variance in Intelligence ($\beta = .35$, $z = 4.33$, $p < .01$). When education was added as a predictor of Intelligence in a model having Vision, Hearing, and age as intercorrelated predictors, the amount of variance explained increased by 3.9% (i.e., from 52.0% to 55.9%), $\Delta\chi^2(1, N = 154) = 8.09, p < .01$. When only Vision and Hearing were considered as predictors, the amount of variance explained increased by 3.7% after adding education, $\Delta\chi^2(1, N = 154) = 6.76, p < .01$. Clearly, then, education was a less powerful predictor of intellectual functioning than either age (which, taken by itself, explained 40.9% of the variance in intellectual functioning), Vision (41.3%), or Hearing (34.6%). At the same time, however, about a third of the predictive variance of education (3.9%/12.4% × 100 = 31.5%) was orthogonal to the other three predictors. Similarly, 82.3% of the predictive variance of Vision and Hearing was unrelated to education, that is, $(1 - [12.4 - 3.7]/49.2) \times 100$.[5]

[5] Consistent with earlier findings (Lindenberger et al., 1993), there was a significant path from education to knowledge after controlling for the effect of education on Intelligence ($\beta = .18$, $z = 3.53$, $p < .01$). The results reported here are based on models that included a direct path from education to knowledge to account for this effect.

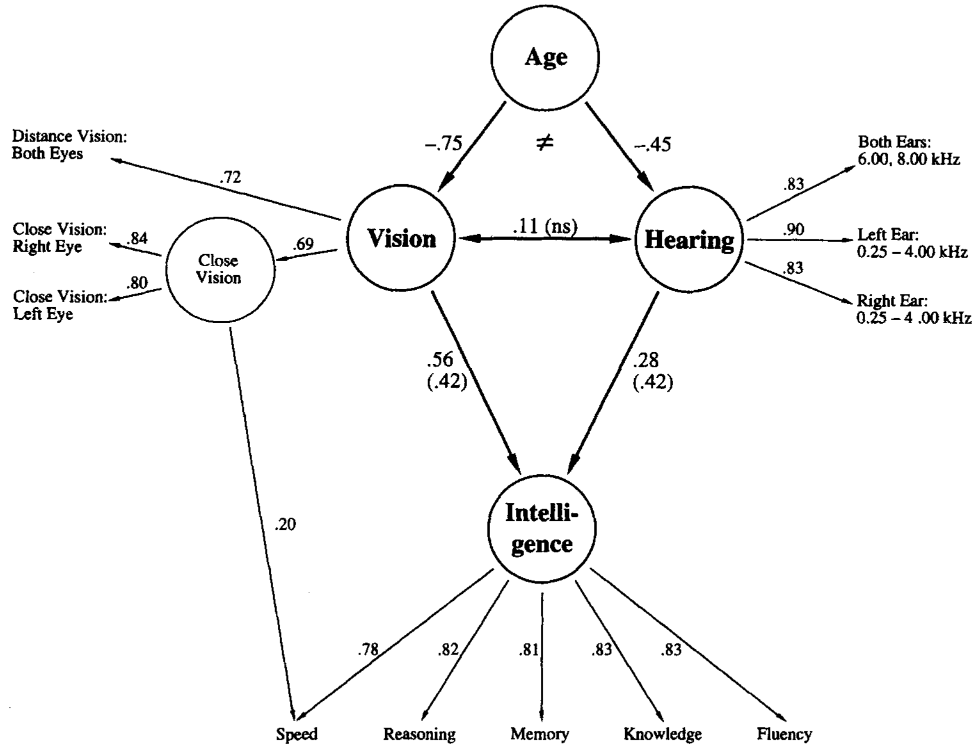

Figure 4. The structural model of the relationship between age, visual acuity, auditory acuity, and intellectual functioning; for fit statistics, see Table 4. The path coefficient from age to vision was significantly higher than the path coefficient from age to hearing (≠). The correlation between vision and hearing did not differ significantly from zero (*ns*). The path coefficients from vision to intelligence and from hearing to intelligence did not differ significantly from each other; the magnitude of the constrained estimate was β = .42.

Group Comparisons

Effects of age group. On the basis of the hypothesis that sensory functioning emerges as a predictor of intelligence late in life, we were interested to know whether the relationship between visual and auditory acuity, on the one hand, and intellectual functioning, on the other, was more pronounced in very old than in old subjects. To examine this issue, the total sample was divided into a younger (N = 76, age range = 70–84 years, M age = 77.3 years, SD = 4.7) and an older (N = 78, age range = 85–103 years, M age = 92.6 years, SD = 4.7) subsample, and the original structural model (i.e., SENS1 in Table 4) was respecified as a two-group model. Variables were standardized within age groups to a mean of 5 and a standard deviation of 2, and constraints were imposed on the estimates of the following parameters: (a) the paths from the factors to their indicators, (b) the paths from age to Vision and from age to Hearing, (c) the paths from Hearing and Vision to Intelligence, (d) the paths from Close Vision to Vision and from Close Vision to speed, and (e) the Hearing–Vision residual covariance estimate. For each equality constraint, it was inspected whether its release was associated with a significant increment in fit using the Lagrange Multiplier test in EQS (Bentler, 1989). With all equality constraints imposed, the model fit the data well, $\chi^2(111, N_1 = 76, N_2 = 78) = 132.42, p = .08$, CFI = 0.975, NNFI = 0.970, where N_1 is the sample size for the younger subsample and N_2 is the sample size for the older subsample. The release of any of the constraints was not associated with a significant increment in fit (all ps > .10). Moreover, in both age groups, allowing for a direct path from age to Intelligence was not associated with a significant increment in fit: younger group, $\Delta\chi^2(1, N = 76) = 0.15, p > .10$; older group, $\Delta\chi^2(1, N = 78) = 0.01, p > .10$. Thus,

Table 6
Predicting Intelligence: Unique and Shared Variance Components of Age, Vision, and Hearing

Component	Variance explained (%)
Unique age	2.8
Unique vision	2.8
Unique hearing	5.4
Shared age, vision	11.8
Shared age, hearing	2.4
Shared vision, hearing	2.9
Shared age, vision, hearing	23.8
Total variance explained	52.0

Note. N = 154. Variance components were computed by regressing Intelligence on all possible combinations of age, Vision, and Hearing in a latent structural model using Bentler's Structural Equations Program (EQS; Bentler, 1989).

contrary to our expectations, the correlational structure of the data as captured by the structural model did not vary significantly as a function of age group.

Effects of gender. Although we had no specific expectations in this regard, the equal number of men ($N = 77$) and women ($N = 77$) in our sample provided for a good opportunity to test whether parameters of the structural model varied in some important way as a function of gender. As in the previous analysis, the original structural model (i.e., SENS1 in Table 4) was respecified as a two-group model to examine this issue. With all equality constraints imposed, the model fit the data very well, $\chi^2(111, N_1 = 77, N_2 = 77) = 99.44, p = .78$, CFI = 1.000, NNFI = 1.012. The release of any of the constraints was not associated with a significant increment in fit (all $ps > .10$), and allowing for a direct path from age to Intelligence was not associated with a significant increment in fit: men, $\Delta\chi^2(1, N = 77) = 2.31, p > .10$; women, $\Delta\chi^2(1, N = 77) = 0.28, p > .10$.[6]

Exclusion of subjects with diagnosis of dementia. One of the anonymous reviewers raised the question of whether our findings are conditional on the presence of demented subjects in this sample. As reported elsewhere (Helmchen & Linden, 1993), 34 of the 154 subjects were diagnosed by an experienced psychiatrist to be at least mildly demented according to the *Diagnostic and Statistical Manual of Mental Disorders* (3rd edition, revised; *DSM-III-R*; American Psychiatric Association, 1987) criteria. Findings reported in this article did not change substantially when these subjects were not included in the analysis. For instance, the main structural model (i.e., SENS1 in Table 4) continued to fit the data very well, $\chi^2(48, N = 120) = 59.45, p = .12$, CFI = 0.984, NNFI = 0.979, and allowing for a direct path from age to Intelligence was not associated with a significant increment in fit, $\Delta\chi^2(1, N = 120) = 0.27, p > .10$. Thus, excluding subjects with a clinical diagnosis of dementia did not alter the gist of the findings.

Exclusion of subjects with severe sensory impairment. As an additional test of the generality of the effect of sensory functioning on intellectual functioning in the very old, we removed all subjects from the analysis who showed very low levels of functioning with respect to hearing or vision. Specifically, only subjects with a hearing threshold in the speech range below 70 dB (cf. Mhoon, 1990) and a Snellen decimal value above .28 (cf. Biglan, Van Hasselt, & Simon, 1988) were included in the analysis. Hearing thresholds in the speech range were defined as the average over 0.50, 1.00, and 2.00 kHz for the better ear. Visual acuity was based on close vision in the better eye.

This procedure resulted in a reduced sample of 100 individuals (M age = 82.6, $SD = 8.5$). Again, the structural model (i.e., SENS1 in Table 4) fit the data very well, $\chi^2(48, N = 100) = 54.44, p = .24$, CFI = 0.989, NNFI = 0.985, and the addition of a direct path from age to Intelligence did not lead to a significant increment in fit, $\Delta\chi^2(1, N = 100) = 1.87, p > .10$. Parameter estimates did not differ substantively from estimates found for the total sample. Clearly, this result is not consistent with the idea that the mediator role of sensory functioning was due to the presence of a rather large number of subjects with severe sensory impairments in the total sample. Instead, relations among age, vision, hearing, and intellectual functioning did not seem to vary considerably over the range of sensory functioning represented in this heterogeneous sample of very old persons because vision and hearing continued to explain all of the age-related variance in intellectual functioning when subjects with major sensory impairments were not included in the model.

Speed Versus Sensory Acuity as Predictors of Age Differences in Intellectual Functioning

In an earlier report based on the same sample, Lindenberger et al. (1993) examined the ability structure of the cognitive measures and the relationship of this within-intelligence structure to age. The role of age differences in sensory functioning (i.e., in measures of vision, hearing, and balance–gait) was not examined in this earlier article. As the main result, Lindenberger et al. (1993) found that a latent factor defined by psychometric measures of speed fully mediated the relationship between age and the four remaining intellectual abilities (i.e., the common and specific variances of reasoning, knowledge, fluency, and memory).

In the present article, the data space was expanded to include measures of sensory functioning. In the main analysis, measures of visual and auditory acuity served as mediators of age-related variance and fully predicted age differences in intelligence (see Figure 4). Compared with Lindenberger et al. (1993), speed was not used as a mediator of age differences but as one of five unit-weighted intellectual ability composites defining a latent factor of general intellectual ability (Intelligence).

The purpose of this section is to examine the relative power of sensory functioning and speed as predictors of age-related variance. To examine whether speed, in addition to mediating age differences in intelligence (i.e., the finding reported in Lindenberger et al., 1993), would also account for age-related differences in vision and hearing, we specified a model representing the assumption that speed mediates age differences in intellectual ability, vision, and hearing. In that model, age affects speed, which in turn affects intellectual ability, vision, and hearing. Vision and hearing were defined in the same way as in the other structural analyses of this article (see Figure 4). Speed was represented as a latent factor defined by the three tests of speed to give speed a fair chance to mediate more of the age-related variance in intelligence than hearing and vision. Finally, intellectual ability (i.e., Intelligence) was defined by the unit-weighted composites of the tests of reasoning, knowledge, fluency, and memory.

This model fit the data quite well but did not fully recover the observed variances and covariances, $\chi^2(72, N = 154) = 110.65, p < .01$, CFI = 0.975, NNFI = 0.968. Consistent with analyses reported in Lindenberger et al. (1993), allowing for a direct effect of age on Intelligence′ did not lead to significant increments in fit, $\Delta\chi^2(1, N = 154) = 0.02, p > .10$. However, the specification of direct paths from age to vision and from age to hearing led to significant increments in fit: vision, $\Delta\chi^2(1, N = 154) = 18.52, p < .01$; hearing, $\Delta\chi^2(1, N = 154) = 7.95, p < .01$, which means that speed did not account for all of the age-related variance in vision and hearing. When direct paths of age were added, the proportion of total variance explained in-

[6] Both with respect to age group and gender, analogous results were obtained when variables were standardized across, rather than within, groups.

creased from 59.3% to 67.4% for vision and from 34.7% to 37.3% for hearing. When age was the only predictor, it accounted for 55.5% of the variance in vision and for 28.8% of the variance in hearing. Thus, 14.6%, that is, 100 × (67.4 − 59.3)/55.5, of the age-related variance in vision and 9.0%, that is, 100 × (37.3 − 34.7)/28.8, of the age-related variance in hearing were not predicted by speed.

To examine whether vision and hearing would predict age differences in speed, we specified a model—very much like the main model shown in Figure 4—in which vision and hearing were used to predict age differences in speed, which in turn predicted age differences in Intelligence′. In this model, age affects vision and hearing, vision and hearing affect speed, and speed affects Intelligence′. This model allowed for an adequate reproduction of observed variances and covariances, $\chi^2(70, N = 154) = 82.88$, $p = .14$, CFI = 0.992, NNFI = 0.989, and did not demand, as was the case for the model with speed as the primary mediator of age differences, the addition of direct age paths. Specifically, allowing for direct effects of age on speed or of age on Intelligence′ did not lead to significant increments in fit: age on speed, $\Delta\chi^2(1, N = 154) = 0.55$, $p > .10$; age on Intelligence′, $\Delta\chi^2(1, N = 154) = 3.01$, $p > .05$. Thus, the data were consistent with a model in which vision and hearing mediated all of the age-related variance in both speed and the rest of intelligence. The only difference between this model and the main model of data analysis shown in Figure 4 is that speed was defined as a separate factor and was not subsumed under the general ability factor.

What is the significance of these added analyses focusing on speed as the primary mediator of age differences in intellectual functioning? As was already shown in Lindenberger et al. (1993), speed was a perfect predictor of negative age differences in the common variance of the remaining other four intellectual abilities. Thus, as a mediator of age differences in the remaining four intellectual abilities, the predictive power of speed was equivalent to that of sensory functioning. However, speed failed to explain all of the age-related variance in vision and hearing, whereas hearing and vision accounted for all of the age-related variance in intellectual functioning including speed. This is seen by contrasting the model with speed as the primary mediator of age differences both to the main model of this article shown in Figure 4 and to the variant of the main model reported in this section where speed is defined as a separate factor. Thus, when all variables are considered, vision and hearing were more powerful predictors of negative age differences in this data set than speed.

Influence of Performance Factors

As noted before, the close connection between sensory functioning and intellectual ability found is open to different interpretations. First, as captured by the sensory deprivation model, visual and auditory impairments may affect cognitive functioning over time because they reduce the opportunity for cognitively stimulating interactions with the environment. Second, as expressed in a form of the status-related common cause model, the close-to-perfect identity of the age-related variance in the two sensory domains may reflect the consequences of a generalized physiological deterioration of the aging brain.

A third, less far-reaching possibility concerns the existence of "ability-extraneous" sensory performance factors (Furry & Baltes, 1973), that is, factors related to the sheer administration of the cognitive measures. Although one of the guiding motives for constructing the cognitive test battery used in this study was to reduce the impact of such factors (Lindenberger et al., 1993), the possibility that sensory performance factors played a role in the administration of the battery needs to be examined.

The 14 measures of the battery can be classified according to the performance demands they impose on auditory as compared with visual acuity. Eight of the tasks (Digit Letter, Digit Symbol, Identical Pictures, Figural Analogies, Letter Series, Paired Associates, Practical Reasoning, and Spot-a-Word) require processing of visual stimulus materials to arrive at a correct conclusion. One of the memory tasks (Memory for Text) was primarily auditory in character because subjects listened to a short story and answered questions regarding its content. The 5 remaining tasks (Activity Recall, Categories, Letter *S*, Practical Knowledge, and Vocabulary) required only a minimal amount of sensory input.

As a first approach to the issue of ability-extraneous sensory performance factors, we examined whether tasks that require primarily visual input correlated more highly with vision than with hearing and vice versa. If performance factors played a major role, we would expect (a) that the eight tasks requiring visual input would be linked more closely to vision than to hearing, (b) that Memory for Text would be more closely related to hearing than to vision, and (c) that the five cognitive tasks with low sensory demands would show lower correlations to vision than the visual tasks and lower correlations to hearing than Memory for Text.

Table 7 displays the correlations of the 14 tests with vision, hearing, and age. Mean correlations were computed using Fisher's *r*-to-*Z* transformation. Differences in the magnitude of correlations were tested according to Equations 1 and 6 of Meng, Rosenthal, and Rubin (1992). The mean disattenuated correlation for the 8 tasks with visual stimulus materials was .45 for hearing and .51 for vision; the difference in correlation was not significant (i.e., $r = .45$ vs. $r = .51$; correlation between vision and hearing, $r = .41$; $N = 156$; $z = -.82$; $p > .10$). Memory for Text did not correlate significantly higher with hearing than with vision ($r = .48$ vs. $r = .36$; correlation between vision and hearing, $r = .41$; $N = 156$; $z = 1.54$; $p > .05$). Finally, the 5 tasks with low sensory demands had a mean disattenuated correlation of .42 with vision and of .47 with hearing. Compared with the 8 tests requiring visual input, the correlations of these 5 tests with vision were significantly lower ($r = .51$ vs. $r = .42$; median disattenuated correlation among the tests, $r = .70$; $N = 156$; $z = 4.03$; $p < .01$). An inspection of Table 7 suggests that this difference was mainly due to the speed tests. In fact, the difference in correlation for tests with low versus high visual demand was no longer significant when the speed tests were not included in the comparison ($r = .46$ vs. $r = .42$; median disattenuated correlation among the two sets of tests, $r = .69$; $N = 156$; $z = 1.64$; $p < .10$).

These analyses, which as a whole demonstrated a test-general rather than modality-specific pattern, do not support the assumption that the origin of the importance of sensory factors in intellectual functioning was located primarily in the ability-extraneous sensory conditions of test administration. This conclusion is supported by a consideration of individual test char-

Table 7
Correlations of Cognitive Tests With Visual and Auditory Acuity

Test	Vision		Hearing	
	dis. *r*	raw *r*	dis. *r*	raw *r*
Tests with visual stimulus items				
Digit Letter Test	.61	.59	.49	.47
Digit Symbol Substitution	.54	.51	.51	.48
Identical Pictures	.58	.56	.48	.46
Figural Analogies	.44	.39	.33	.30
Letter Series	.43	.37	.38	.33
Practical Reasoning	.52	.46	.49	.44
Paired Associates	.45	.39	.43	.51
Spot-a-Word	.47	.39	.39	.32
Tests with verbal stimulus materials				
Memory for Text	.36	.29	.48	.39
Tests with low sensory demands				
Fluency: Animals	.48	.44	.46	.43
Fluency: Letter *S*	.39	.34	.53	.46
Vocabulary	.41	.37	.46	.42
Practical Knowledge	.47	.44	.49	.47
Activity Recall	.34	.31	.42	.39

Note. $N = 154$. Vision and hearing scores were computed analogously to the structural model. Thus, the vision score was computed as the unit-weighted composite of close visual acuity averaged over both eyes and distance visual acuity. The hearing score was based on the unit-weighted composite of the three indicators (i.e., right ear, 0.25–4.00 kHz; left ear, 0.25–4.00 kHz; both ears, 6.00 kHz and 8.00 kHz). To facilitate comparisons across different cognitive tests, both disattenuated (dis.) and raw correlations are reported. Correlations were disattenuated using the beta coefficients (confirmatory factor loadings) of the cognitive tests on their factors (see Figure 1).

acteristics. For instance, the only requirement for performing the fluency tasks (Letter *S* and Animals) was that subjects understood that they had to come up with many words of a certain kind (e.g., words beginning with the letter *S* or animals) in a limited amount of time. This instruction was given to them both visually, using very large fonts (i.e., Times Roman Bold 48), and auditorily, and all subjects were able to understand the instruction. Nevertheless, the fluency tasks showed sizable correlations to both hearing and vision.

The three speed tests (Digit Letter Substitution, Digit Symbol Substitution, and Identical Pictures) constitute the only important exception in this regard. As reported in the sections on structural modeling, there was a residual effect of close vision on speed after controlling for the effect of vision on intellectual functioning (see Figure 4). As can be seen in Table 7, this surplus covariation can also be observed at the level of individual tests. The three highest correlations with vision were obtained for the three speed tests, a result that is highly unlikely by chance (i.e., $p = 1/14! \times 3! \times 11! = .003$). All three speed tests required the fast execution of relatively simple operations on the basis of visual material. It is possible, therefore, that individuals with poor visual acuity experienced greater difficulty in the fast visual perception of stimulus features.

However, it should be kept in mind how difficult it is to separate ability-intrinsic from ability-extraneous components. Individual differences can originate at several points in information processing from input to output. With the present data, it is not possible to pinpoint the critical locations in the chain of processing events. From a more general point of view, sensory aspects of test administration can be seen as part and parcel of ability-intrinsic components. The only question, then, is whether ability tests differ in sensory saliency. The present analysis suggests that such differences are relatively small for this battery of cognitive tests, with the possible exception of the speed tests.

The possible presence of a visual bias in the speed tests does not compromise our structural modeling results because we specified a path from close vision to speed before analyzing the structural relationship among age, vision, hearing, and intellectual functioning. An even more radical possibility would be to eliminate speed from the model altogether. Removing speed from the structural model did not alter any of the results reported above. For instance, the structural model again had an excellent fit, $\chi^2(38, N = 154) = 42.91, p = .27$, NNFI = 0.992, CFI = 0.995, and allowing for a direct path from age to intellectual functioning did not lead to a significant increment in fit, $\Delta\chi^2(1, N = 154) = 2.17, p > .10$.

To summarize, there is little evidence to suggest that the present set of results is easily explained by ability-extraneous sensory performance factors operating during the administration of the cognitive tests. With the possible exception of the speed tests, the magnitude of sensory-cognitive correlations did not vary substantially as a function of test-specific sensory performance demands.

Discussion

In this study, we examined the importance of visual and auditory acuity as correlates of intellectual functioning in a heterogeneous sample of old and very old individuals (70–103 years). The relevant constructs (i.e., acuity for close and distance vision, pure-tone thresholds at eight different frequencies, and intellectual functioning) were defined as latent factors in a structural model (Bentler, 1989).

Visual acuity explained 41.3% and auditory acuity 34.6% of the reliable total variance in intellectual functioning; in combination, vision and hearing accounted for 49.2% of the total and 93.1% of the age-related variance. A structural model in which age differences in intellectual functioning are fully mediated by vision and hearing (i.e., SENS1 in Table 4) fit the data very well and did not differ statistically from a model that allowed for a direct effect of age on intellectual functioning.[7]

[7] In SENS1 of Table 4, age, vision, and hearing form a saturated preceding block (cf. Breckler, 1990; MacCallum, Wegener, Uchino, & Fabrigar, 1993). Therefore, 26 additional models with identical fit functions exist if both reciprocal and unidirectional paths among age, Vision, and Hearing are considered. This number is reduced to three if all models are excluded in which age receives inputs from either Vision or Hearing (i.e., Hearing → age; Vision → age; Hearing ↔ age; Vision ↔ age). The only difference among the three remaining models concerns the relationship between Vision and Hearing (i.e., Hearing → Vision; Vision → Hearing; Vision ↔ Hearing, i.e., SENS1 of Table 4). In addition to the issue of mathematically equivalent models, other models with different theoretical implications may happen to fit the data equally well or better for empirical reasons. For instance, we found a different way to model the common cause hypothesis. In this alternative model, there is a higher order latent factor defined by Vision, Hearing, and Intelligence as well as a single directed path of age on that factor. This model also had an excellent fit, $\chi^2(49, N = 154) = 54.53, p = .27$, CFI = 0.995, NNFI = 0.993, which means that all of the age-related

In accordance with an earlier report that focused on the psychometric structure of the cognitive tests and its relationship to age (Lindenberger et al., 1993), a latent factor of mental speed was found to perfectly predict negative age differences in the rest of intelligence (i.e., in a general cognitive ability factor defined by the unit-weighted composites of tests of reasoning, knowledge, fluency, and memory). Thus, as a mediator of negative age differences in the four remaining intellectual abilities, the predictive power of speed (cf. Salthouse, 1991) was equivalent to the predictive power of vision and hearing. However, whereas vision and hearing accounted for all of the negative age differences in speed, speed did not account for all of the negative age differences in vision or hearing. In this sense, vision and hearing were more powerful predictors of negative age differences than speed.

The present findings suggest that sensory functioning is an important correlate of individual differences in intellectual functioning in old and very old age. The magnitude of the relationship between sensory and intellectual functioning observed in this study stands in sharp contrast to findings in younger age groups including young–old segments of the elderly population (Era et al., 1986; Owsley et al., 1991; Thomas et al., 1983). The powerful role of sensory functioning is further supported by the result that balance–gait, a measure of sensorimotor bodily efficacy, was similarly predictive of individual differences in intellectual functioning as vision and hearing.

The predictive power of sensory functioning in this data set also speaks to the question of life-span continuity versus discontinuity. It seems reasonable to argue that vision and hearing as well as balance–gait are largely orthogonal to influences affecting intellectual functioning during earlier phases of the life span. As a consequence, the increased importance of sensory functioning would lead to a reshuffling of individual differences in intellectual functioning in old and very old age (cf. Hertzog & Schaie, 1986, 1988). In line with this argument, more than 80% of the interindividual variability in intellectual functioning predicted by vision and hearing was orthogonal to years of education, a typical life-history predictor of intellectual functioning. Although more refined measures of experiential life history may yield a different picture, this pattern of findings lends at least preliminary support to the notion of a shift in the predictive salience of factors regulating interindividual differences in intellectual abilities across the adult life span. It should be cautioned, however, that about 44% of the reliable (i.e., latent factor) variance in intellectual functioning was not predicted by age, vision, hearing, balance–gait, or years of education. We do not know whether this unexplained variability is related to factors favoring continuity or discontinuity of interindividual differences in intellectual functioning across the life span.

Evaluation of Guiding Hypotheses

Theoretically, this study was informed by two general guiding hypotheses, both predicting a strong link between sensory and intellectual functioning in old age. According to the sensory deprivation hypothesis, sensory functioning is closely related to intellectual functioning because protracted sensory underload (Sekuler & Blake, 1987) reduces individuals' likelihood to engage in cognitively stimulating interactions with their environment. According to the common cause hypothesis, negative age differences in both domains (sensory and cognitive) reflect an age-associated loss in the integrity of brain physiology. Age differences in intellectual and sensory functioning, then, are seen as the outcome of a third common factor or ensemble of factors, that is, aging changes in the physiological state of the brain. Measures of sensory functioning are expected to mediate age differences in intellectual functioning because they permit a more direct assessment of this third common factor.

Although our results do not allow for a conclusive distinction between the two hypotheses, we believe that they are more consistent with the common cause hypothesis. First, with the sensory deprivation hypothesis, one would expect that abilities more closely related to social interaction such as knowledge or fluency would be more highly correlated with sensory functioning than cognitive abilities that are less social in character such as speed or reasoning. However, no residual relations of this sort were observed.

Second, according to the sensory deprivation hypothesis, one may assume that the link between sensory and intellectual functioning is stronger at lower levels of sensory functioning because of a nonlinear (e.g., quadratic or thresholdlike) negative relationship between sensory functioning and sensory deprivation. However, the data did not follow this pattern: When we eliminated all subjects with severe sensory impairments, the structural relations among age, vision, hearing, and intelligence remained unchanged.

Clearly, longitudinal information would be very helpful to disentangle the two hypotheses. For instance, the sensory deprivation hypothesis implies that the duration of sensory impairment would predict low-level intellectual functioning after controlling for concurrent sensory status. Moreover, it would also suggest that interventions in the sensory domain at the level of the end organ (i.e., the prescription of hearing aids and corrective glasses) would have positive time-lagged effects on intellectual functioning.

Alternative Interpretations and Suggestions for Further Research

The size of the relationship between sensory and intellectual functioning found in this study suggests a number of caveats and additional lines of interpretation not contained in our original research questions. In particular, we wonder about an additional alternative interpretation that would focus less on the role of sensory functioning for cognitive performance than on the changing role of intelligence in the assessment of sensory functioning in old age. Possibly, the assessment of visual and auditory acuity is "transformed" into a task of cognitive functioning with advancing age. Such changes in the validity of tasks are known from psychometric research in child development (Reinert, 1970) and from research on processes of learning (Ackerman, 1988).[8]

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variance in Vision, Hearing, and Intelligence was shared among the three constructs.

[8] One reviewer suggested that the strong relationship between sensory and intellectual functioning found in this study may reflect the use of a computerized cognitive test battery. We do not believe that this is a likely explanation. As described in more detail in Lindenberger et al. (1993),

One possibility would be that older individuals are more reluctant to report the presence of a sensory signal. In that case, the age-induced correlation between sensory acuity and intelligence would reflect the cognitive tendency to adopt a more conservative response bias with advancing age. This interpretation, however, is inconsistent with recent studies reporting an absence of adult age differences in response bias for sensory signal-detection tasks (Baron & LeBreck, 1987; Marshall, 1991; Morrison & Reilly, 1986; cf. Corso, 1987). Thus, the negative age differences found for the sensory acuity measures most probably reflect a true age-associated decrement in sensitivity (i.e., sensory ability) rather than age differences in bias.

Nevertheless, one may still speculate about the attentional demands of the sensory measures. The visual acuity tests required subjects to read letters and digits that were set in type of decreasing size. This procedure may also capture individual differences in subjects' ability to identify letters and digits on the basis of degraded (e.g., hardly visible) stimulus materials. During pure-tone audiometry, the loudness of signals was continuously increased until subjects were able to hear the tone. This arrangement may be sensitive to individual differences in subjects' ability to sustain attention while waiting for the perception of an auditory signal. Negative age differences have been found both for the ability to identify stimuli under degraded conditions (Madden, 1988) and for sustained attention (Barr & Giambra, 1990). Attentional factors have been found to influence the electrophysiological response to auditory stimuli during very early stages of information processing (Tiitinen et al., 1993). Thus, a certain proportion of the variability in the sensory measures may be due to processing components that are not strictly visual or auditory in character but draw on more general processes of attention and discrimination.

These ambiguities in interpretation call for the development of sensory acuity measures that are as "modular" (e.g., modality specific) and "cognition free" as possible. It may be possible, however, that difficulties in finding such measures are directly related to the changing nature of sensory and sensorimotor functioning in old age. Specifically, decrements in sensory functioning may require aging individuals to invest an increasing amount of cognitive resources (e.g., attention) into the ongoing coordination and compensatory management of sensorimotor behavior. As a result, and similar to effects studied in dual-task paradigms, the cognitive reserve capacity available for other cognitive activities, such as taking intelligence tests, is reduced (cf. Fleury, Teasdale, Bard, & Lajoie, 1993; Maylor, 1994; Teasdale et al., 1992).

Conclusions

In conclusion, the results of this study point to a new finding in cognitive aging, that is, a powerful connection between intellectual and sensory functioning in old and very old age. The interpretation of this finding is unclear. On the one hand, the data can be taken as initial evidence that visual and auditory systems evolve as powerful regulators of intellectual performance in old and very old age or that sensory and cognitive functions undergo a common process of aging-induced dedifferentiation. On the other hand, the data are also consistent with the view that standard clinical measures of visual and auditory acuity are overly sensitive to negative age differences in cognitive processes such as sustained attention and discrimination.

In any case, we suggest that the finding requires new efforts at theory and experimentation. Among the new lines of work suggested is longitudinal work on the relationship between sensory and intellectual functioning. In addition, age-comparative work is needed to examine the magnitude of the relationship between sensory and intellectual functioning across the life span. For instance, in contrast to our initial expectations, the correlation between sensory acuity and intelligence was not higher in very old than in old subjects. It remains to be determined whether and at what age the magnitude of the relationship between the two domains of functioning begins to increase. Moreover, age-comparative work may also help to examine the possible existence of age differences in the cognitive demand characteristics of standard sensory acuity measures. Finally, we suggest experimental age-simulation research in which the sensory systems of younger adults are temporarily impaired to explore whether such an intervention produces effects that are similar to those obtained in the present study with old adults (e.g., decrease in level, increase in correlations).

only 5 of the 14 tests have a computerized response format. In the remaining tasks, the computer is used for instruction and stimulus presentation only, or not used at all. For instance, the fluency tasks simply require subjects to name as many animals or words starting with the letter *S*, and the Digit Symbol Substitution test is administered in a paper-and-pencil format according to Wechsler (1955). There is no evidence in these data to suggest that the strength of the relationship between intellectual and sensory functioning was related to the degree of computerization of the tests.

References

Ackerman, P. L. (1988). Determinants of individual differences during skill acquisition: Cognitive abilities and information processing. *Journal of Experimental Psychology: General, 117,* 288–318.

American Psychiatric Association. (1987). *Diagnostic and statistical manual of mental disorders* (3rd ed., rev.). Washington, DC: Author.

Balazsi, A. G., Rootman, J., Drance, S. M., Schulze, M., & Douglas, G. R. (1984). The effect of age on the nerve fiber population of the human optic nerve. *American Journal of Ophthalmology, 97,* 760–766.

Baltes, M. M., Mayr, U., Borchelt, M., Maas, I., & Wilms, H.-U. (1993). Everyday competence in old and very old age: An interdisciplinary perspective. *Ageing and Society, 13,* 657–680.

Baltes, P. B. (1973). Prototypical paradigms and questions in life-span research on development and aging. *Gerontologist, 13,* 458–467.

Baltes, P. B. (1987). Theoretical propositions of life-span developmental psychology: On the dynamics between growth and decline. *Developmental Psychology, 23,* 611–626.

Baltes, P. B., Mayer, K. U., Helmchen, H., & Steinhagen-Thiessen, E. (1993). The Berlin Aging Study (BASE): Overview and design. *Ageing and Society, 13,* 483–515.

Baltes, P. B., Reese, H. W., & Nesselroade, J. R. (1988). Life-span developmental psychology. *Introduction to research methods.* Hillsdale, NJ: Erlbaum.

Baron, A., & LeBreck, D. B. (1987). Are older adults more conservative? Some negative evidence from signal detection analyses of recognition memory and sensory performance. *Experimental Aging Research, 13,* 163–165.

Barr, R. A., & Giambra, L. M. (1990). Age-related decrement in auditory selective attention. *Psychology and Aging, 5,* 597–599.

Bentler, P. M. (1989). *EQS. Structural equations manual.* Los Angeles: BMDP Statistical Software.

Bergman, M. (1983). Central disorders of hearing in the elderly. In R. Hinchcliffe (Ed.), *Hearing and balance in the elderly* (pp. 145–158). Edinburgh, England: Churchill Livingstone.

Biglan, A. W., Van Hasselt, V. B., & Simon, J. (1988). Visual impairment. In V. B. Van Hasselt, P. S. Strain, & M. Hersen (Eds.), *Handbook of developmental and physical disabilities* (pp. 471–502). Needham Heights, MA: Allyn.

Birren, J. E., Botwinick, J., Weiss, A. D., & Morrison, D. F. (1963). Interrelations of mental and perceptual tests given to healthy elderly men. In J. E. Birren, R. N. Butler, S. W. Greenhouse, & M. R. Yarrow (Eds.), *Human aging: A biological and behavioral study* (pp. 143–156). Washington, DC: Government Printing Office.

Borchelt, M. F., & Steinhagen-Thiessen, E. (1992). Physical performance and sensory functions as determinants of independence in activities of daily living in the old and the very old. *Annals of the New York Academy of Sciences, 673,* 350–361.

Braden, J. P. (1985). The structure of nonverbal intelligence in deaf and hearing subjects. *American Annals of the Deaf, 130,* 496–501.

Breckler, S. J. (1990). Applications of covariance structure modeling in psychology: Cause for concern? *Psychological Bulletin, 107,* 260–273.

Cerella, J. (1990). Aging and information-processing rate. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (3rd ed., pp. 201–221). San Diego, CA: Academic Press.

Cogan, D. G. (1985). Visual disturbances with focal progressive dementing disease. *American Journal of Ophthalmology, 100,* 68–72.

Colsher, P. L., & Wallace, R. B. (1990). Are hearing and visual dysfunction associated with cognitive impairment? A population-based approach. *The Journal of Applied Gerontology, 9,* 91–105.

Corso, J. F. (1987). Sensory-perceptual processes and aging. In K. W. Schaie & C. Eisdorfer (Eds.), *Annual review of gerontology and geriatrics* (pp. 29–55). New York: Springer.

Craig, H. B., & Gordon, H. W. (1988). Specialized cognitive function and reading achievement in hearing-impaired adolescents. *Journal of Speech and Hearing Disorders, 53,* 30–41.

DeBeni, R., & Cornoldi, C. (1988). Imagery limitations in totally congenitally blind subjects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 650–655.

Devaney, K. O., & Johnson, H. A. (1980). Neuron loss in the aging visual cortex of man. *Journal of Gerontology, 35,* 836–841.

Era, P., Jokela, J., Qvarnberg, Y., & Heikkinen, E. (1986). Pure-tone thresholds, speech understanding, and their correlates in samples of men of different ages. *Audiology, 25,* 338–352.

Fleury, M., Teasdale, N., Bard, C., & Lajoie, Y. (1993, July). *Attentional cost as a determinant of stability and efficiency in posture and locomotion in the elderly.* Paper presented at the Biennial Meeting of the International Society for the Study of Behavioral Development, Recife, Brazil.

Fozard, J. L. (1990). Vision and hearing in aging. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (3rd ed., pp. 150–170). San Diego, CA: Academic Press.

Fozard, J. L., Metter, E. J., & Brant, L. J. (1990). Next steps in describing aging and disease in longitudinal studies. *Journals of Gerontology: Psychological Sciences, 45,* P116–P127.

Furry, C. A., & Baltes, P. B. (1973). The effect of ability-extraneous performance variables on the assessment of intelligence in children, adults, and the elderly. *Journal of Gerontology, 28,* 73–80.

Geigy, J. R. (1977). *Wissenschaftliche Tabellen* [*Scientific tables*]. Basel, Switzerland: J. R. Geigy AG.

Gerok, W., & Brandtstädter, J. (1992). Normales, krankhaftes und optimales Altern: Variations-und Modifikationsspielräume [Normal, pathological, and optimal aging: Zones of variation and modification]. In P. B. Baltes & J. Mittelstrass (Eds.), *Zukunft des Alterns und gesellschaftliche Entwicklung* [*The future of aging and societal development*] (pp. 356–385). Berlin, Germany: de Gruyter.

Gilhome Herbst, K., & Humphrey, C. (1980). Hearing impairment and mental state in the elderly living at home. *British Medical Journal, 281,* 903–905.

Granick, S., Kleban, M. H., & Weiss, A. D. (1976). Relationships between hearing loss and cognition in normally hearing aged persons. *Journal of Gerontology, 31,* 434–440.

Groenveld, M., & Jan, J. E. (1992). Intelligence profiles of low vision and blind children. *Journal of Visual Impairment and Blindness, 84,* 68–71.

Helmchen, H., & Linden, M. (1993). The differentiation between depression and dementia in the very old. *Ageing and Society, 13,* 589–617.

Hertzog, C. (1989). Influences of cognitive slowing on age differences in intelligence. *Developmental Psychology, 25,* 636–651.

Hertzog, C., & Schaie, K. W. (1986). Stability and change in adult intelligence: 1. Analysis of longitudinal covariance structures. *Psychology and Aging, 1,* 159–171.

Hertzog, C., & Schaie, K. W. (1988). Stability and change in adult intelligence: 2. Simultaneous analysis of longitudinal means and covariance structures. *Psychology and Aging, 3,* 122–130.

Hinton, D. R., Sadun, A. A., Blanks, J. C., & Miller, C. A. (1986). Optic-nerve degeneration in Alzheimer's disease. *New England Journal of Medicine, 315,* 485–487.

Horn, J. L. (1980). Concepts of intellect in relation to learning and adult development. *Intelligence, 4,* 285–317.

ICD. (1988). *International classification of diseases, injuries, and causes of death (ICD).* Köln, Germany: Kohlhammer.

Jones, D. A., Victor, C. R., & Vetter, N. J. (1984). Hearing difficulty and its psychological implications for the elderly. *Journal of Epidemiology and Community Health, 38,* 75–78.

Lindenberger, U., & Baltes, P. B. (in press). Aging and intelligence. In R. J. Sternberg et al. (Eds.), *Encyclopedia of intelligence.* New York: MacMillan.

Lindenberger, U., Gilberg, R., Little, T., & Baltes, P. B. (1994). *Sample selectivity in the Berlin Aging Study.* Unpublished manuscript.

Lindenberger, U., Mayr, U., & Kliegl, R. (1993). Speed and intelligence in old age. *Psychology and Aging, 8,* 207–220.

MacCallum, R. C., Wegener, D. T., Uchino, B. N., & Fabrigar, L. R. (1993). The problem of equivalent models in applications of covariance structure analysis. *Psychological Bulletin, 114,* 185–199.

Madden, D. J. (1988). Adult age differences in the effects of sentence context and stimulus degradation during visual word recognition. *Psychology and Aging, 3,* 167–172.

Marsh, H. W., Balla, J. R., & McDonald, R. P. (1988). Goodness-of-fit indexes in confirmatory factor analysis: The effect of sample size. *Psychological Bulletin, 103,* 391–410.

Marshall, L. (1991). Decision criteria for pure-tone detection used by two age groups of normal-hearing and hearing-impaired listeners. *Journals of Gerontology: Psychological Sciences, 46,* P67–P70.

Maylor, E. A. (1994, April). *Age differences in postural stability are increased by additional cognitive demands.* Poster presented at the 5th Cognitive Aging Conference, Atlanta, GA.

Meng, X.-L., Rosenthal, R., & Rubin, D. B. (1992). Comparing correlated correlation coefficients. *Psychological Bulletin, 111,* 172–175.

Mhoon, E. (1990). Otology. In C. K. Kassel, L. B. Sorensen, D. E. Riesenberg, & J. R. Walsh (Eds.), *Geriatric medicine* (pp. 405–419). New York: Springer.

Morrison, J. D., & Reilly, J. (1986). An assessment of decision-making as a possible factor in the age-related loss of contrast sensitivity. *Perception, 15,* 541–552.

Myerson, J., Hale, S., Wagstaff, D., Poon, L. W., & Smith, G. A. (1990). The information-loss model: A mathematical theory of age-related cognitive slowing. *Psychological Review, 97,* 475–487.

Neugarten, B. L. (1974, September). Age groups in American society and the rise of the young-old. *Annals of the American Academy of Political and Social Science*, pp. 187–198.

Ohta, R. J., Carlin, M. F., & Harmon, B. M. (1981). Auditory acuity and performance on the mental status questionnaire in the elderly. *Journal of the American Geriatrics Society, 29*, 476–478.

O'Neil, P. M., & Calhoun, K. S. (1975). Sensory deficits and behavioral deterioration in senescence. *Journal of Abnormal Psychology, 84*, 579–582.

Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging, 6*, 403–415.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research, 23*, 689–699.

Rabbitt, P. (1990). Applied cognitive gerontology: Some problems, methodologies, and data. *Applied Cognitive Psychology, 4*, 225–246.

Raz, N., Moberg, P. J., & Millman, D. (1990). Effects of age and age-related differences in auditory information processing on fluid and crystallized intelligence. *Personality and Individual Differences, 11*, 1147–1152.

Reinert, G. (1970). Comparative factor analytic studies of intelligence throughout the life span. In L. R. Goulet & P. B. Baltes (Eds.), *Life-span developmental psychology: Research and theory.* San Diego, CA: Academic Press.

Sadun, A. A., Borchert, M., DeVita, E., Hinton, D. R., & Bassi, C. J. (1987). Assessment of visual impairments in Alzheimer's disease. *American Journal of Ophthalmology, 104*, 113–120.

Salthouse, T. A. (1985). *A theory of cognitive aging.* Amsterdam: North-Holland.

Salthouse, T. A. (1991). Mediation of adult age differences in cognition by reductions in working memory and speed of processing. *Psychological Science, 2*, 179–183.

Schaie, K. W., Baltes, P. B., & Strother, C. R. (1964). A study of auditory sensitivity in advanced age. *Journal of Gerontology, 19*, 453–457.

Sekuler, R., & Blake, R. (1987). Sensory underload. *Psychology Today, 21*, 48–51.

Shallice, T. (1988). *From neuropsychology to mental structure.* Cambridge, England: Cambridge University Press.

Shindell, S. (1989). Assessing the older adult with visual impairment. In T. Hunt & C. J. Lindley (Eds.), *Testing older adults: A reference guide for geropsychological assessments* (pp. 135–149). Austin, TX: Pro Ed.

Steinhagen-Thiessen, E., & Borchelt, M. (1993). Health differences in advanced old age. *Ageing and Society, 13*, 619–655.

Teasdale, N., Bard, C., Dadouchi, F., Fleury, M., Larue, J., & Stelmach, G. E. (1992). Posture and elderly persons: Evidence for deficits in the central integrative mechanisms. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior II* (pp. 917–931). New York: Elsevier Science.

Thurstone, L. L., & Thurstone, T. G. (1949). *Examiner's manual: SRA Primary Mental Abilities Test (Form 11-17).* Chicago: Science Research Associates.

Thomas, P. D., Hunt, W. C., Garry, P. J., Hood, R. B., Goodwin, J. M., & Goodwin, J. S. (1983). Hearing acuity in a healthy elderly population: Effects on emotional, cognitive, and social status. *Journal of Gerontology, 38*, 321–325.

Tiitinen, H., Sinkkonen, J., Reinikainen, K., Alho, K., Lavikainen, J., & Näätänen, R. (1993). Selective attention enhances the auditory 40 Hz transient response in humans. *Nature, 364*, 59–60.

Tinetti, M. E. (1986). A performance-oriented assessment of mobility problems in elderly patients. *Journal of the American Geriatric Society, 34*, 119–126.

Vernon, M. (1968). Fifty years of research on the intelligence of deaf and hard of hearing children: A review of the literature and discussion of implications. *Journal of Rehabilitation of the Deaf, 1*, 1–12.

Vernon, M. (1989). Assessment of older persons with hearing disabilities. In T. Hunt & C. J. Lindley (Eds.), *Testing older adults: A reference guide for geropsychological assessments* (pp. 150–162). Austin, TX: Pro Ed.

Weale, R. A. (1987). Senescent vision: Is it all the fault of the lens? *Eye, 1*, 217–221.

Wechsler, D. (1955). *Wechsler Adult Intelligence Scale* (7th ed.). New York: Psychological Corporation.

Werner, J. S., Peterzell, D. H., & Scheetz, A. J. (1990). Light, vision, and aging. *Optometry and Vision Science, 67*, 214–229.

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