Journal of Gerontology: PSYCHOLOGICAL SCIENCES
2001, Vol. 56B, No. 1, P3–P11

A Reevaluation of the Common Factor Theory of Shared Variance Among Age, Sensory Function, and Cognitive Function in Older Adults

Kaarin J. Anstey,[1] Mary A. Luszcz,[2] and Linnett Sanchez[3]

[1]Prince of Wales Medical Research Institute, University of New South Wales, Randwick, Australia.
[2]School of Psychology and [3]Department of Speech Pathology, Flinders University of South Australia, Adelaide.

The common cause hypothesis of the relationship among age, sensory measures, and cognitive measures in very old adults was reevaluated. Both sensory function and processing speed were evaluated as mediators of the relationship between age and cognitive function. Cognitive function was a latent variable that comprised 3 factors including memory, speed, and verbal ability. The sample was population based and comprised very old adults (*n* = 894; mean age = 77.7, *SD* = 5.6 years) from the Australian Longitudinal Study of Ageing. The results showed that there was common variance in the cognitive factor shared by age, speed, vision, and hearing but that specific effects of age on cognition remained. Furthermore, speed did not fully mediate the effect of age or sensory function on cognition. Some age differences in cognitive performance are not explained by the same processes that explain age differences in sensory function and processing speed.

SEVERAL empirical studies have demonstrated a robust association between sensory and cognitive function in old age (Anstey, 1999; Anstey, Lord, & Williams, 1997; Anstey & Smith, 1999; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Salthouse, Hambrick, & McGuthry, 1998; Salthouse, Hancock, Meinz, & Hambrick, 1996; Stankov, 1986). A *common cause* explanation suggests that this association occurs because "both sets of measures are an expression of the physiological architecture of the aging brain" (Baltes & Lindenberger, 1997, p. 13). Measures of sensory acuity have been reliably shown to explain large amounts of age-related variance in cognition. For example, Lindenberger and Baltes (1994) found that sensory variables explained more than 90% of the age-related variance in a general cognitive factor. Likewise, Anstey and Smith (1999) found that a latent variable of indicators of biological age (including vision, hearing, forced expiratory volume, vibration sense, and grip strength) fully mediated the relationship between age and a general cognitive factor. Studies such as these indicate that age differences in sensory functioning may provide a window through which to view age differences in cognitive function (Baltes & Lindenberger, 1997).

Interpreted in the broadest sense, a common factor theory of cognitive aging predicts that all factors mediating age-cognition relations are measures of the same common factor. For example, both processing speed and sensory function should explain the same portion of age-related variance in cognitive function. The role of processing speed has been central to theories of cognitive aging for more than 30 years (Birren, 1965; Salthouse, 1991). Many studies have shown that speed reduces or eliminates the age effect on a range of cognitive tasks (e.g., Bors & Forin, 1995; Bryan & Luszcz, 1996; Lindenberger, Mayr & Kliegl, 1993; Nettelbeck & Rabbitt, 1992; Salthouse, 1992a, 1992b, 1996). It is therefore pertinent for researchers to evaluate the importance of sensory function as a mediator of the relationship between age and cognition concurrently with processing speed.

Lindenberger and Baltes (1994) evaluated the relative importance of speed and sensory function in cross-sectional models of age differences in cognition. In one model, they found that speed did not fully mediate the effect of age on sensory function but did fully mediate the effect of age on cognition. In a second model, they found that the effect of age on speed was fully mediated by sensory function, and the effect of sensory function on cognition was fully mediated by speed. They concluded that, although speed and sensory function were equivalent in their capacity to mediate the association between age and cognition, vision and hearing were more important predictors of age differences because they explained all age-related variance in cognition (including speed) whereas speed did not explain all the age-related variance in sensory function. These authors did not find that sensory function explained any more age-related variance in cognitive function than processing speed. In terms of models of cognitive aging, sensory function and speed were equally powerful mediators. However, in terms of explaining overall age differences, sensory function was a more powerful predictor than speed. That is, compared with speed, sensory function explained a larger proportion of the variance in age, consistent with the view that sensory function is a reliable biomarker (Anstey & Smith, 1999).

Another approach to evaluating mediators of the relationship between age and cognition is in terms of the mediators' theoretical independence from cognitive function (Lindenberger & Potter, 1998). Measures of processing speed are essentially cognitive variables may overlap theoretically and empirically with measures of cognitive function. For example, many measures of cognitive function are conducted under time limits, so the explanatory power of processing speed may be partly due to the fact that it measures this speeded aspect of cognitive performance. Furthermore, measures of processing speed often entail a small memory load, as do many measures of cognitive function (Piccinin & Rabbitt, 1999). For example, participants must often hold elements of the cognitive task in their mind while performing cognitive operations. Measures of sensory function are from a qualitatively different domain than measures of cognitive function. Although they involve some cognitive processing in that participants must understand test instructions, sensory acuity tests are not speeded or timed.

On the other hand, the fact that sensory function alone (Lindenberger & Baltes, 1994) and in conjunction with other biomarkers (Anstey & Smith, 1999) has been shown to explain all age differences in measures of cognitive abilities may indicate that sensory acuity is just a proxy for age (Salthouse et al., 1998). It is possible that sensory function is no more than an index of age or time. If this is the case, sensory acuity may not be a meaningful mediational construct in this context and does not provide a substantive explanation of age differences in cognition. Consequently, the recent emphasis placed on sensory function as a mediator of age-cognition relations may be misguided, and the empirical findings relating to the importance of sensory function may be spurious, a proposition raised by Salthouse and colleagues (1998). At the conceptual level, this criticism may be refuted: one would argue that even if the association between sensory variables and cognition is due to the fact that sensory variables are good measures of age, then it is still more informative to relate age differences in cognition to a physiological variable than to a measure of time. This is particularly true in late adulthood, when individual differences in biological aging increase.

Empirical evidence against the "spuriousness" interpretation of the association between sensory function and cognition in old age would be found if sensory acuity explained individual differences in cognitive function that were independent of age differences, or if experimental manipulations of sensory acuity resulted in changes in cognitive performance. Anstey and Smith (1999) reported that biomarkers including measures of sensory acuity explained individual differences in measures of crystallized intelligence that were independent of age. Studies of young adults have also shown associations among sensory variables and individual differences in intelligence (Li, Jordanova, & Lindenberger, 1998; Roberts, Stankov, Pallier, & Dolph, 1997). Experimental evidence for the effect of sensory deficit on cognitive performance was also reported by Dickinson and Rabbitt (1991), although Lindenberger, Scherer, and Baltes (1999) did not find a significant effect of simulated sensory deficit on cognitive performance.

Explanations such as the common cause model (Lindenberger & Baltes, 1994) relate the domains of sensory and cognitive performance at the level of brain functioning. The common cause model does not necessarily exclude the possibility of small specific associations existing between sensory and cognitive variables that are not shared with the more significant common factor. It is possible that, in addition to generalized brain aging, peripheral changes in sense organs affect perceptual and cognitive processing. Age-related loss of sensory receptors and neurons may result in slowing of perceptual processing and less effective and slower encoding of new information. This may directly lead to slowing of cognitive processing and increased errors on cognitive tasks. In the present study we reexamined the role of sensory function as a mediator of the association between age and cognitive abilities in late adulthood in a large population-based sample.

Our specific goal in this study was to see whether the empirical findings Lindenberger and Baltes (1994)—of a large proportion of shared age-related variance among sensory function, age, and cognition—would be replicated in the Australian Longitudinal Study of Ageing (ALSA). The sensory measures used in the ALSA and the age range of the sample are similar to those used in the Berlin Aging Study (BASE), but the cognitive battery is much smaller and includes measures of episodic memory that were not included in BASE. Nevertheless, if a common factor is responsible for the observed association among cognitive and sensory function generally, it is reasonable to expect that this factor would operate for a wide range of cognitive measures. Similar to Lindenberger and Baltes (1994), in this study we used speed as a part of the cognitive factor for evaluating the general model, and then we removed speed and used it as a mediating factor in subsequent models.

Methods

Sample

The sample was drawn from participants in the ALSA (see Luszcz, Bryan, & Kent, 1997, for more details). The ALSA used the South Australian Electoral Roll as a sampling frame to identify households with residents 70 years and older. The sample was stratified by age and sex into three 5-year cohorts: 70–74, 75–79, 80–84, and a fourth cohort of individuals older than 85. Individuals randomly sampled within these cohorts were invited to participate in the ALSA on a voluntary basis. The participation rate for the baseline data collection (Wave 1) was 55%.

Data were collected in two phases with two different formats. A comprehensive 2-h home interview was followed by a further individual clinical assessment conducted approximately 2 weeks later. The home interview yielded demographic data and information on self-rated health, depression, medical conditions, cognitive status, memory, and subjective measures of vision, audition, and physical performance. Individual clinical assessments provided objective cognitive and sensory data. For the first wave of the study, 1,947 participants (1,039 men) were interviewed, and 1,511 underwent portions of the clinical assessment. The sample for the present study comprised participants who completed the clinical assessment and interview and had complete data on the variables used in structural equation modeling. This included 894 participants aged 70–98 (M = 78.16, SD = 6.69) of whom approximately 51% were male.

Measures of Cognitive Function

Most of the cognitive measures have been described more fully elsewhere (Luszcz et al., 1997). Some were based on measures developed as part of the Canberra Inventory for the Elderly (CIE; see Christensen et al., 1994); these included Similarities, Definitions, and Address Memory. Measures are grouped according to the latent variables used in the structural equation models.

Verbal.—Verbal skills were assessed with four measures.

1. *Similarities.* Three items (apple-banana, boat-car, egg-seed) taken from the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler, 1981) assessed verbal reasoning. They were scored 0 (incorrect) or 1 (correct) to give a possible total of 3.
2. *Definitions.* Using vocabulary items drawn from the WAIS-R (Wechsler, 1981), participants defined three items (repairman, terminate, compassion), which were scored 0 (incorrect) or 1 (correct) for a possible total of 3. Test-retest reliability was .69.
3. *Confrontation naming.* A short form of the Boston Naming Test (Mack, Freed, Williams, & Henderson, 1992) was used for assessment of confrontation naming. The four different versions of this test were counterbalanced across participants. They were shown drawings, one at a time, and asked to name the object illustrated. According to standard instructions, if participants were unable to name the object or seemed confused about what it was, they were given a stimulus cue (semantic cue). If they were still unable to name the item, a phonemic cue was given. Up to 20 s were allowed for each response. If participants were still unable to name the item after both cues had been presented, the label was provided. This procedure ensured that participants knew the name of each item. A score of 1 was given for each item correctly named without cues, for a maximum possible total of 15. Observed scores on confrontation naming ranged from 6 to 15.
4. *The National Adult Reading Test* (NART; Nelson, 1982) measures verbal knowledge as an element of crystallized ability (Crawford, 1992). It comprises 50 infrequent words of irregular pronunciation that respondents are asked to read aloud. The number of items named correctly was used. Test-retest reliability was .83 (Luszcz et al., 1997).

Speed.—The Digit Symbol Substitution (DSS) subscale of the WAIS-R (Wechsler, 1981) was used for assessment of processing speed (Bryan & Luszcz, 1996; Salthouse, 1991). The participant was required to substitute symbols corresponding to the numbers 1 through 9 into a randomly ordered array of 93 digits. Symbols to be used were available throughout the task on a code sheet illustrating the 9 digit-symbol pairs. The participant was required to make substitutions as rapidly as possible. The number of substitutions completed correctly in 90 s made up the measure of processing speed. Observed scores ranged from 0 to 67. Test-retest reliability was .79 (Luszcz et al., 1997).

Memory.—Symbol, picture, and address memory were assessed.

1. *Symbol memory*. The DSS also provided a basis for incidental symbol memory. Participants were required to complete all 93 substitutions to equate exposure to the stimuli. Upon completion of the DSS, participants were given a symbol recall sheet with the numbers 1 through 9 minus the symbols and asked to draw as many of the symbols as they could remember with each number. Participants had not been informed at any time that they would be required to recall the symbols. The possible score for symbols correctly recalled was 9, and this was used as a measure of incidental symbol memory. Observed scores ranged from 0 to 9. Test-retest reliability was .73 (Luszcz et al., 1997).
2. *Picture memory.* The Boston Naming Test also provided a basis for incidental free recall of pictures (Luszcz et al., 1997). Participants were asked (without prior warning) to recall the 15 pictures immediately after the test.
3. *Address memory.* Respondents were required to recall a single name and address (Christensen et al., 1994). The name and address were repeated up to five times until the respondent remembered them. Immediate recall after the first trial for the five components of the item and delayed recall a few minutes later were recorded. The maximum score was 10.

Vision and hearing measures.—Vision and hearing were measured as follows.

1. *Distance visual acuity*. Corrected distance visual acuity was measured at 3 m for each eye with a well illuminated Snellen chart. If the participant wore glasses or contact lenses but did not have them at hand, corrected visual acuity was measured with pinhole testing. The eye not being tested was covered with an occluder and testing began on the 6/12 (.50) line. If the participant seemed hesitant or unsure of him- or herself, testing began with the next largest print, that is, the 6/18 (.33) line. The participant was encouraged to read the smallest line possible. The criterion for distance visual acuity was the smallest line read successfully, (i.e., with at least half of the characters in the line correctly read). For structural equation modeling, the logarithm of the minimum visual angle resolvable in the better eye was used as an indicator of a latent variable called vision.
2. *Near visual acuity.* This was measured at 20 cm with a chart containing short passages of text printed in ascending sizes of font from 5 to 18. The left eye and right eye were tested separately, and the score was the smallest font at which the participant could read. A logarithmic transformation of this variable called near vision was used for structural equation modeling.
3. *Audiometry.* Portable audiometers with standard earphones were used for threshold testing. The participant was initially asked whether he or she had a better ear; if so, testing began with that ear. Otherwise testing began with the right ear. A bracketing technique was used to test seven thresholds for each ear: 0.5, 1, 2, 3, 4, 6, and 8 kHz. After a successful response, the presentation tone was decreased by 10 dBHL; if the participant did not re-

spond, the tone was increased by 5 dBHL. Audiometric threshold for each frequency was determined when the participant responded consistently (i.e., 2 of 3 times) to the minimum presentation level on the ascend. For structural equation modeling, two ear-specific and one frequency-specific indicators were used. The ear-specific indicators consisted of the average of the frequencies of 0.5-, 1-, 2-, and 3-kHz scores in the left and right ears, and the frequency-specific indicator was the average of the left and right ear values for 4 kHz. There were large amounts of missing data for the highest test frequencies, 6 and 8 kHz, so these data were not used in the analyses.

Statistical Analysis

We conducted structural equation modeling to evaluate alternative multivariate models of the interrelationships among the sensory and cognitive variables and age. For all analyses we analyzed the raw data matrix using Maximum Likelihood. If necessary, the direction of scoring of sensory and cognitive variables was reversed so that higher scores indicated better functioning. Isolated missing values of pure tone thresholds were imputed on the basis of the participant's entire audiogram by the third author, a practising audiologist. No other missing data were imputed.

In the measurement model, all loadings were free, factor variances were fixed at 1, and covariances among all factors were estimated. We then specified structural models to depict alternative interpretations of the data and tested them for significance. There were three cognitive factors (Speed, Memory, and Verbal) and two sensory factors (Vision and Hearing). Three groups of models were tested. The first group was based on the common cause model reported by Lindenberger and Baltes (1994). The second and third models were also based on models reported by Lindenberger and Baltes (1994) and involved removing Speed as a cognitive factor and using it as a mediator.

Results

Zero Order and Age-Partialled Correlations Among Sensory and Cognitive Variables

Table 1 presents the zero order correlations and age-partialled correlations among all variables. The correlations between measures of sensory function and age are similar in size to the correlations between measures of cognitive function and age. From this table it is evident that associations among cognitive variables were only slightly reduced after age was partialled. Some large reductions in the size of correlations among sensory and cognitive variables were evident after we controlled for age. There were even larger reductions in the correlations between the measures of vision and the measures of hearing after we controlled for age. For example, the correlation between distance vision and right ear average 0.5–3 kHz was reduced from .22 to .08, and the correlation between distance vision and average of 4 Fs was reduced from .17 to .04 after we controlled for age.

Measurement Model

The initial measurement model (MM1) included six factors (Memory, Verbal, Speed, Vision, Hearing, and Age). Both Speed and Age were single indicator factors, and their factor loadings were fixed to 1.0. The data fitted well (see Table 2) except that the La Grange Multiplier test suggested that confrontation naming be allowed to load onto the Memory factor, reflecting a semantic memory component, as well as on the Verbal factor. When this alteration was made and the model (MM2; see Table 3 for factor loadings) was re-run, there was a significant improvement in fit ($\Delta\chi^2 = 36.6$, $p < .01$).

The intercorrelations among the six factors in the MM2 are shown in Table 4. The sensory factors, Speed and Memory, had similar-sized negative correlations with age in this sample, whereas the Verbal factor had a small negative age correlation. This pattern of age associations is consistent

Table 1. Zero Order Correlations and Age-Partialled Intercorrelations

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Age													
2. Similarities	−.17												
3. Definitions	−.07	.30/.29											
4. NART	−.07	.30/.29	.34/.34										
5. Confrontation naming	−.31	.25/.21	.23/.22	.43/.43									
6. Processing speed	−.45	.32/.28	.22/.21	.39/.40	.42/.33								
7. Symbol memory	−.28	.16/.11	.05/.04	.14/.12	.26/.19	.36/.27							
8. Picture memory	−.30	.21/.16	.15/.13	.26/.25	.45/.39	.48/.40	.43/.38						
9. Address memory	−.21	.25/.21	.21/.20	.24/.23	.26/.19	.35/.26	.29/.23	.36/.30					
10. Near vision	−.08	.05/.01	.01/.00	.06/.05	.14/.08	.20/.12	.19/.06	.11/.05	.09/.03				
11. Distance vision	−.39	.09/.03	.10/.08	.11/.10	.21/.10	.33/.19	.13/.02	.17/.06	.06/.05	.31/.25			
12. Left ear average 0.5–3 kHz	−.37	.08/.01	.10/.08	.16/.15	.18/.08	.25/.10	.18/.09	.20/.10	.19/.10	.10/.02	.19/.06		
13. Right ear average 0.5–3 kHz	−.40	.09/.02	.09/.08	.19/.17	.23/.12	.27/.11	.17/.06	.20/.09	.18/.09	.12/.04	.22/.08	.69/.64	
14. Average of 4 Fs	−.35	.11/.05	.12/.10	.19/.18	.16/.12	.29/.16	.15/.05	.20/.11	.21/.13	.08/.01	.17/.04	.71/.67	.70/.65

Notes: Similarities = similarities items from the Wechsler Adult Intelligence Scale-Revised (WAIS-R); definitions = definition items from the WAIS-R; NART = National Adult Reading Test; confrontation naming = Boston Naming Test short form score; processing speed = Digit Symbol Substitution (DSS) test; symbol memory = recall of the symbols from the DSS; picture memory = immediate recall of the Boston Naming Test items; address memory = recall of a single name and address; near vision = log of near vision score in better eye; distance vision = logMAR of distance vision score in better eye; left ear average 0.5–3 kHz = average of 0.5-, 1-, 2-, and 3-kHz frequencies in the left ear; right ear average 0.5–3 kHz = average of 0.5-, 1-, 2-, and 3-kHz frequencies in the right ear; average of 4 Fs = average 4 kHz in left and right ears.

Table 2. Goodness of Fit Indices of Measurement and Structural Models ($n = 894$)

Model	CFI	NNFI	SRMR	χ^2	*df*
Measurement Models					
MM1	.97	.96	.03	150.6	52
MM2	.98	.97	.03	114.00	51
Structural Models					
COMCAUS1[a]	.97	.96	.03	146.64	58
COMCAUS2[b]	.98	.97	.03	129.20	57
SENSPEED1[c]	.95	.93	.05	252.30	70
SENSPEED2[d]	.96	.94	.04	238.74	69
SENSPEED3[e]	.96	.94	.04	223.78	68
SENSPEED4[f]	.96	.94	.04	223.78	67
SENSPEED5[g]	.96	.94	.04	210.55	66
SPEED1[h]	.90	.88	.07	420.90	71
SPEED2[i]	.91	.88	.07	407.34	70
SPEED3[j]	.93	.91	.01	324.10	69
SPEED4[k]	.96	.94	.04	221.67	68

Notes: CFI = Comparative Fit Index; NNFI = Non-Normed Fit Index; SRMR = Standardized Root Mean Squared Residual.

[a]Age mediated by Vision and Hearing.

[b]COMCAUS1 with Age to Cognition added.

[c]Age mediated by Vision and Hearing, Vision and Hearing mediated by Speed.

[d]SENSPEED1 with Age to Cognition added.

[e]SENSPEED1 with Age to Cognition, Age to Speed added.

[f]SENSPEED1 with Age to Cognition, Age to Speed, Vision to Cognition added.

[g]SENSPEED1 with Age to Cognition, Age to Speed, Hearing to Cognition added.

[h]Age to Vision, Age to Hearing, and Age to Cognition mediated by Speed.

[i]SPEED1 with Age to Cognition added.

[j]SPEED1 with Age to Cognition, Age to Vision added.

[k]SPEED1 with Age to Cognition, Age to Vision, Age to Hearing added.

Table 3. Standardized Factor Loadings for Measurement Model MM2

	Age	Verbal	Speed	Memory	Vision	Hearing
Age	1.00					
Similarities		.45				
Definitions		.47				
NART		.74				
Confrontation naming		.34		.39		
Processing speed			1.00			
Symbol memory				.55		
Picture memory				.75		
Address memory				.51		
Near vision					.40	
Distance vision					.73	
Left ear average 0.5–3 kHz						.84
Right ear average 0.5–3 kHz						.83
Average of 4 Fs						.85

Notes: Similarities = similarities items from the Wechsler Adult Intelligence Scale-Revised (WAIS-R); definitions = definition items from the WAIS-R; NART = National Adult Reading Test; processing speed = Digit Symbol Substitution (DSS) test; symbol memory = recall of the symbols from the DSS; confrontation naming = Boston Naming Test short form score; picture memory = immediate recall of the Boston Naming Test items; address memory = recall of a single address; near vision = log of near vision score in better eye; distance vision = logMAR of distance vision score in better eye; left ear average 0.5–3 kHz = average of 0.5-, 1-, 2-, and 3-kHz frequencies in the left ear; right ear average 0.5–3 kHz = average of 0.5-, 1-, 2-, and 3-kHz frequencies in the right ear; average of 4 Fs = average 4 kHz in left and right ears.

with two factor theories of intelligence (Baltes, 1987; Horn, 1987).

Evaluation of the Common Factor Model With Structural Equation Modeling

The initial version of the common cause model (COMCAUS1) we tested was the same as that reported by Lindenberger and Baltes (1994). Memory, Speed, and Verbal loaded onto a single factor called *Cognition*. In this model the effect of Age on Cognition was mediated by Vision and Hearing, and there was no direct effect of Age on Cognition. The larger than desirable ratio of χ^2 to degrees of freedom in these analyses is partly due to the large sample size in the present study. All other goodness of fit indices indicated that this model was highly acceptable (Table 2). A second version of this model was tested that included the path from Age to Cognition and resulted in a significant improvement in fit ($\Delta\chi^2 = 17.44$, $df = 1$, $p < .01$). This model is depicted in Figure 1.

To evaluate whether specific effects of Age on Memory, Speed, and Verbal were unaccounted for the model shown in Figure 1, we tested further models that were the same as COMCAUS2 except that direct paths were included from Age to each of Memory, Verbal, and Speed. For the model including a direct path from Age to Speed and the model including a direct path from Age to Verbal, a linear dependency occurred for the path between Age and Cognition. For the model including a direct path from Age to Memory, a linear dependency occurred for the variance of the Cognition factor, and the model where Age was allowed to load on all Verbal, Memory, and Speed simultaneously had a linear dependency between the Memory and the Cognition factor. The model shown in Figure 1 therefore provided the best fit of the data. According to this model, most of the Age-related variance in Cognition was shared with sensory function, but a small amount of unique Age-related variance remained.

Estimation of the Age-Related Variance in Cognition Shared With Sensory Function

To allow for a direct comparison of results between the present study and that of Lindenberger and Baltes (1994),

Table 4. Factor Intercorrelation Matrix for Measurement Model MM2

	1	2	3	4	5
1. Age					
2. Verbal	−.16				
3. Speed	−.45	.52			
4. Memory	−.47	.50	.65		
5. Vision	−.53	.26	.45	.33	
6. Hearing	−.44	.27	.32	.35	.30

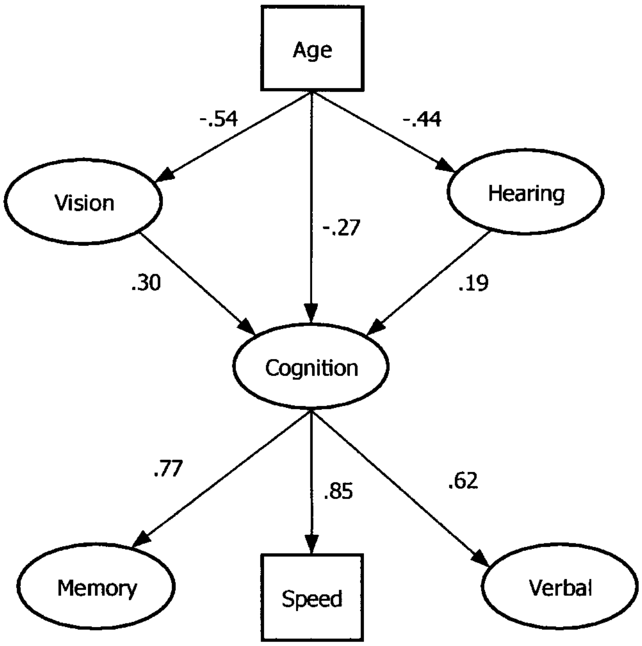

Figure 1. The common cause model including standardized path coefficients with an additional path from Age to Cognition (COMCAUS2).

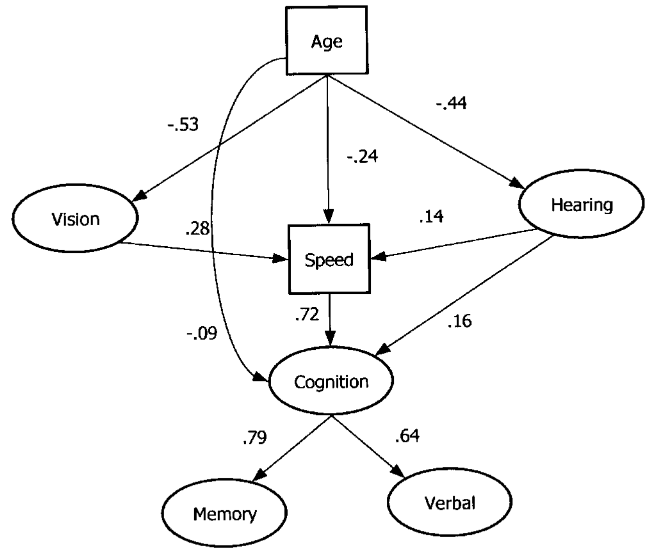

Figure 2. A model of Speed mediating the effects of Age, Vision, and Hearing on Cognition (SENSPEED5).

we calculated the proportion of age-related variance in Cognition shared with sensory function. This analysis was conducted in latent space (Bentler, 1995) where the square of the residual coefficient subtracted from 1 gives the multiple correlation coefficient for the equation. The variance in Cognition explained by Age was 22.56%, the variance in Cognition explained by Vision and Hearing was 31.94%, and the variance in Cognition explained by Age, Vision, and Hearing was 36.80%. Therefore, 78.46% of the Age-related variance in Cognition was shared with sensory function.

Speed as a Mediator of Sensory and Age Effects on Cognition

In the next model (SENSPEED1) the Speed factor was removed from the Cognition factor and used as a mediator of the effect of Age and sensory function on Cognition. In this model, Age had direct paths to Vision and Hearing, Vision and Hearing had direct paths to Speed, and Speed had a direct path to Cognition. This model also provided acceptable fit of the data but did not provide information about direct paths from Age, Vision, and Hearing to Cognition and Age to speed. In SENSPEED2, a direct path from Age to Cognition was included, resulting in a significant improvement in fit ($\Delta\chi^2 = 15$, $p < .01$; Table 2). In SENSPEED3, an additional direct path from Age to Speed was also included, and this also resulted in a significant improvement in fit ($\Delta\chi^2 = 14.96$, $p < .01$). In SENSPEED4, a path was added from Vision to Cognition. Although this path was significant, it did not improve the fit of the model. In SENSPEED5, the path from Vision to Cognition was removed and a path from Hearing to Cognition was added (Figure 2). This resulted in a significant improvement in fit ($\Delta\chi^2 = 13.23$, $p < .01$) and was accepted as the final model of the relationships among Speed, Vision, Hearing, Age, and Cognition. When an additional model with additional direct paths from Age to Memory was tested, linear dependencies occurred for the path from Age to Cognition. A model testing the additional direct path from Age to Verbal did not converge.

Speed as a Mediator Between Age and Vision, Hearing, and Cognition

The next series of models were based on the analyses reported by Lindenberger and Baltes (1994) that examined Speed as a mediator of the relationships between Age and sensory function and Age and Cognition. In this model, Speed was used as a mediator between Age and Vision, Age and Hearing, and Age and Cognition. SPEED1 included a direct path from Age to Speed and direct paths from Speed to Vision, Speed to Hearing, and Speed to Cognition. The fit of this model was barely acceptable (Table 2). The addition of a path from Age to Cognition in SPEED2 resulted in a significant improvement in fit ($\Delta\chi^2 = 13.56$, $p < .01$). In SPEED3 a path was added from Age to Vision, also resulting in a better fitting model ($\Delta\chi^2 = 83.24$, $p < .01$). Finally, in SPEED4, a path was added from Age to Hearing, resulting in a further improvement in fit ($\Delta\chi^2 = 102.43$, $p < .01$). Figure 3 shows the standardized path coefficients for SPEED4. This model showed that Speed did not fully mediate the effect of Age on sensory function or Cognition as measured by Verbal and Memory factors.

To test whether direct effects from age to Memory and Age to Verbal remained, we tested two models. In the first, a path from Age to Verbal was added to SPEED4. This resulted in a linear dependency for the path from Cognition to Memory. In the second, a path from Age to Memory was added to SPEED4. This resulted in a linear dependency for

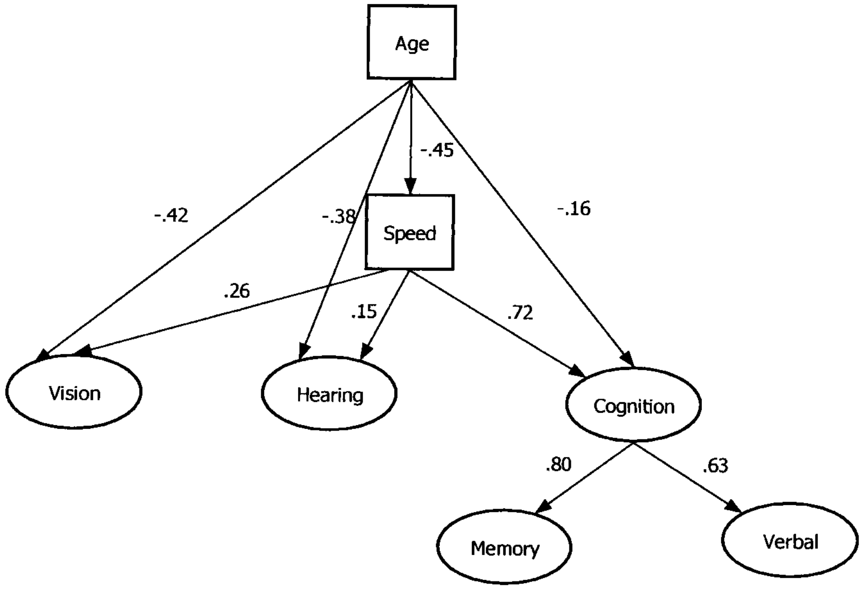

Figure 3. A model of Speed mediating the effect of Age on Vision, Age on Hearing, and Age on Cognition (SPEED4).

the path from Speed to Cognition. Therefore, SPEED4 remained the model that best fitted the data.

Estimation of the Amount of Variance in Cognition That Speed Shared With Sensory Function and Age

We calculated multiple correlations in latent space to enable an estimate of the amount of variance shared between Speed and Age and Speed and sensory function. For these analyses Cognition was a second-order factor onto which Verbal and Memory loaded. For these analyses, the variance in Cognition explained by Age was only 19.9%, the variance in Cognition explained by Vision and Hearing was 21.50%, and the variance in Cognition explained by Speed was 51.30%. Of the Age-related variance in this cognitive factor, 54.27% was shared with Speed and 68.34% was shared with Vision and Hearing. Of the Vision and Hearing–related variance in cognitive factor, 53.02% was shared with Speed.

Summary of Results

We tested three groups of models that aimed to evaluate whether a single mediational factor could explain the relationship between Age and Cognition. The first group of analyses showed that the common factor model fitted the data well but that a model including a unique effect of Age in addition to sensory function provided the best fit. Nearly 80% of the Age-related variance in Cognition was shared with sensory function. The second group of analyses evaluated the role of Speed as a mediator of the effect of sensory function and Age on Cognition. Additional paths from Age to Cognition and Hearing to Cognition improved the fit of this model significantly, indicating that Speed did not mediate all the Age-related and Hearing-related variance in Cognition. A third group of models was tested in which Speed mediated the effect of Age on both sensory and cognitive function. These models showed that additional direct paths from Age to Vision, Age to Hearing, and Age to Cognition were significant. This indicates that a significant proportion of the Age-related variance in Vision, Hearing, and Cognition was not mediated by Speed. Compared with Age and sensory function, Speed shared a larger total amount of total variance with Cognition (i.e., the factor that comprised Verbal and Memory). However, of the total age-related variance in Cognition, a larger proportion was shared with sensory function than with Speed.

Discussion

We used structural equation modeling to identify a common factor underlying age differences in sensory function, processing speed, and cognition. Overall, the results of these analyses are consistent with those of Lindenberger and Baltes (1994) and support the view that a common factor explains most of the shared variance among cognition, age, speed, and sensory function. However, significant unique effects of age, speed, and sensory function were not shared, indicating that small, unique effects of these factors must be accounted for in theoretical accounts of the relationships among these variables. The finding of unique effects of age and sensory function in the present study, which were not present in the Lindenberger and Baltes study, is likely due to the much larger sample size and smaller cognitive test battery we used.

The cognitive battery in the present study was limited by the small number of test items on some of the verbal tasks, the single indicator of speed, and the limited number of cognitive factors represented. This was a result of time limitations placed on the cognitive component of this large epidemiological study. Although the DSS is a well validated measure and widely used in cognitive aging research (Salthouse, 1992b), additional of indicators of speed would have improved the measurement of this construct for use in structural equation modeling. Nevertheless, speed was retained as a separate factor in this study because of the important role that it has had historically as a mediator in cognitive aging research. Because of the limited number of cognitive factors represented in this study, analyses involving speed were conducted on a cognitive factor comprised only of verbal and memory factors. Verbal did not have a strong association with age, which reduced the proportion of age-related variance in the cognitive factor. Previous analyses of these data have also shown that age remains a significant predictor of memory after control of cognitive and noncognitive variables (Luszcz et al., 1997). It may be that memory does not have as strong a connection with sensory function as do measures of general cognitive ability reported in other studies (Anstey & Smith, 1999; Baltes & Lindenberger, 1997). This may be due to age-related differences in strategy use being present on memory tasks but not present on tasks of spatial and verbal abilities (e.g., Moshe & Craik, 1996).

In the present study, sensory function explained more age-related variance in cognition than that explained by speed, even though speed explained more of the total variance in cognition than sensory function. These results are consistent with those of Lindenberger and Baltes (1994) in showing that at the statistical level, sensory function is equally, if not more, important than speed as a mediator of age-cognition relations.

The measures of hearing did not include the highest frequencies, 6 and 8 kHz. These highest frequencies are known to be unreliable (Hickling, 1966), and the measurable rate of change in the very old is greater in the speech range (0.5–2 kHz) frequencies because of loss of hearing in the highest frequencies (Brant & Fozard, 1990). If age differences in cross-sectional patterns of hearing can be inferred from longitudinal patterns of hearing changes in old age, it is unlikely that the lack of these highest frequencies resulted in a significant reduction in the size of the association between hearing and age. Consequently, not including these frequencies would not reduce the likelihood of finding support for the common cause hypothesis.

The limitations of the sensory and cognitive test battery are somewhat compensated by the large sample used in this study in that the study had a larger statistical power. This increased statistical power also revealed unique effects of age and sensory function that may not emerge in a smaller sample. Readers should therefore consider the size of the effects found in the present study when considering the importance of the findings.

Compared with results reported by Lindenberger and Baltes (1994), we did not find that as large a proportion of the age-related variance in cognition was explained by speed, although the general results were replicated. It is likely that the discrepancy in the effect sizes between studies is due to the fact that in the present study the cognitive factor examined in relation to speed comprised only verbal and memory tasks, whereas in the BASE study the cognitive factor included measures of reasoning, memory, knowledge, and fluency.

The results of the models involving speed as a mediator also provide some evidence that the relationship between sensory and cognitive function in old age is not fully explained by age and is therefore not spurious. An independent effect of hearing on cognition was observed that was not mediated by speed.

Altogether these results present a complex picture of the relationships among sensory and cognitive function. It is possible that a common factor representing general age-related changes in neurophysiological integrity, along with specific age-related and sensory-related factors, contributes to individual differences in cognitive performance in very old adults. The specific factors may relate to both test taking and cognitive processing. Possible specific causes of sensory effects on cognition include age-related changes in sense organs and the effects of disease on specific parts of the brain.

Another possibility raised by our results is that different relationships pertain between memory and sensory function, compared with other general cognitive abilities and sensory function. Further research is required to determine whether specific disease processes are responsible for these specific relationships and whether a decline in both cognitive and sensory aging is indicative of pathological aging. At this stage we still do not know if changes in specific sensory abilities indicate changes in specific cognitive abilities.

Most of the research conducted in this field has used only threshold measures of sensory function. It is possible that other measures and methods, such as sensory discrimination tasks and signal detection analysis, may provide useful approaches to understanding the specific relationships among these factors. Sensory and cognitive performance in old age is also influenced by a number of contextual factors not included in the models presented here (Anstey & Smith, 1999; Luszcz, 1998). Researchers must conduct longitudinal and experimental analyses of the relationships among sensory and cognitive function to test and develop further hypotheses about the general versus specific nature of the effects of sensory function on cognition in old age.

Acknowledgments

This study was partly funded by a National Health and Medical Research grant (No. 987100). We thank Ulman Lindenberger for his comments on the manuscript, and we gratefully acknowledge the assistance of all the men and women who participated in this study and of the Centre for Ageing Studies, under the direction of Professor Gary Andrews, for coordinating data collection and management.

Address correspondence to Kaarin Anstey, Prince of Wales Medical Research Institute, Barker St., Randwick, 2031, Australia. E-mail: k.anstey @unsw.edu.au

References

Anstey, K. J. (1999). Sensorimotor variables and forced expiratory volume as correlates of speed, accuracy and variability in reaction time performance in late adulthood. *Aging, Neuropsychology and Cognition, 6*, 84–95.

Anstey, K. J., Lord, S. R., & Williams, P. (1997). Strength in the lower limbs, visual contrast sensitivity and simple reaction time predict cognition in older women. *Psychology and Aging, 12*, 137–144.

Anstey, K. J., & Smith, G. A. (1999). Interrelationships among biological markers of aging, health, activity, acculturation and cognitive performance in late adulthood. *Psychology and Aging*, *14*, 605–618.

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., & Lindenberger, U. (1997). Emergence of a powerful con-

nection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology and Aging, 12*, 12–21.
Bentler, P. M. (1995). *EQS structural equations program manual.* Encino, CA: Multivariate Software, Inc.
Birren, J. E. (1965). Age changes in speed of behavior: Its central nature and physiological correlates. In A. T. Welford & J. E. Birren (Eds.), *Behavior, aging and the nervous system* (pp. 191–216). Springfield, IL: Thomas.
Bors, D. A., & Forin, B. (1995). Age, speed of information processing, recall, and fluid intelligence. *Intelligence, 20*, 229–248.
Brant, L., & Fozard, J. L. (1990). Age changes in pure tone hearing thresholds in a longitudinal study of normal human aging. *Journal of the Acoustical Society of America, 88*, 813–820.
Bryan, J., & Luszcz, M. A. (1996). Speed of information processing as a mediator between age and free recall performance. *Psychology and Aging, 11*, 3–9.
Christensen, H., Mackinnon, A., Jorm, A. F., Henderson, A. S., Scott, L. R., & Korten, A. E. (1994). Age differences in interindividual variation in cognition in community-dwelling elderly. *Psychology and Aging, 9*, 381–390.
Crawford, J. R. (1992). Current and premorbid intelligence measures in neuropsychological assessment. In J. R. Crawford, D. M. Parker and W. W. McKinlay (Eds.), *A handbook of neuropsychological assessment* (pp. 21-49). East Sussex, England: Erlbaum.
Cunningham, W. R. (1980). Age comparative factor analysis of ability variables in adulthood and old age. *Intelligence, 4*, 133–149.
Cunningham, W. R., & Birren, J. E. (1980). Age changes in the factor structure of intellectual abilities in adulthood and old age. *Educational and Psychological Measurement, 40*, 271–290.
Dickinson, C. M., & Rabbitt, P. M. A. (1991). Simulated visual impairment: Effects on text comprehension and reading speed. *Clinical Vision Science, 6*, 301–308.
Hickling, S. (1966). Studies on the reliability of auditory threshold values. *Journal of Auditory Research, 6*, 39–46.
Horn, J. L. (1987). A context for understanding information processing studies of human abilities. In P. A. Vernon (Ed.), *Speed of information processing and intelligence* (pp. 201–238). Norwood, NJ: Ablex.
Li, S.-C., Jordanova, M., & Lindenberger, U. (1998). From good senses to good sense: A link between tactile information processing and intelligence. *Intelligence, 26*, 99–122.
Lindenberger, U., & Baltes, P. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging, 9*, 339–355.
Lindenberger, U., Mayr, U., & Kliegl, R. (1993). Speed and intelligence in old age. *Psychology and Aging, 8*, 207–220.
Lindenberger, U., & Potter, U. (1998). The complex nature of unique and shared effects in hierarchical linear regression: Implications for developmental psychology. *Psychological Methods, 3*, 218–230.
Lindenberger, U., Scherer, H., & Baltes, P. B. (1999). *The strong connection between sensory and cognitive performance in old age: Not due to sensory acuity reductions operating during cognitive assessment*. Manuscript submitted for publication.
Luszcz, M. A. (1998). A longitudinal study of psychological changes in cognition and self in late life. *Australian Educational and Developmental Psychology, 15*, 39–61.
Luszcz, M., Bryan, J., & Kent, P. (1997). Predicting episodic memory performance of very old men and women: Contributions from age, depression, activity, cognitive ability and speed. *Psychology and Aging, 12*, 340–351.
Mack, W. J., Freed, D. M., Williams, B. W., & Henderson, V. W. (1992). Boston Naming Test: Shortened versions for use in Alzheimer's disease. *Journal of Gerontology: Psychological Sciences, 47*, P154–P158.
Moshe, N.-B., & Craik, F. I. M. (1996). Effects of perceptual and conceptual processing on memory for words and voice: Different patterns for young and old. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 49A*, 780–796.
Nelson, H. E. (1982). *National Adult Reading Test (NART).* Berkshire, England: NFER–Nelson.
Nettelbeck, T., & Rabbitt, P. M. A. (1992). Aging, cognitive performance and mental speed. *Intelligence, 16*, 189–205.
Piccinin, A., & Rabbitt, P. M. A. (1999). Contribution of cognitive abilities to performance and improvement on a substitution coding task. *Psychology and Aging, 14*, 539–551.
Roberts, R. D., Stankov, L., Pallier, G., & Dolph, B. (1997). Charting the cognitive sphere: Tactile-kinesthetic performance within the structure of intelligence. *Intelligence, 25*, 111–148.
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.
Salthouse, T. A. (1992a). *Mechanisms of age-cognition relations in adulthood.* Hillsdale, NJ: Erlbaum.
Salthouse, T. A. (1992b). What do adult age differences in Digit Symbol reflect? *Journal of Gerontology: Psychological Sciences, 47*, P121–P128.
Salthouse, T. A. (1996). General and specific speed mediation of adult age differences in memory. *Journal of Gerontology: Psychological Sciences, 51B*, P30–P42.
Salthouse, T. A., Hambrick, D. Z., & McGuthry, K. E. (1998). Shared age-related influences on cognitive and non-cognitive variables. *Psychology and Aging, 13*, 486–500.
Salthouse, T. A., Hancock, H. E., Meinz, E. J., & Hambrick, D. Z. (1996). Interrelations of age, visual acuity, and cognitive functioning. *Journal of Gerontology: Psychological Sciences, 51B*, P317–P330.
Stankov, L. (1986). Age-related changes in auditory abilities and in a competing task. *Multivariate Behavioral Research, 21*, 65–76.
Wechsler, D. (1981). *Wechsler Adult Intelligence Scale–Revised manual.* New York: Psychological Corporation.

Received October 7, 1998
Accepted June 5, 2000
Decision Editor: Toni C. Antonucci, PhD