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Evaluating the Interdependence of Aging-Related Changes in Visual and Auditory Acuity, Balance, and Cognitive Functioning

Scott M. Hofer
Pennsylvania State University

Stig Berg
University College of Health Sciences

Pertti Era
University of Jyväskylä

High proportions of shared age-related variance are found among measures of perceptual acuity, balance, muscle strength, and cognitive capabilities in age-heterogeneous, cross-sectional studies. Reliance on cross-sectional studies is problematic, however, because associations may arise from age-related mean trends. Narrow age-cohort samples provide an alternative basis for testing hypotheses regarding associations among rates of change. Cross-domain associations were evaluated in combined 75-year-old cohort samples from Denmark, Finland, and Sweden. In general, no consistent associations were found across sensory, balance, strength, and cognitive domains. These findings indicate that the effects of aging on sensory acuity, balance, and cognitive functioning are likely to be largely independent, multidimensional, and complex at the level of the individual.

A major focus of cognitive aging research is the description and explanation of aging-related changes in cognitive capabilities. While it is well known that longitudinal studies are required for understanding within-person changes over time, empirical generalizations and theories of cognitive aging (e.g., general slowing hypothesis, common-cause hypothesis) have been based almost exclusively on results from cross-sectional samples varying widely in age. One such example, cited in a recent report, *The Aging Mind*, by the National Research Council (2000) is the link between cognitive, sensory, and motor changes with age. A general conclusion from many studies, reviewed later, is that the majority of *age-related variance* in cognitive abilities is accounted for by age-related differences in sensory–motor functioning. Several explanations for understanding this finding have been proposed (e.g., Lindenberger & Baltes, 1994, 1997; National Research Council, 2000)—including (a) decline in sensory–motor functioning causes cognitive decline, (b) cognitive decline causes decline in sensory–motor performance, (c) unknown "third" variables produce the age changes in both sensory–motor and cognitive functioning, and (d) a "common cause" of brain aging produces declines in sensory, motor, and cognitive capabilities. This latter hypothesis regarding common cause has become a dominant theme in current cognitive aging research. There are, however, additional alternative explanations for the sensory–cognitive link that include operational confounds of sensory measures with cognitive tests; long-term influences of socioeconomic status (SES), health, and nutrition; short-term effects of health-related decline in older populations (i.e., terminal decline); and inferential problems that result from reliance on cross-sectional studies of variables that exhibit age-related mean differences. This article emphasizes this last explanation with the understanding that each alternative explanation may account for only a proportion of the observed population covariance among these functions and perhaps only for particular subsamples of the population.

Our central thesis is that high levels of shared chronological age-related variance, as is typically found in cross-sectional studies of physiological and cognitive capabilities, do not necessarily provide information about associations among rates of aging. Rather, covariance in age-heterogeneous, cross-sectional studies is highly confounded and is, at least in part, a product of age-related mean trends in the population. By definition, each age-related variable exhibits differences—on average—across individuals varying in age. In cross-sectional analysis, these population-level mean differences will alone produce associations among variables, observed as shared age-related variance, even when the variables are causally independent in regards to aging-related changes that occur within individuals. This poses a substantial problem for the evaluation of aging-related causal hypotheses that rely on typical cross-sectional analyses as all chronological age-related variables will exhibit some degree of association with one another. In terms of covariance among age-related processes, cross-sectional, age-heterogeneous designs are the most confounded of all study designs because population-level, age-related mean differences con-

Scott M. Hofer, Department of Human Development and Family Studies, Pennsylvania State University; Stig Berg, Institute of Gerontology, University College of Health Sciences, Jönköping, Sweden; Pertti Era, Department of Health Sciences, University of Jyväskylä, Jyväskylä, Finland.

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Correspondence concerning this article should be addressed to Scott M. Hofer, Department of Human Development and Family Studies, 110 South Henderson Building, Pennsylvania State University, University Park, Pennsylvania 16802. E-mail: smh21@psu.edu

tribute to the covariance in addition to covariance that is due to initial individual differences and covariation among rates of change. This will typically result in severe confirmatory bias in terms of *shared age-related variance* because time-related mean differences occur in most variables of interest to researchers investigating developmental or aging phenomena.

An alternative to the age-heterogeneous, cross-sectional design involves the study of associations within narrow age-cohort (NAC) samples. Assuming individual differences in rates of aging, correlated rates of aging across variables will produce increasing associations among variables as they are observed across subsequent slices of time, with increasing levels of association in older and older age-cohort samples. Indeed, increasing correlations are a function of time, as the effects of aging (rates of change) will have had longer opportunity to influence and "reorganize" individual differences at cross section that become more and more in accord with individual differences in rates of aging. This mechanism of correlated individual change might drive differentiation in childhood (caused by differential rather than common rates of change) and dedifferentiation later in the adult life span (e.g., Balinsky, 1941; Garrett, 1946; Reinert, 1970), in which a common aging-related mechanism for changes occurring across systems of variables is presumed. The evaluation of cross-sectional studies of NAC samples is not a substitute for within-individual (longitudinal) analysis of associations among trajectories of change. However, the analysis of NAC samples permits an alternative approach to understanding aging-related associations by using existing cross-sectional data without the positive bias related to population-level mean trends in the more typical age-heterogeneous, cross-sectional designs.

In this examination of theoretical and methodological issues related to understanding common and specific causes of aging-related changes, we review the evidence for the sensory–cognitive link; describe in greater detail the assumptions, limitations, and strengths associated with age-heterogeneous and age-homogeneous cross-sectional designs; and present evidence regarding the independence of aging effects across sensory, motor, and cognitive domains. A cohort study of 75-year-old individuals assessed with laboratory measures of auditory and visual acuity, balance, muscle strength, and cognitive functioning was used.

Associations Between Physiological and Cognitive Functioning

Measures of sensory acuity have long been considered useful as indicators of functional age (see Anstey, Lord, & Smith, 1996), and there have been numerous studies on the association between sensory acuity, motor function, and cognition. Table 1 lists several of the characteristics and general outcomes of studies that have examined associations between physiological, sensory, and cognitive capabilities. Although researchers have approached the question with different methodological designs and interpretations of the findings, nearly all of the evidence for associations among these domains has been based on cross-sectional analysis of individuals varying broadly in age. While the types of statistical analyses vary across studies, the emphasis is typically on the covariance (correlation) and includes (a) direct inspection of correlations, (b) inspection of patterns of correlations across independent age groups, (c) evaluation of correlations after controlling for age-related variance, and (d) use of multiple regression or factor models to estimate direct and indirect effects and the proportion of age-related variance across measures. In several studies, researchers emphasized the operational dependency of cognitive performance on sensory acuity with the potential for underestimating the level of functioning in individuals with reduced sensory acuity (e.g., Granick, Kleban, & Weiss, 1976; Ohta, Carlin, & Harmon, 1981; Snyder, Pyrek, & Smith, 1976). These studies called into question the results from gerontological studies in which visual and auditory acuity were not measured and controlled. More recently, interpretations of associations across sensory and cognitive domains have focused on shared age-related variance and common factor models, with the general result that a common aging factor accounts for a broad spectrum of age-related declines in functioning with relatively few or weak specific effects of chronological age (e.g., Christensen, Mackinnon, Korten, & Jorm, 2001; Salthouse & Czaja, 2000; Salthouse, Hambrick, & McGuthry, 1998; but see Allen et al., 2001).

Clearly, questions regarding the association among sensory–motor and cognitive variables are important for predicting gerontologically relevant outcomes, in which the emphasis is less on causal pathways than on prediction of age-related differences in functional ability. For example, many studies have focused on the age-related changes of balance and gait for clinical and therapeutic purposes (Alexander, 1994; S. R. Lord, Clark, & Webster, 1991b; Tinetti, 1986; Tinetti & Ginter, 1988). Abnormality in maintaining balance is a major risk factor for falling in older adults (see Alexander, 1994), and there is unanimity among researchers that maintaining balance is essential to carrying out daily tasks without falling (Alexander, 1994; Lajoie, Teasdale, Bard, & Fleury, 1996; Shumway-Cook & Woollacott, 1995; Tinetti, 1986). Movement of the body or a segmental movement, even in very simple daily tasks, depends on some degree of balance or movement control (Kreighbaun & Barthels, 1996). S. R. Lord, Clark, and Webster (1991a), S. R. Lord and Ward (1994), and Alexander (1994) found, in a comprehensive review of the literature, that many age-associated differences on sensory tests (visual acuity, somatosensory thresholds, and vestibular function) are interrelated and may predict falls and balance. In a study of 550 women ranging from 20 to 85 years and over, S. R. Lord and Ward found the static balance contribution made by vision increased up until the age 65–69 years old before declining. The contribution by vestibular sense declined linearly, while the contribution by peripheral input, when participants were tested with eyes closed and different conditions of the standing surface, increased with age. These studies demonstrate that peripheral visual acuity is important for the control of posture (e.g., S. R. Lord & Ward, 1994) but does not account for all of the individual differences in postural stability (S. R. Lord & Menz, 2000).

However, in many of the studies listed in Table 1, the emphasis is on chronological age as an independent variable and the degree to which the association with chronological age is "shared" across variables. These studies typically utilize variance decomposition models—such as common factor analysis, mediation models, or commonality analysis—to describe the proportions of variance any one variable has in common with chronological age and with other variables. In studies focused on understanding individual differences in cognitive aging, age-related variance in measures of visual and auditory acuity, balance, gait, and aspects of cognitive

functioning in middle and late adulthood has been reported to be largely or totally shared. Lindenberger and Baltes (1994) reported that visual and auditory acuity and balance account for most of the age-related variance in general cognitive functioning. These findings were further replicated in a larger sample of older adults over 70 years of age and in a sample of younger adults between 25 and 69 years old (Baltes & Lindenberger, 1997). In addition, these findings were extended to measures of activities of daily living and have been shown to account for most of the age-related variance (Marsiske, Klumb, & Baltes, 1997). Table 1 contains numerous recent studies that reach similar conclusions as well as other studies showing that while a majority of age-related variance is shared, the mediation of age-related variance is not total. Several studies simply report the association between sensory and cognitive variables, whereas a number of studies report associations between sensory and cognitive measures in young adulthood and may be interpreted as evidence for stable individual differences at earlier periods in the life span (e.g., Li, Jordanova, & Lindenberger, 1998; Roberts, Stankov, Pallier, & Dolph, 1997).

The general finding of common age-related associations across a diverse set of sensory, motor, strength, and cognitive functions is limited by the reliance on age-heterogeneous, cross-sectional designs. Studies of relatively NAC samples, which do not have the potential confounding influence associated with average age differences, have reported relatively weak relationships across sensory and cognitive domains (e.g., Era, 1987; Era, Jokela, & Heikkinen, 1986) or exhibit reduced associations when the age range is restricted (Salthouse et al., 1998). For example, Era et al. examined associations between simple and choice reaction time, vibrotactile threshold, postural sway, isometric strength (e.g., grip strength, knee extension velocity), visual acuity (e.g., dark adaptation, lens accommodation), and auditory acuity (pure-tone audiometry) in groups of men aged 31–35, 51–55, and 71–75, with the finding of relatively few substantively significant associations across domains. Several studies have attempted to look for differences in magnitude of association at different periods in the life span by using multiple-group strategies. Lindenberger and Baltes (1994) found similar and moderate magnitudes of association in groups aged 70–84 and 85–103. Salthouse et al., in one of several studies reported, examined a common factor model of cognitive and noncognitive variables across two subsamples aged 18–49 and 50–88. In this subgroup analysis, grip strength and systolic blood pressure were no longer significantly related to the common factor through which chronological age had an effect and most of the common factor loadings were reduced compared with the analysis of the full sample. In general, the magnitudes of associations between sensory and cognitive variables were reduced in samples with restricted age ranges, as is the usual case with analyses that partial or control for age-related variance.

A major source of confound for the interpretation of covariances or shared age-related variance in results derived from age-heterogeneous samples is that of population mean differences—which, by definition, age-related variables exhibit. It must be regarded as less than optimal that theories of aging (and empirical generalizations) are based on results that partially reflect and may be entirely due to population-level mean trends. Although the limitations of cross-sectional methodology for understanding intraindividual aging-related changes have been well documented (e.g., Baltes & Nesselroade, 1979; Horn & Hofer, 1992; Schaie & Hofer, 2001), the potential for spurious associations among age-related variables in age-heterogeneous designs has not been as well recognized (but see Featherman & Petersen, 1986; Hofer & Sliwinski, 2001; Hofer, Sliwinski, & Flaherty, 2002; Kraemer, Yesavage, Taylor, & Kupfer, 2000; Wohlwill, 1970).

Methodological Issues in Examining the Dimensionality of Aging

Age-related variation is observed on a great many biological and psychological processes across both individuals varying in chronological age and individuals observed over long periods of time. Of central importance to gerontological researchers is the structure (i.e., interrelatedness) of these observations, with emphasis on the relative independence or interdependence of such aging-related processes within the population and within the individual. Indeed, whether causal pathways of aging are few or many and whether outcomes share the same aging-related cause or pattern of change are motivating questions for life-span researchers. Such evidence can lead to the development of a hierarchical organization of related aging-dependent outcomes and indicate the potential points in the process in which interventions might have the strongest effect.

Experimental designs are, or course, required to test causal associations but have obvious limitations for research on aging. Longitudinal designs are most useful and permit quasi-experimental evaluation of individual rates and patterns of aging, associations among rates of aging across different outcomes, and predictors of initial status and change, as well as other dynamic models. However, the design most often used for understanding associations among age-related variables is the cross-sectional study based on age-heterogeneous samples. As introduced previously, cross-sectional designs can take the form of a sample varying broadly and continuously in age or can be based on relatively narrow age groups (e.g., comparison of samples of young and old individuals). The following section describes cross-sectional analysis from the perspective of sampling from within-individual trajectories—a natural approach for understanding the properties of cross-sectional designs and analysis because such designs often serve as a proxy for investigating change within individuals.

Age-Heterogeneous, Cross-Sectional Designs

The study of individual differences as they relate to chronological age in the cross-sectional analysis has taken several forms. In terms of the substantive questions of interest here, analyses have been driven by a particular statistical methodology, namely, *commonality analysis* (e.g., Lindenberger & Potter, 1998; Luszcz & Bryan, 1999; Pedhazur, 1997; Sliwinski & Hofer, 1999), and may take the form of mediation or common factor models. These models permit the examination of common and specific sources of between-person difference variances associated with chronological age. Commonality analysis typically relies on a linear regression approach to examine the *shared* age-related variance across variables—using chronological age as an individual differences variable. The concern of such analysis is the amount of overlap in age-related variance that one variable shares with another, interpreted as *explained* age-related variance. Many studies, reported in

Table 1
Studies of Associations Between Physiological and Cognitive Functioning in Adulthood

Reference	Sample size	Age range	Cognitive measures	Physiological measures	General outcome
Clark (1960)	102	20–70	Thurstone's PMA Reasoning and Space tests, Perceptual Speed, RT	Near visual accommodation distance, grip strength, auditory threshold, and blood pressure	Weak-to-moderate associations among cognitive and physiological measures; PMA tests and visual accommodation showed 50–60% shared age-related variance (see Salthouse, Hancock, Meinz, & Hambrick, 1996)
Schaie, Baltes, & Strother (1964)	24 M 23 W	70–88	Thurstone's PMA tests	Auditory acuity	Moderate association in men, weak association in women
Heron & Chown (1967)	300 M 240 W	20–79	Raven's Progressive Matrices	Visual acuity	31% (men) and 46% (women) shared age-related variance (see Salthouse et al., 1996)
Birren, Botwinick, Weiss & Morrison (1971)	47 M	65–91	WAIS, Raven's Progressive Matrices, Digit Span	Auditory acuity (best ear, 2000 Hz)	Nonsignificant weak-to-moderate associations
Dirken (1972)	316	30–70	RT, Digit Span, Concentration, Fluency, Visual Memory	Visual and auditory acuity, vital capacity, blood pressure, and grip strength	Age-related factors and associations across factors
Clement (1974)	2,033	16–96+	Vocabulary, Coding Speed	Grip strength	No consistent pattern of correlations observed across successive 5-year age groups
O'Neil & Calhoun (1975)	42	70+	Mental Status Evaluation	Visual and auditory acuity, tactile sensitivity	Significant associations across measures
Granick, Kleban, & Weiss (1976)	47 M 38 W	71.5 (4.8) 75.9 (5.3)	WAIS subscales, Raven's Progressive Matrices	Auditory acuity	Age-partial correlations demonstrate verbal/nonverbal distinction with auditory acuity
Gilhome-Herbst & Humphrey (1980)	253	70–85+	Mental State Exam	Auditory acuity	No association between deafness and dementia after age is controlled . . . "both are functions of age"
Ohta, Carlin, & Harmon (1981)	27	48–96	Mental Status Questionnaire	Auditory acuity	Correlations ranging from −.32 to −.65
Thomas et al. (1983)	259	60–89	Cognitive Screening Exam, Halstead Category Test, and WMS	Auditory acuity, Speech perception in noise test	Significant age-corrected correlations (~0.20) with verbal tests and nonsigificant correlations with nonverbal test (Halstead Category Test)
Dubina, Mints, & Zhuk (1984)	163	60–100	Short-term memory	Grip strength, vibrotactile sensitivity	Correlations with age between −.55 and −.76 and among one another, .49 and .55
Jones, Victor, & Vetter (1984)	657	70–85+	Functional Disability Scale, memory indicated by Mental Status evaluation	Three-item hearing difficulty scale	No significant association between hearing loss and memory; association between hearing loss and functional disability
Era, Jokela, & Heikkinen (1986)	176 188 183	31–35 51–55 71–75	Visual and Auditory RT, Tapping, and WAIS subscales	Auditory acuity, muscle strength, VO_2 max., postural sway, and vibration sensitivity	RT associated with balance, vibration sensitivity, and musclular force; covariates of RT included education and health
Era, Jokela, Qvarnberg, & Heikkinen (1986)	176 188 183	31–35 51–55 71–75	Simple and Choice Visual RT, Tapping, WAIS subscales	Auditory acuity, muscle strength, VO_2 max., postural sway	Significant mean differences across age groups with weak associations (e.g., avg. r = .13 with auditory acuity) within groups
Chodzko-Zajko & Ringel (1987)	70 M	40–84	Choice RT (easy/difficult discrimination)	Auditory acuity, lens accommodation, tactile sensitivity, forced vital capacity and volume	A derived index of physiological functioning was moderately associated with RT

Table 1 (*continued*)

Reference	Sample size	Age range	Cognitive measures	Physiological measures	General outcome
Sands & Meredith (1989)	247	40–61	WAIS and WAIS–R subscales	Physician rating for visual and auditory functioning, motor functioning	Hearing functioning predicts residual change in information and comprehension over an 8-year period; variability in change in other scales was not predicted.
Cook et al. (1991)	3,582	65+	Mental Status, Digit Span	PEF	Lower PEF associated with lower cognitive abilities
Anstey, Stankov, & Lord (1993)	100	65–91	Fluid Reasoning, Broad Visualization, Perceptual Speed, digit Span, Simple RT, Broad Auditory Ability	Strength, contrast sensitivity, visual acuity, proprioception, vibration sense, body sway	Age differences in sensory–motor functions predict age-related differences in cognition
Lindenberger & Baltes (1994)	156	70–103	Processing Speed, Reasoning, Memory, Knowledge, Word Fluency	Visual and auditory acuity, balance/gait	Visual and auditory acuity accounted for 49% of the total variance and 93% of the age-related variance in a cognitive factor
Era, Berg, & Schroll (1995)	1,365	75	Visual and Auditory RT	Bicycle ergometer	Fitness associated with RT although mixed levels of association were found among men and women, ranging from .06 to −.50
Finkel, Whitfield, & McGue (1995)	237 twin pairs	27–88	Processing Speed, WAIS–R subscales, WMS, Reasoning	Forced vital capacity and expiratory volume, blood pressure	Three factors (physiological, cognitive, and processing speed) accounted for 66% age variance
Era et al. (1996)	1,365	75	Simple and Choice RT	Balance (three conditions), visual and auditory acuity, and muscle strength	Balance was associated (11–13% explained variance) with visual acuity, low vibrotactile thresholds, and psychomotor speed
Salthouse et al. (1996)	77 127 197	18–80+ for all studies	Perceptual Speed, RT, Working Memory, Associative Learning, Wisconsin Card Sort	Corrected visual acuity	Visual acuity and RT share most of the age-related variance in working memory, associative learning and concept identification
Anstey, Lord, & Williams (1997)	202	60–86	Raven's Progressive Matrices, Picture Arrangment, Digit Span, Vocabulary	Muscle strength, RT, Visual contrast sensitivity	Low correlations (~.04–.30) across physiological and cognitive measures, strength, in addition to sensory acuity, accounts for significant proportions of shared age-related variance
Baltes & Lindenberger (1997)	315	25–101	Perceptual Speed, Reasoning, Knowledge, Memory, Word Fluency	Visual and auditory acuity	Visual and auditory acuity account for most of the shared age-related variance in a cognitive composite
Marsiske, Klumb, & Baltes (1997)	516	70–103	Everyday activity participation	Visual and auditory acuity, balance	Sensory variables explained all of the age-related variance in everyday activities
Li, Jordanova, & Lindenberger (1998)	179	30–51	Perceptual Speed, Reasoning, Knowledge, Memory, and Word Fluency	Tactile discrimination and pressure sensitivity, and visual and auditory acuity	Correlations with intellectual ability with tactile sensitivity (.18–.33), auditory acuity (.15), and visual acuity (.20)
Salthouse, Hambrick, & McGuthry (1998)	380	18–87	Perceptual speed, reasoning, memory, and spatial abilities	Visual acuity, grip strength, and blood pressure	Large proportion of shared age-related variance between cognitive and noncognitive variables; substantially reduced after controlling for age
Stevens, Cruz, Marks, & Lakatos (1998)	15 22	18–27 65–80+	Memory, Naming	Taste, smell, temperature, touch, and hearing acuity	Combined age group analysis yielded some low, but mainly moderate to high associations across cognitive and sensory measures

Table 1 (*continued*)

Reference	Sample size	Age range	Cognitive measures	Physiological measures	General outcome
Anstey (1999)	180 W	60–90	Visual and Auditory Simple and Choice RT	Visual and auditory acuity, grip strength, FEV, and vibration sense	Common factor related to age with evidence for differential effects across some measures
Anstey & Smith (1999)	180 W	60–90	Fluid Reasoning, Crystallized Knowledge, Spatial, Perceptual Speed, and Working Memory	Visual and auditory acuity, grip strength, blood pressure, and vibration sense	Substantial shared age-related variance with "biological age" factor but direct associations with age also significant
Kügler (1999)	289	18–98	Visual event-related P300 potentials, MMSE, Memory, and Attention	Corrected visual acuity	Visual acuity associated with P300 variability in addition to age
Sayer, Osmond, Briggs, & Cooper (1999)	717	64–74	Difference Score (Mill Hill vocabulary-AH4 reasoning)	Visual and auditory acuity, lens opacity, grip strength, skin thickness, number of teeth, and blood pressure	Correlations with age were weak (.04–.20); no associations among variables provided
Heuvelen, Kempen, Brouwer, & De Greef (2000)	409	65–91	MMSE, RT	Walking endurance, flexibility, grip strength, balance, manual dexterity, and ADL/IADL	Correlations of RT and MMSE with physiological variables ranging from .09–.39 and .00–.19, respectively
Anstey, Luszcz, & Sanchez (2001)	894	70–98	Memory, Processing Speed, Verbal	Distance and near visual acuity, auditory acuity	Common factor model did not fully mediate age differences: Specific associations with age were required for sensory and cognitive variables
Christensen, Korten, et al. (2001)	425	70–93	Crystallized Intelligence, Speed, Memory	Self-report sensory disability, and grip strength	Changes over 3.5 years in grip strength, speed, and memory moderately correlated
Christensen, Mackinnon, et al. (2001)	374	70–79	Memory, Processing Speed, Verbal, and Simple and Choice RT	Grip strength, visual acuity, forced expiratory volume, and blood pressure	Common factor accounted for age-related variance (though grip strength and visual acuity required separate age paths); Similar factor structure in narrow age subgroups
Dulay & Murphy (2002)	98 103	18–45 55–97	Verbal Learning, Vocabulary, Raven's Progressive Matrices, Trail-Making, Word Fluency	Olfactory acuity	Greater associations between olfactory and cognitive tests in older age group

Note. Studies are ordered by publication date. PMA = Primary Mental Abilities; WAIS = Wechsler Adult Intelligence Scale; RT = reaction time; WMS = Wechsler Memory Scale; PEF = peak expiratory flow; MMSE = Mini Mental State Examination; FEV = forced expiratory volume; ADL = activities of daily living; IADL = instrumental activities of daily living; M = men; W = women.

Table 1, have used this approach and have found substantial amounts of shared age-related variance (sometimes nearly 100%) accounted for by other variables, such as speed and working memory (e.g., Lindenberger, Mayr, & Kliegl, 1993; Luszcz & Bryan, 1999; Salthouse, 1992; Verhaeghen & Salthouse, 1997), and sensory functioning (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). Interestingly, the correlation among variables need not be high (and may be of relatively weak magnitude) for shared age-related variance to be high.

However, age-heterogeneous, cross-sectional designs are hardly conclusive regarding the dependence or independence of aging-related differences. The limitations of cross-sectional designs, as they are applied to understanding developmental processes, are well understood (e.g., Baltes & Nesselroade, 1979; Horn & Hofer, 1992; Kraemer, Yesavage, Taylor, & Kupfer, 2000; Pedhazur, 1997; Schaie & Hofer, 2001; Wohlwill, 1970). Nevertheless, cross-sectional studies, typically of broad age ranges, often serve as the basis for theory and hypothesis development, and these cautions and limitations regarding their use are often ignored. Numerous confounds can produce or attenuate covariance among age-related variables. Besides the well-known limitations associated with using chronological age-related differences as a proxy for age-related changes (e.g., age-cohort confound, differential selection), a major problem with this form of analysis is that associations may arise simply because of mean changes that occur, on average, in a population and not necessarily from associations among rates of aging within persons. Figures 1A and 1B show two variables, *X* and *Y*, that exhibit mean differences across two age

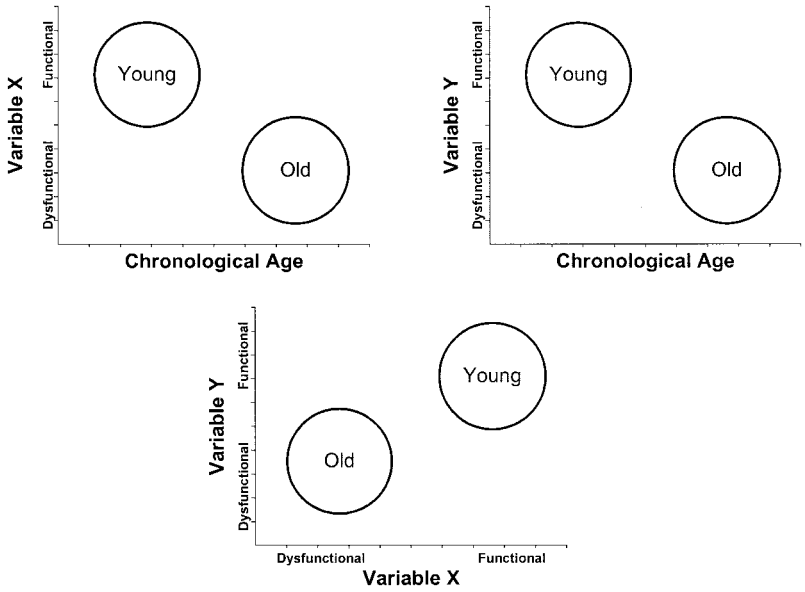

Figure 1. Association that is due to age-related mean differences in age-heterogeneous, cross-sectional samples.

groups (to simplify the diagram, we show only two groups, but a continuum of ages could be present). In these figures, associations within age groups are zero, and all that is present are mean differences across groups of individuals of the same chronological age. Figure 1C shows that under such conditions, the association between variables *X* and *Y* would be moderate to high and result solely from the mean differences across groups or individuals differing on age.

Hofer and Flaherty (2001; see also Hofer & Sliwinski, 2001; Hofer et al., 2002; Kraemer et al., 2000) demonstrated the confounding influence of mean trends on cross-sectional covariance. Hofer and Flaherty (2001) derived the age-heterogeneous, cross-sectional covariance based on a simple linear model (e.g., Laird & Ware, 1982) of two processes, *X* and *Y*, that are a function of their initial level (*L*) and rate of change (slope, or *S*) over time. This linear model is made up of both fixed (population averages, such as the group mean differences shown in Figure 1) and random (individual deviations about the average) effects for initial status and rate of change. The covariance derivation is shown to be a function of many different components involving the fixed and random effects of initial status and rate of change in both processes. To demonstrate the effects of mean trends on cross-sectional covariances, Hofer and Flaherty (2000; Hofer & Sliwinski, 2001) considered a situation in which two processes—*X* and *Y*—were independent, but both exhibited systematic average change over time (i.e., fixed age effects). Therefore, all terms involving individual differences (i.e., random effects: terms subscripted by *i*) were zero and were, therefore, dropped. This is essentially the example shown in Figure 1. With only fixed effects present, the covariance derivation simplifies to

$$Cov(X, Y) = S_x S_y t_i^2. \quad (1)$$

Equation 1 shows that covariance terms in age-heterogeneous, cross-sectional samples are a function of the magnitude of mean change or slope (S_x, S_y) in processes *X* and *Y* and the variance in age (t_i^2). This analytical demonstration shows that a nonzero covariance can arise solely from average age differences. Hofer and Flaherty (2000, 2001) showed, in a simulation study, that even when rates of aging within individuals are uncorrelated or negatively correlated, the association between *X* and *Y* will be strong and positive when mean trends are present and congruent in direction of change. We can infer from Equation 1 that stronger covariation will be observed in samples that vary broadly in age and when greater mean trends across particular periods of the life span are present (i.e., childhood, later adulthood).

The general problem associated with aggregating groups that differ, on average, on various attributes is known as the *ecological fallacy* (Goodman, 1953; Robinson, 1950), *Simpson's Paradox* (Mittal, 1991; Simpson, 1951; Thorndike, 1939; Yule, 1903), and a special case of Simpson's Paradox known as *Lord's Paradox* (F. M. Lord, 1967, 1969; Werts & Linn, 1969). Yule described this problem as one resulting in an "illusory association," derived from the pooling of distinct groups in which differences in the variables to be correlated were both associated with group status. In age-heterogeneous, cross-sectional studies, group status is age, and the attributes under study exhibit mean shifts across age. Spurious correlations resulting from between-individual differences are similar, in concept, to the problems of mean trends in time series analysis (e.g., Yule, 1921, 1926). In the previous section, we showed how covariances may result, at least in part, from the mean differences resulting from the aggregation of individuals of different ages. The result is a confounding of between-individual effects (fixed age effects) and within-individual effects (random age effects) in age-heterogeneous, cross-sectional analyses. Though this general problem is well known in particular areas of social science and statistics, limitations for developmental and gerontological studies have not been as well acknowledged (but see Hofer &

Sliwinski, 2001; Hofer et al., 2002; Kraemer et al., 2000; Storandt & Hudson, 1975; Vaupel & Yashin, 1985; Wohlwill, 1970).

The potential for spurious associations in cross-sectional studies of time-dependent phenomena is profound, and the resulting bias on cross-sectional results and conclusions from behavioral and biological studies of aging may be general. An alternative cross-sectional approach to understanding shared process is the analysis of NAC groups—an approach applied to single-age/single-cohort data, which can also involve a sequential analysis of NACs on the basis of existing age-heterogeneous, cross-sectional data. This design provides another window to view associations among aging-related changes without the confound resulting from mean trends (fixed age effects) in age-heterogeneous samples.

Age-Homogeneous, Cross-Sectional Designs

In the NAC analysis, we assume that there are individual differences in the rates of aging-related change such that individual differences in rates of aging will reorganize the initial (e.g., childhood, early adulthood) associations among levels of functioning. Over time, the initial individual differences will proportionally become a smaller component of the covariance. Given individual differences in rates of change, there will be a reordering of individuals relative to each other at any particular time that will increasingly reflect the associations among rates of change. For example, in an analysis of a 75-year-old cohort, we assume that aging within and across individuals has occurred and that the covariation of interindividual differences across domains will reflect covariation among rates of aging to a large degree. This type of evidence is related to the concept and method for evaluating differentiation and dedifferentiation, the finding of decreasing or increasing covariance in cognitive functions in childhood and adulthood, respectively (Balinsky, 1941; Cornelius, Willis, Nesselroade, & Baltes, 1983; Garrett, 1946; Reinert, 1970). The utility of this approach is expanded to include a broader spectrum of variables and has shown to be a useful alternative to age-heterogeneous designs for the evaluation of the interdependence of aging-related changes.

Hofer and Flaherty (2000; Hofer & Sliwinski, 2001) derived the covariance for an NAC sample on the basis of a simple linear model,

$$Cov(X,Y) = Cov(L_{xi}L_{yi}) + [t]Cov(L_{xi}S_{yi}) + [t]Cov(S_{xi}L_{yi}) + [t^2]Cov(S_{xi}S_{yi}). \quad (2)$$

The covariance of any single age-cohort group is shown to be a function of the covariance among initial levels, covariance between levels and slopes, and covariance related to rates of change. Covariance that is due to fixed effects will not be present because such effects will be constant within a fixed age sample. Equation 2 shows that as age (t) increases, the effect of the covariance among the rates of change in the processes increases quadratically (function of t^2 rather than t) and thus will increasingly overwhelm the contributions of the covariances involving the level and level–slope terms. The key concept motivating the use of the NAC design is that the covariance (e.g., rank order) across individuals of the same age will become more and more informative regarding the associations among rates of change (covariance among slopes) in old and older samples and that average population change will not enter into the estimate of association.

Therefore, the expected outcome in this study is that at least moderate associations across sensory and cognitive domains will be observed in later adulthood if aging has a common effect on these different systems (i.e., the rates of change are associated). A common-cause aging influence will produce associations among interdependent variables or processes that are hierarchically organized and mutually dependent on lower order functions. Of course, in a single age-homogeneous sample, associations across domains may be due to initial individual differences in addition to correlated rates of aging. However, because covariance in a single age-cohort group can arise from two sources—initial level of functioning and rates of change—it would only be in the unlikely case that rates of change cancel the initial individual differences such that no covariance would be observed in an older sample of individuals. Comparison of sequential narrow age-cohort (SNAC) samples, shown in Figure 2, can provide further evidence as to whether the associations among domains of variables increase or decrease across samples of subsequently older ages (representing greater elapsed time). The analysis of multiple NAC samples permits a distinction to be made regarding covariance among rates of change from that of initial covariance. Evidence of associations across sensory and cognitive domains from either the NAC or the SNAC design would provide further evidence that common aging influences were producing a reordering of individual differences.

The NAC design offers several advantages over the age-heterogeneous, cross-sectional analysis but retains other limitations of cross-sectional designs (Hofer & Sliwinski, 2001; Li & Schmiedek, 2002). The single NAC design, nevertheless, provides stronger evidence for dissociation of aging effects than analysis of age-heterogeneous, cross-sectional samples. In other words, finding weak or no associations among age-related variables in a single NAC design would serve as evidence for the relative independence of aging-related changes as it would be unlikely that initial indi-

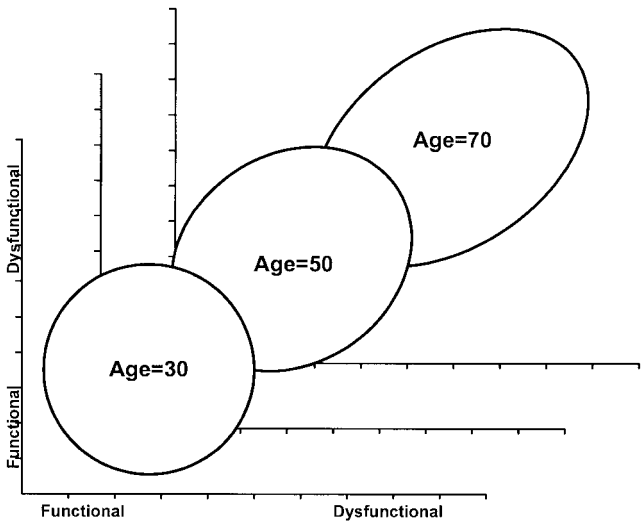

Figure 2. Expectations for increasing associations between two age-related processes across narrow age-cohort samples assuming common aging effects.

vidual differences would be completely cancelled by differences in rates of aging.

Purpose of this Study

The general aim of this study was to examine the interdependence between aging-related changes in cognition, sensory acuity, balance, and presumably more distal measures of physiological aging processes. This study, based on data from an international collaborative research project on functional aging in 75-year-old cohort samples, will permit evaluation of the perceptual–cognitive link hypothesis from the NAC perspective in individuals of advanced age.

The inclusion of age-related markers that are theoretically independent or distal to the outcome variables provides an important test of discriminant validity. We regard this as essential—particularly for studies of multiple causes in which results might be overly influenced by particular methodological or statistical methods and assumptions. Therefore, in addition to measures of sensory acuity and balance measures, markers considered to be more distal to potential effects of brain aging (e.g., grip strength, knee extension, number of teeth) were included. If the effects of aging on the central nervous system are simple and global, our expectations are the following:

1. Moderate-to-strong correlations ($r > .30$) will be observed across all sensory measures (visual acuity, auditory acuity, balance) and at least moderate associations will be observed across all sensory measures and all cognitive measures (regardless of the primary sensory domain required by the cognitive test).

2. Age-related markers considered distal to the common-cause, brain-aging hypothesis (i.e., number of teeth) will show no reliable association with either sensory or cognitive markers.

If no consistent associations across the perceptual and cognitive domains are found, the results will be in concordance with an independent aging effects hypothesis, suggesting different rates and patterns of aging across sensory, motor, and cognitive domains. These patterns, of course, may include individuals in which common aging influences are producing declines among all functions; whereas in others, one particular domain of functioning may show greater decline over another and, perhaps, as a result of different aging-related causes. Sensory and cognitive systems of variables may also appear to overlap, but primarily in terms of operations required to perform the task, and so indicate peripheral involvement. Operationally, but not causally, the effects of aging or time (exposure) on particular sensory systems will appear as declines in cognitive performances that rely on a particular sensory domain. For example, we would expect to see visual acuity and grip strength to be more highly associated with the Digit Symbol Substitution test because visual processing and motor coordination are required to perform this speeded task. Health-related and SES factors may also influence (or have been influenced) by level of functioning and, therefore, have effects on individual differences in functioning across the life span. If the rates of change were related to lifelong nutrition and health-related factors (e.g., Abrahams, 1976), rather than to more specific aging-related changes in the central nervous system, we would expect moderate relationships between the noncognitive physiological markers (muscle strength, number of teeth) and cognitive performance.

Method

Participants

The Nordic Research on Aging Study (NORA; Schroll, Steen, Berg, Heikkinen, & Viidik, 1993; Heikkinen, Berg, Schroll, Steen, & Viidik, 1997) is a comparative study on functional capacity and health in 75-year-old men and women. Population-based random samples of 75-year-old residents were obtained in Glostrup, Denmark, and Gothenburg, Sweden. An invitation to participate was given to all residents of Jyväskylä, Finland. The participation rates for the targeted samples were high: Jyväskylä, Finland ($n = 355$; 93%); Gothenburg, Sweden ($n = 368$; 83%); and Glostrup, Denmark ($n = 481$; 85%). For further details of the sample, see Era et al. (1996). The total sample size available for this study was 1,041 and was based on the following sample sizes: Jyväskylä ($n = 309$), Gothenburg ($n = 322$), and Glostrup ($n = 410$). There were 445 men and 596 women in the study. The rates of glaucoma, cataract, and macular degeneration were 9.6%, 25.4%, and 5.8%, respectively. Subsample analysis excluding individuals with these medical conditions is described below.

Measures

Visual acuity. Corrected and uncorrected visual acuity for the right and left eye were obtained using a computerized refractometer (Topcon RM-A2300). Composite scores were derived using the average of right and left vision scores and were used in all analyses. As measures of true functional aging, uncorrected visual and auditory acuity should be used. However, corrected vision and hearing should be used for evaluating associations with cognitive tests so as not to confound performance with peripheral changes in sensory acuity. Corrections to visual acuity may also depend on appropriate and up-to-date prescriptions and potentially be related to SES. Both corrected and uncorrected vision scores were used in this study to evaluate the differential effects on cognitive performance.

Auditory acuity. Air-conducted auditory pure-tone thresholds (dB) were measured using clinical audiometers in soundproof rooms. Thresholds were measured for both ears at each of seven standard frequencies: 0.125, 0.25, 0.50, 1.00, 2.00, 4.00, and 8.00 kHz. These thresholds were combined to form low (0.25 kHz), middle (0.50, 1.00, and 2.00 kHz), and high (4.00 and 8.00 kHz) composite threshold scores. The 0.125 frequency threshold was not obtained in Gothenberg and was omitted from the composite scoring for all samples. The portion of the sample with hearing aids was 9.4% ($n = 111$).

Balance. Balance was assessed under two conditions of body sway: (a) normal standing, eyes open and (b) normal standing, eyes closed (Era et al., 1996). Measurements of direction (*x*-path, mm; *y*-path, mm) and speed (*x*-speed, mm/s; *y*-speed, mm/s) were obtained to allow computation of mean velocity and area of movement. The *x*- and *y*-speeds were used to operationalize the measure of balance. Height was positively correlated with body sway and was partialed from the balance scores prior to all analyses.

Cognitive ability. The Wechsler Adult Intelligence Scale—Revised (WAIS–R; Wechsler, 1986) Digit Symbol test requires the transcription of digit–symbol codes to a series of symbols. The number of correct responses within 90 s was used in all analyses. Raven's Progressive Matrices (Raven, 1960) is a test of inductive reasoning that requires comparison and logical reasoning to complete a matrix of figures. A 5-min limit was imposed. The Word Fluency Task (Dureman & Salde, 1959) requires the participant to produce as many words as possible within a 3-min time limit. The words must begin with the letter *K* in Finland and the letter *S* in Denmark and Sweden (based on common word frequencies). The number of correct responses (without repetitions) was scored. The Digit Span Forward test (Wechsler, 1986) involves the reproduction of a series of verbally presented digits. The number of digits presented increases until two successive failures. The Digit Span Backward test (Wechsler, 1986) follows the same

procedure, except the participant must verbally repeat the digits in backward sequence.

Reaction time measures permit analysis of both visual and auditory stimuli. The average visual simple reaction time and movement (decision) time were computed over 12 trials given a single visual stimulus. The average visual choice reaction time and movement (decision) time were computed over 12 trials given multiple visual stimuli. The average auditory choice reaction time and movement (decision) time were computed over 12 trials given multiple auditory stimuli (see Era, Jokela, & Heikkinen, 1986, for further details).

Distal age-related measures. Maximal isometric strength (hand grip, arm flexion, knee extension) was assessed using special-built dynamometers (Era et al., 1994). Forced expiratory volume was assessed. Self-reported health was measured on a 5-point scale. In addition, as a distal measure of the brain-aging hypothesis, number of teeth was used to indicate aging, which has long been considered to be a biomarker of aging and has been included in previous studies (Osterberg, Era, Gause-Nilsson, & Steen, 1995).

Procedure

Participants were interviewed in their home in addition to a 1-day laboratory examination. Participation on the different cognitive tests varied depending on illness, language difficulties, problems with hearing, vision, or other handicaps (Steen, Fromholt, Äystö, & Berg, 1997). The cognitive portion of the assessment battery took approximately 30 min to complete.

Statistical Analysis

Combined analysis of locality. Data from the three cities were combined for a single analysis. To eliminate the confound of mean and variance differences between locality and sex (see Era et al., 1996), all variables were standardized within city and sex before data were combined. Thus, all analyses are based on locality- and sex-partialed measures of sensory acuity, balance, and cognition.

Missing data. Several of the variables were not collected in all localities; in other cases, particular variables are missing on a proportion of the participants because of design and scheduling issues (seen in Table 1). For example, because the same reaction time apparatus was utilized at all three sites, missing data for reaction time were due mainly to scheduling difficulties across sites. As there is no known scheduling bias in the samples, this form of missing data is not considered to affect the general inferences of this study. Maximum likelihood estimates of means and covariances were obtained using EMCOV (Graham & Hofer, 1993; Graham, Hofer, & Piccinin, 1994) and were based on an inclusion criterion of having complete data for at least one domain of functioning.

General overview. This single-age study design permits analysis of the association among variables within and across domains. We report maximum likelihood correlations for the entire sample ($N = 1{,}041$) and for a subsample of individuals who did not use hearing aids; who were not diagnosed with eye disease, glaucoma, or cataracts; and who did not reside in a nursing or retirement home ($n = 531$). Correlations between .10 and .29 are described as weak, between .30 and .50 as moderate, and above .51 as strong.

Results

Summary statistics by locality are shown in Table 2, and correlations among variables within and across domains for the full sample and subsample without related disease or disability are

Table 2
Descriptive Statistics by Locality

Variable	Jyväskylä			Gothenburg			Glostrup		
	n	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
Digit Symbol	297	21.10	9.81	301	30.74	12.53	387	29.82	11.01
Raven's Progressive Matrices	297	14.50	4.39	303	16.96	5.11	389	16.85	4.62
Word Fluency	300	29.11	11.10	306	25.88	12.58	397	22.14	9.30
Digit Span Forward	301	5.30	0.97	308	5.60	1.31	397	5.81	1.13
Digit Span Backward	301	3.76	1.09	309	4.14	1.26	397	3.66	1.33
RT: Visual	130	699.42	290.01	245	733.55	350.36	288	774.07	343.21
Choice RT									
Visual	129	1,098.25	585.65	239	1,184.95	579.82	286	1,202.22	598.46
Auditory	128	1,194.02	521.45	234	1,466.97	675.03	286	1,369.10	581.42
Hearing									
0.25 kHz	285	44.30	24.87	197	40.41	22.75	333	45.96	23.76
0.50 kHz	284	51.30	26.01	197	45.41	25.58	333	47.80	26.02
1.00 kHz	283	53.50	28.19	197	51.24	29.21	335	52.67	30.20
2.00 kHz	284	72.13	33.18	197	71.37	32.75	335	69.82	33.38
4.00 kHz	281	101.05	37.75	197	107.97	39.12	334	103.95	38.12
8.00 kHz	248	123.35	30.53	197	144.70	41.40	294	134.76	31.96
Visual acuity									
Not corrected	272	0.73	0.41	199	0.88	0.44	0	—	—
Corrected	258	1.36	0.41	156	1.42	0.43	0	—	—
Balance									
Eyes open	219	33.69	9.49	145	45.16	21.45	353	60.09	72.35
Eyes closed	218	45.57	15.91	141	52.35	27.52	353	58.86	43.36
Grip strength	290	278.19	99.40	213	344.27	122.01	404	349.28	164.33
Arm flexion strength	290	192.07	61.81	214	242.84	91.89	404	258.20	131.12
Knee extension strength	290	282.98	100.81	204	316.41	106.95	402	344.14	256.53
Self-rated health	301	2.98	0.58	308	2.39	0.93	409	2.18	0.87
Forced expiratory volume	285	2.12	0.56	192	2.23	0.55	403	2.27	0.70
Number of teeth	299	2.34	1.80	306	3.73	1.95	410	2.75	1.91

Note. Dashes indicate data were not collected for those Glostrup values. RT = reaction time.

shown in Table 3. Given the relatively large sample size, correlations above .10 are typically significant with power of .90. However, the focus of the results is on the overall pattern of findings rather than on particular significant associations among variables. Results are first presented within major domains to demonstrate that consistent associations are found of approximately the same magnitude as in age-heterogeneous, cross-sectional studies. This is important to demonstrate because low magnitudes of associations could result from restricted range of measurement. These results are followed by presentation of cross-domain relations.

Associations Within Domain

Associations within sensory and balance domains. The correlations between low-middle, middle-high, and low-high auditory acuity were .80, .63, and .43, respectively, and slightly lower in the subsample without hearing and other disabilities. Corrected and uncorrected visual acuity were correlated .54 and .51 in the full sample and subsample Digit Span Forward, respectively. The two balance conditions, eyes open and eyes closed, were only weakly correlated .29 in the full sample and .21 in the subsample.

Associations within cognitive domain. Correlations among the cognitive tests were all at least moderately positive and did not exhibit substantial differences across the full and subsample. In the full sample, the Digit Symbol test had the highest correlation with Raven's Progressive Matrices (.62) and the lowest correlation with the Digit Span Forward (.37); all other correlations were approximately at the .50 level. Raven's Progressive Matrices correlated approximately .40 with all measures except for Digit Span Forward (.32). Correlations were lowest between the reaction time measures and the span memory measures (ranging from .14 to .34).

Associations Across Sensory and Balance Domains

Correlations between visual and auditory acuity were low, ranging from .00 to .07. Associations between hearing and balance ranged from .00 to .03. Correlations between visual acuity and the balance conditions were higher, with correlations approximately .20 (.18–.21) except for uncorrected vision with eyes closed balance at .01.

Associations Across Sensory and Cognitive Domains

Of the correlations with the set of cognitive variables, the highest correlations were with corrected vision. Figures 3A and 3B show that these associations are between .20 and .40 (visual choice reaction time), with the highest associations on the tests requiring visuomotor performance. Lower associations were observed with uncorrected vision, with few differences observed across the full sample and the subsample without hearing or eye disease.

The laboratory hearing tests used in this study exhibited correlations with cognitive functioning that were typically less than .10, shown in Figures 4A and 4B, thus accounting for a negligible amount of variance in cognitive performance. The range of correlation was stable across the set of cognitive tests, with the auditory choice reaction time test showing no higher association with hearing acuity than the visual choice reaction time test. There were no findings in either the full sample or the sample without eye or ear disease that were sufficient to warrant further inspection. Figures 5A and 5B show that the associations between balance measures and cognitive performance were all negligible, with correlations rarely exceeding .10.

Associations With Distal Age-Related Markers

Measures of grip, arm, and knee extension strength were positively correlated with measures of cognitive performance, shown in Figures 6A and 6B, with correlations ranging from .02 to .25 (knee extension/visual reaction time) and most correlations between .10 and .20 (interpreted as sharing between 1% and 4% of the variance in functioning). Knee extension strength showed the highest and most consistent correlations of these three measures of strength. The reaction time measures were most consistently correlated with measures of strength.

Self-reported health status correlated between .11 and .29 (Digit Symbol test) in the full sample (Figure 7A) and exhibited approximately the same level of correlation in the subsample delimited on health-related exclusionary criteria (Figure 7B). Pulmonary expiratory force also correlated between .10 and .24 with the cognitive measures. No strong pattern of findings was observed across these tests.

Number of teeth, perhaps one of the most distal measures to the brain-aging hypothesis, was one of the strongest predictors of cognitive performance from this broad set of sensory, motor, and distal age-related markers. The correlations with cognitive abilities ranged from .13 to .31. Correlations were highest for the Digit Symbol test, the Raven Progressive Matrices, and the Word Fluency Task and lowest for the reaction time measures.

Summary of Results

Moderate-to-high correlations were found within specific sensory and cognitive domains. There were few relatively low cross-domain sensory correlations. Moderate correlations within specific sensory and cognitive domains were observed. Comparison of the full sample and subset without major hearing and eye disease found relatively few differences, and, when observed, these differences were negligible.

Nevertheless, all correlations across domains were positive, indicating that the associations were not completely random (as would be expected with correlations centered around zero). However, associations of the same magnitude as the highest sensory–cognitive associations were observed for distal measures of aging, including muscle strength, pulmonary expiratory volume, and, of particular interest, number of teeth. No common factor model was estimated given the relatively low correlations among measurement domains.

Discussion

In general, no consistent associations were found across measurement domains of visual acuity, auditory acuity, balance, muscle strength, and cognitive abilities. Within-domain evidence from this large three-sample study of 75-year-old individuals demonstrated moderate-to-strong associations within the sensory, balance, and cognitive domains. However, cross-domain associations were weak and inconsistent and could be interpreted as more indicative of common health and SES influences rather than com-

Table 3
Maximum Likelihood Correlations Among Variables for Full Sample and Subsample Without Disease or Disability

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Digit Symbol	—	.62	.52	.37	.47	.43	.46	.47	.13	.12	.14	.16	.30	.11	.13	.11	.11	.24	.24	.31	.29
2. Raven Matrices	.57	—	.42	.33	.46	.35	.39	.40	.09	.06	.05	.10	.24	.13	.12	.09	.06	.15	.14	.24	.17
3. Word Fluency	.49	.35	—	.42	.46	.30	.29	.33	.14	.12	.14	.15	.24	.08	.04	.15	.15	.19	.19	.27	.15
Digit Span																					
4. Forward	.32	.23	.37	—	.53	.15	.14	.21	.08	.06	.07	.08	.17	.07	.10	.02	.03	.13	.14	.17	.11
5. Backward	.42	.41	.40	.47	—	.20	.21	.34	.10	.06	.08	.12	.22	.04	.10	.02	.03	.11	.10	.21	.14
6. RT: Visual	.40	.31	.26	.15	.18	—	.58	.47	.13	.04	.02	.19	.29	.02	.09	.23	.21	.25	.17	.16	.20
Choice RT																					
7. Visual	.44	.39	.29	.14	.28	.60	—	.51	.17	.12	.12	.20	.44	.12	.12	.19	.22	.19	.20	.15	.20
8. Auditory	.45	.34	.30	.17	.32	.45	.56	—	.11	.06	.09	.04	.27	.12	.12	.14	.13	.18	.15	.13	.13
Hearing																					
9. Low	.14	.11	.15	.05	.11	.19	.22	.19	—	.80	.43	.04	.07	.03	.03	.14	.08	.10	.13	.16	.07
10. Middle	.11	.08	.14	.04	.03	.09	.09	.06	.75	—	.63	.04	.05	.02	.01	.10	.05	.06	.09	.14	.03
11. High	.08	.02	.11	.05	.04	.04	.08	.07	.34	.58	—	.01	.00	.02	.02	.08	.06	.06	.12	.14	.01
Vision																					
12. Uncorrected	.26	.14	.15	.11	.09	.24	.27	.06	.07	.05	.02	—	.54	.21	.01	.04	.13	.11	.07	.11	.14
13. Corrected	.37	.28	.26	.22	.21	.33	.52	.38	.04	.00	.10	.51	—	.20	.19	.09	.18	.12	.19	.15	.20
Balance																					
14. Eyes open	.05	.07	.01	.05	.01	.03	.11	.12	.07	.03	.02	.21	.09	—	.29	.04	.06	.04	.09	.01	.06
15. Eyes closed	.08	.07	.01	.10	.03	.05	.14	.14	.00	.02	.07	.08	.08	.21	—	.03	.03	.01	.05	.06	.09
16. Grip strength	.08	.05	.11	.03	.01	.28	.20	.16	.14	.11	.10	.02	.13	.01	.04	—	.40	.36	.26	.10	.11
17. Arm flexion strength	.05	.04	.13	.01	.01	.20	.20	.12	.12	.09	.08	.02	.12	.04	.06	.39	—	.39	.30	.05	.15
18. Knee extension strength	.20	.09	.19	.12	.08	.22	.12	.15	.13	.09	.08	.21	.21	.00	.03	.37	.31	—	.25	.15	.23
19. Forced expiratory volume	.17	.06	.15	.09	.02	.15	.16	.13	.10	.02	.01	.06	.19	.06	.04	.29	.29	.25	—	.19	.25
20. Number of teeth	.30	.18	.25	.15	.17	.11	.18	.10	.14	.14	.13	.16	.23	.01	.08	.08	.03	.19	.12	—	.15
21. Self-rated health	.27	.15	.12	.12	.10	.14	.21	.11	.06	.02	.02	.23	.21	.01	.02	.07	.11	.20	.24	.13	—

Note. Correlations are based on aggregate sample after standardizing within locality and sex. Correlations for the full sample are shown above the diagonal; correlations for subsample without significant eye or ear disease or disability are shown below the diagonal. RT = reaction time.

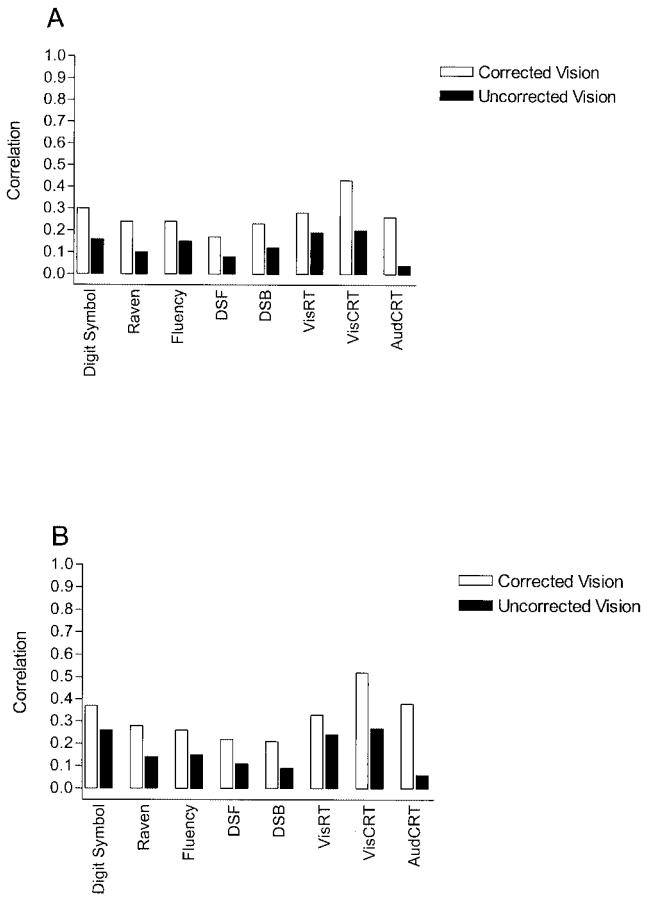

Figure 3. A: Associations between vision and cognition in full sample. B: Associations between vision and cognition in subsample excluding hearing problems and eye disease. Digit Symbol = Digit Symbol Substitution test, Raven = Raven's Progressive Matrices, Fluency = Word Fluency Task, DSF = Digit Span Forward, DSB = Digit Span Backward, VisRT = visual reaction time, VisCRT = visual choice reaction time, AudCRT = auditory choice reaction time.

mon central nervous system or physiological aging. We conclude that effects of aging on sensory acuity, balance, and cognitive functioning are likely to be relatively independent, multidimensional, and complex given the relatively weak associations across variables.

Our analysis of multiple domains of sensory, motor, and psychomotor processes replicates the previous findings based on NAC samples (Era, 1987) in which no substantial and general association was found across all sensory and cognitive domains. However, there was some evidence for domain specificity of functional associations (specific peripheral sensory declines affecting specific types of cognitive performance). Individual differences in SES, health, and health-related behaviors may account for some of the associations across domains and were particularly evident in the associations with the distal age markers. For example, number of teeth was associated with cognitive variables at the same level of magnitude as visual acuity. Number of teeth in adulthood, long considered a marker of aging, was associated with social class and economic status (Ambjornsen, 1986; Griep, Mets, Collys, Ponjaert-Kristoffersen, & Massart, 2000; Sayer, Osmond, Briggs, & Cooper, 1999), and loss of teeth presumably resulted from unavailability of health-related resources across the life span, including nutrition and preventive care.

Given the consistently weak correlations across sensory, motor, and cognitive domains, it is possible that initial individual differences in early periods of the life span can account for these general findings. While in this study, the pattern of correlations across variables varied, most were of small effect size and only rarely exceeded $r = .30$. Indeed, the magnitude of associations in the NORA Study is similar to associations reported for sensory and cognitive variables assessed in early and middle adulthood (e.g., Li et al., 1998; Roberts et al., 1997) as well as other studies of middle and later adulthood. These general findings may indicate shared individual differences that may be relatively stable over time and are thus distinct from the aging of these functions. We would have expected higher magnitudes of association across domains of functioning had the rates of aging been largely influenced by common aging-related influences because the rank ordering within

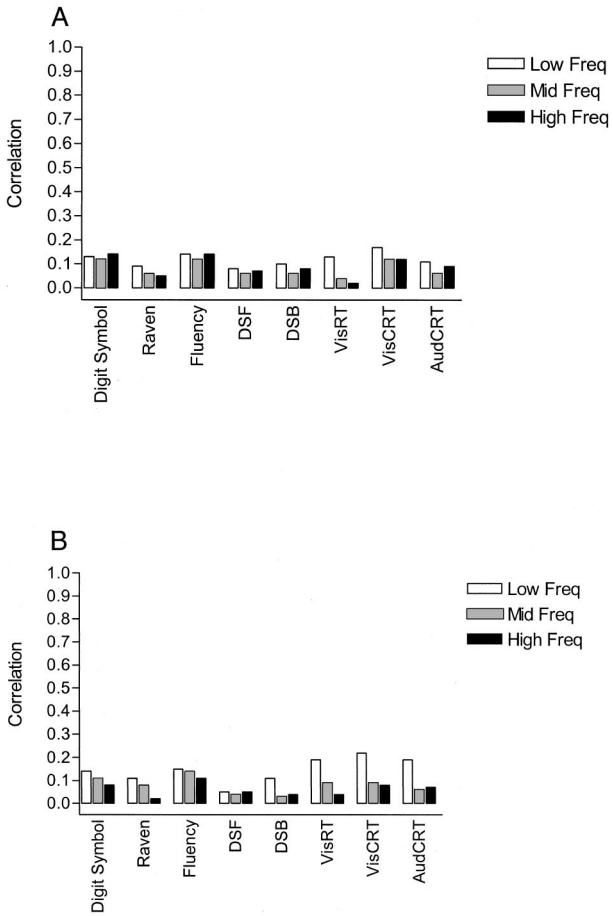

Figure 4. A: Associations between hearing and cognition in full sample. B: Associations between hearing and cognition in subsample without hearing problems and eye disease. Freq = frequency, Digit Symbol = Digit Symbol Substitution test, Raven = Raven's Progressive Matrices, Fluency = Word Fluency Task, DSF = Digit Span Forward, DSB = Digit Span Backward, VisRT = visual reaction time, VisCRT = visual choice reaction time, AudCRT = auditory choice reaction time.

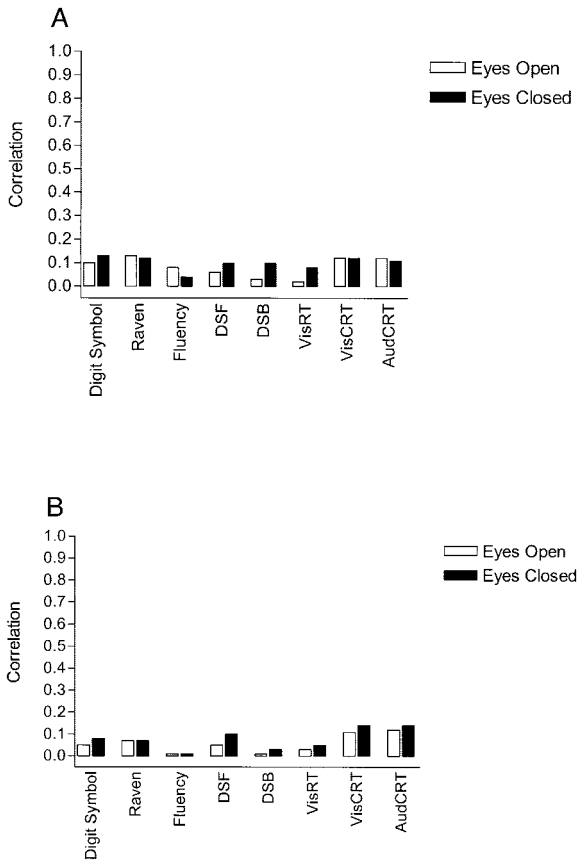

Figure 5. A: Associations between balance and cognition in full sample. B: Associations between balance and cognition in subsample without hearing problems and eye disease. Digit Symbol = Digit Symbol Substitution test, Raven = Raven's Progressive Matrices, Fluency = Word Fluency Task, DSF = Digit Span Forward, DSB = Digit Span Backward, VisRT = visual reaction time, VisCRT = visual choice reaction time, AudCRT = auditory choice reaction time.

NAC samples later in life will indicate the interdependence among rates of aging to increasing degrees in samples in which the developmental and aging processes have jointly influenced the rates of change. Several recent studies have utilized latent factor models of sensory and cognitive indicators to permit associations between cognitive and sensory variables to be disattenuated for error and systematic unique variance (e.g., Anstey, Luszcz, & Sanchez, 2001; Lindenberger & Baltes, 1994). These methods were not utilized in our research because the number of indicators per factor was insufficient. As correlations/covariances form the basis of factor models and because the correlations were typically low across domains, we presented the sufficient statistics on which more elaborate models are based.

Several studies have examined groups that are less heterogeneous in relation to age. Marsiske et al. (1997) performed a communality analysis by splitting the Berlin Aging Study sample into two groups (70–84 and 85–103). In general, less age-related variance was predicted within groups compared with the full sample, with the shared age-related variance comprising 20% of explained variance in the younger group and about 35% in the older group. Such variance provides evidence that the rates of change were associated among these processes. However, as this study seems to indicate, it remains difficult to interpret this outcome as a result of common aging causes and is perhaps better explained as correlated changes that were due to health-related causes. It may be the case that greater magnitudes of change occurred, on average, across functions in the older sample, which contributed to higher amounts of shared age-related variance.

The potential for peripheral changes to affect performance on tests of cognitive functioning is a more fundamental source of covariance and logically must be evaluated prior to hypotheses of centralized brain-aging hypotheses. Indeed, several studies of the relation between hearing and vision loss and cognitive functioning emphasize the operational confounds associated with sensory deficits (e.g., Gaeth, 1948; Granick et al., 1976; Ohta et al., 1981). For example, stronger associations of hearing loss have been found for verbal compared with nonverbal tests of cognition (Granick et al., 1976; Thomas et al., 1983). Ohta et al. (1981) stated that "these findings were interpreted as providing strong support for a causal relationship between sensory acuity and test performance, indicating that the cognitive capabilities of elderly persons can indeed be underestimated as a result of their reduced sensory acuity" (p.

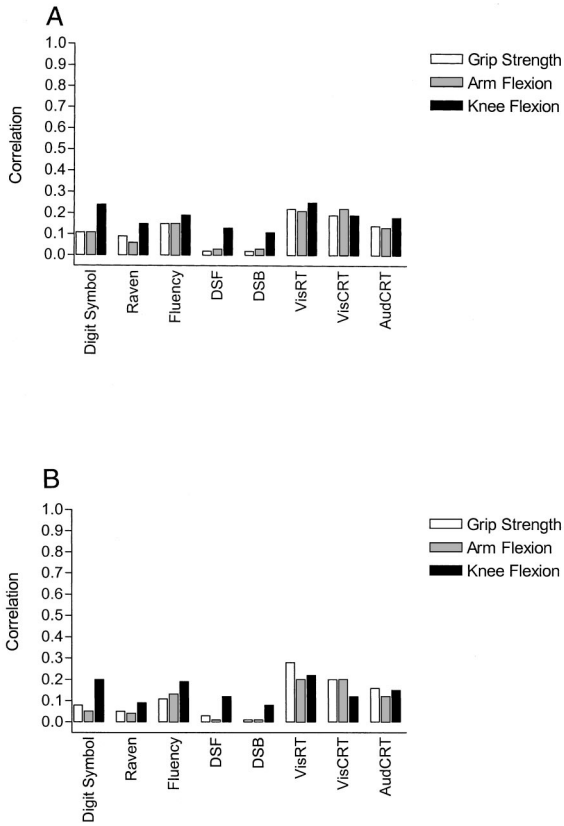

Figure 6. A: Association between strength and cognition in full sample. B: Association between strength and cognition in subsample without hearing problems and eye disease. Digit Symbol = Digit Symbol Substitution test, Raven = Raven's Progressive Matrices, Fluency = Word Fluency Task, DSF = Digit Span Forward, DSB = Digit Span Backward, VisRT = visual reaction time, VisCRT = visual choice reaction time, AudCRT = auditory choice reaction time.

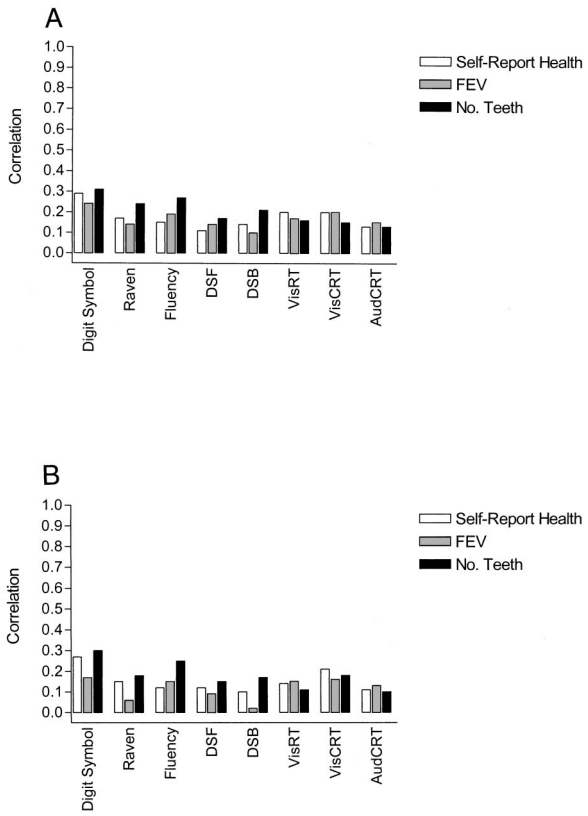

Figure 7. A: Association between health-related variables and cognition in full sample. B: Association between health-related variables and cognition in subsample without hearing problems and eye disease. FEV = forced expiratory volume, Digit Symbol = Digit Symbol Substitution test, Raven = Raven's Progressive Matrices, Fluency = Word Fluency Task, DSF = Digit Span Forward, DSB = Digit Span Backward, VisRT = visual reaction time, VisCRT = visual choice reaction time, AudCRT = auditory choice reaction time.

478). For example, there is sufficient evidence that measures of cognitive capabilities have operational confounds with sensory–perceptual acuity. Experiments that have varied sensory load (e.g., decreasing print size) have demonstrated significant effects on performance, effects that are often differential across age groups (Dickinson & Rabbitt, 1991; Rabbitt, 1968) but have not been a consistent finding across all studies (Lindenberger, Scherer, & Baltes, 2001). These confounds need to be eliminated or minimized before strong conclusions regarding associations between sensory and cognitive domains can be regarded as meaningful. Experimental studies that manipulate sensory deficits have found a differential decrement in performance, whereas other studies of relatively homogeneous adults (ages 30–50) did not find deficits in cognitive performance. The majority of this evidence points to the fundamental problem that higher order cognitive operations cannot be performed if the information was not accurately perceived, which would result in downwardly biased cognitive scores and increasing associations of cognitive performance with sensory acuity.

Research with linkages across these domains should seek to separate peripheral (sensory loss) and central changes (perception). The choice of measurements of different sensory modalities is critical in this regard because certain types of measurements will reflect peripheral and central processing losses to different degrees. The measures used in the present study differ as to whether they reflect primary sensory losses in peripheral sensory organs (and also the effects of specific diseases such as cataracts or macular degeneration) and how much of the possible problem is due to the processing of sensory information within the central nervous system. Auditory acuity, for example, was measured using pure-tone thresholds under optimal conditions (soundproof room, no external disturbance) and are more indicative of peripheral loss than alternative measures using speech audiometry. Correspondingly, visual acuity as measured in our study provides a narrow picture of changes to vision and could be usefully compared with the sensitivity of the visual field or contrast sensitivity at different frequencies (Fozard, 1990; Kline & Schieber, 1985; Kline & Scialfa, 1997). Broader sensory–motor assessment batteries might provide more useful information regarding the link to central or peripheral processing and cognitive changes with age and may lead to development of less biased cognitive assessments.

Commonality and Age-Partial Analysis

In cross-sectional research, variance decomposition and hierarchical regression models have been a method of choice for gerontological research, particularly for cognitive aging research. However, both analytical and empirical evidence calls into question results based solely on cross-sectional, age-heterogeneous samples for understanding whether sensory and cognitive outcomes "age together" and the mechanisms of aging-related change. The confounds in cross-sectional studies of time-dependent processes are many, and the demonstration that mean trends influence the covariance would appear to further weaken opportunities to describe associations among changes in functioning with age. The issues we raise in this regard are more fundamental to various approaches to variance decomposition in cross-sectional studies and the limitations of the commonality analysis described elsewhere (Hofer & Sliwinski, 2001; Lindenberger & Potter, 1998; Pedhazur, 1997; Sliwinski & Hofer, 1999). Hypotheses of interdependence among age-related processes must be regarded as tentative if they rely solely on the analysis of age-heterogeneous, cross-sectional samples.

From the perspective of the SNAC design, partialing the effect of age (time) from two processes—*X* and *Y*—in an age-heterogeneous design is similar to averaging the within-group standardized covariances across SNAC designs (Hofer & Sliwinski, 2001). Figure 8 demonstrates how within-age-group covariances are aggregated to obtain the shared variance that is not age-related but that may still contain aging-related associations in line with the premises of the age-homogeneous, cross-sectional comparisons. Two age groups are shown in Figure 8, with a lower mean and higher association between *X* and *Y* in the older age group relative to the younger age group. Partialing for chronological age variance only partially removes true aging effects that result from covariance associated with the cumulative influences of correlated rates of change described previously in the analysis of age-homogeneous samples. Because covariation associated with true within-person change over time will remain, partialing of age-related variance will not be informative about the level of

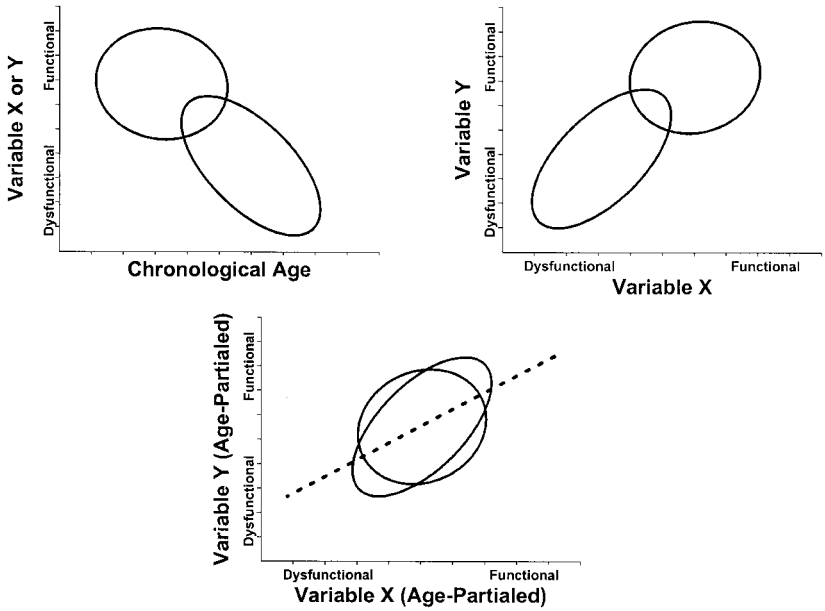

Figure 8. Partial effects of age-related variance provides the association at the average age of narrow age-cohort samples.

association among variables that are "independent" of aging or time. Rather, statistically partialing for age-related variance can be conceptualized as obtaining the average covariance across SNAC samples differing in age.

Therefore, the use of regression analysis for partialing variance associated with chronological age provides an estimate of the NAC association at the average age of the sample. From the perspective of the SNAC design, there is a loss of information when chronological age is partialed from associations in cross-sectional samples varying broadly in age. As described previously, covariance between random slope effects (rates of aging) will be observed as increasing covariances in successively older NAC groups (as in studies of dedifferentiation, described previously). Indeed, if common influences on aging-related changes are operating to produce increasing association in SNAC designs, the age-partialed covariance in the age-heterogeneous design (using the same sample) may be appreciable and due, at least in part, to the covariance among rates of change. However, relative to the SNAC analysis, there is little basis for evaluating the interdependence among aging-related processes—observed as changes in magnitude of covariation (increasing or decreasing interdependence). The comparison of SNAC groups may provide a better approach for understanding whether rates of aging produce higher associations among systems of variables.

The Potential of NAC Designs for Assessing Associated Rates of Aging

We have demonstrated how analysis of age-heterogeneous, cross-sectional samples will lead to findings of associations among age-related variables. Age-related variables, by definition, exhibit mean differences, on average, across individuals varying in age. The confirmatory bias in such analyses, therefore, provides a poor method for evaluating whether rates of aging are common or independent. For most purposes, associations that are due to population mean trends with age do not appear to be desirable. The alternative approach for evaluating associations among age-related variables by using SNAC samples permits stronger tests of associations among age-related variables and is recommended for reevaluating hypotheses when using existing cross-sectional data. However, evidence from longitudinal studies should carry greater weight than results from cross-sectional studies.

Christensen, Mackinnon, et al. (2001) reported a factor analysis of a broad set of age-related variables (e.g., cognitive, visual acuity, forced expiratory volume) and performed the same analysis in two groups: aged 70–74 and 75–79. Though a similar factor structure is reported in the two groups, many of the loadings increased in magnitude, with the largest change seen on the standardized loading for visual acuity (from .36 to .58). This indicates that visual acuity is more associated with the strongly cognitive factor in the older age group and could be indicative of poorer performance on cognitive tests as a function of declining visual acuity or a number of alternative explanations. Nevertheless, it is this sort of evidence in which existing cross-sectional studies have been used that can provide alternative means of examining associations among age-related variables.

The use of cross-sectional results as the basis for theories of aging requires that between-individual differences be informative about within-person change. As developed in this article, sequential age-cohort comparisons provide a stronger basis for evaluating change than typical cross-sectional models because comparison across cohorts differing in age should indicate increasing associations if there is common aging-related change occurring within individuals. However, assumptions required of cross-sectional studies for making inferences regarding within-individual change

are strong and untested except in longitudinal studies (Hofer, Sliwinski, & Flaherty, 2002; Li & Schmiedek, 2002; Salthouse & Nesselroade, 2002). When longitudinal data are available, the findings are usually not in support of common factor theories of cognitive aging (e.g., Anstey, Luszcz, & Sanchez, 2001; Sliwinski & Buschke, 1999). Longitudinal studies emphasizing within-person dynamics are required to fully evaluate hypotheses of common aging-related causes and should be the source of evidence for the development of cognitive aging theories (Sliwinski & Hofer, 1999).

Are the assumptions made in the NAC and SNAC designs valid? This is an important and complex topic and is as relevant to age-heterogeneous and longitudinal sampling as it is to NAC designs (e.g., Hofer, Sliwinski, & Flaherty, 2002; Salthouse & Nesselroade, 2002). One issue is that individual differences in rates of change should lead to increases in variance across age. While it is true that variance will increase under stable conditions in simple linear models, as in the analytical example described previously, in practice, the variance may not appear to increase. The most plausible reason is that sample variance is a function of sample selection over time (i.e., attrition). Evidence for differential attrition (i.e., nonrandom selection over time) has been obtained in numerous longitudinal studies of aging (see Schaie & Hofer, 2001). A majority of attrition from longitudinal studies is related to mortality, with individuals exhibiting poorer health status, higher levels of depression and mental illness, and lower levels and greater change in physiological and cognitive functioning being the most likely to be unavailable at subsequent occasions of measurement (Anstey, Luszcz, Giles, & Andrew, 2001). Therefore, the lower end of the distribution is in a constant state of truncation across age groups and, therefore, affects both cross-sectional samples and longitudinal samples observed across time. The main difference is that in longitudinal studies, the selection process over time is observable and can statistically be modeled. Indeed, attrition presents an even thornier inferential problem for cross-sectional studies because the population process of attrition is not observed with sampling performed on a population with unknown sources of age-based heterogeneity. Therefore, attrition should not be perceived as a limitation of longitudinal studies but is, rather, a key strength in that the selection process can be observed and modeled by observing individuals and patterns of participation over time.

We have shown analytically that if all other influences are constant, correlated rates of change will lead to increasing estimates of association in old and older NAC groups. However, many other influences enter into cross-sectional and longitudinal designs of various types, so this optimal condition will not exist in practice (Hofer & Sliwinski, 2001; Li & Schmiedek, 2002; Schaie & Hofer, 2001). Cohort effects are a potential source of influence in both age-heterogeneous and age-homogeneous forms of cross-sectional and longitudinal studies and, unless measured, might best be assumed to contribute in unknown directions and magnitude to the level of association differences. The increase of disease and mortality in older age-cohort groups will lead to increasingly select samples of individuals—again a problem of both age-heterogeneous and age-homogeneous cross-sectional and longitudinal studies. Such systematic variation in the data will be indistinguishable from other sources of influence and may lead to different patterns of covariance across groups varying in age, particularly if these effects are strong influences on the outcome variables. A major assumption of the NAC/SNAC approach is that the common causal process is constant across the life span. Clearly, there may be distinct age-related influences that have different magnitudes of effects at different ages, which may also lead to imperfect monotonic changes in the covariance structure across sequential NAC samples. All of these influences will affect the covariances within any cross-sectional or longitudinal sample, varying in age or relatively age homogeneous in nature. In general, the NAC/SNAC design is best considered as another perspective from which to view age-related changes. Indeed, further understanding of the change process (i.e., dedifferentiation) may usefully employ the SNAC approach across different time continua, such as time to death or time to diagnosis of dementia.

Evaluating Associations Between Sensory–Motor and Cognitive Abilities

There is evidence for a positive manifold across a variety of physiological and cognitive functions in the clear majority of studies that include sensory and cognitive variables. The correlations tend not to be strong, however. In this study, we found that these associations were weak and accounted for little of the individual variation in cognitive functions. Such evidence for a positive manifold based on weak or moderate correlations can hardly provide an affirmative answer to the question, "Does it all go together when it goes?" (Rabbitt, 1993). It is also clear from a number of studies that one can account for most age-related variance when variables are only weakly correlated. Under these conditions, we might question the utility of such analyses because the observed variation explained is often insignificant. From the extant evidence, it is also clear that alternative hypotheses of the perceptual–cognitive link are not mutually exclusive. In addition to our suggestion of interpreting weak-to-moderate correlations with caution, we propose that a hierarchy of hypotheses regarding relationships between sensory, motor, psychomotor, and cognitive functioning also be considered.

1. *Measurement commonality* of sensory acuity and cognition that is due to testing material confounds (e.g., small print), which reduces the resources available for the cognitive task. This is especially critical if the task is given under speeded conditions.

2. *Peripheral declines in sensory acuity* caused by accumulation of independent age-related effects (e.g., environmental trauma) affecting domain-specific cognitive performance.

3. *General health, disease, or medication related influences* secondarily affecting sensory and cognitive systems. These influences could be considered as general systemic declines in functioning.

4. *Common central nervous system (CNS) aging* changes specifically to the central nervous system affecting perceptual acuity, balance and gait, and cognitive performance. These changes could be pathological or nonpathological in origin.

Assuming that aging is a highly complex, dynamic, and multidimensional process, influences that affect the aging rate of multiple systems may differ across individuals, implying that there will be different patterns of biological and psychological aging. Indeed, a useful distinction can be made between *common cause* and *common outcome* as it is entirely possible that a common cause can lead to different outcomes and that different causes can lead to common outcomes. For example, different aging-related or disease-related processes may influence multiple systems within an individual. These age-related environmental influences or health-related changes may be unique to each individual, although these different causative aging influences may appear as having a common outcome in the population. This is one way that findings of common cause may not be so common. It might be useful to consider the different risk profiles across individuals (with increasing risk probability with age) that have general effects on physiological parameters and through biological changes on psychological health. The difficulty of studying aging-related changes from changes associated with disease processes has been a longstanding and difficult problem. The interaction of changes in functioning associated with the pharmaceuticals used to treat disease adds a further degree of complexity. For example, even when the illness itself does not contribute to peripheral or central hearing loss or balance difficulties, the prescribed drugs may (e.g., Lajoie et al., 1996, reported that such pathological processes may intensify disequilibrium in older adults). We must conclude that even evidence for relationships across domains (i.e., outcomes) does not necessarily imply a common aging pathway.

However, the problems of distinguishing between primary and secondary aging are critical to the interpretation of sensory–motor–cognitive functioning. Increasing associations with successive NAC may be the result of common-cause aging influences but may also be due to disease and health-related changes having broad physiological and behavioral repercussions. This effect has been described as the *terminal drop*, the finding that multiple functions exhibit dramatic declines over a period of time prior to death (e.g., Berg, 1987). Changes occurring among physiological systems may result from complex individual characteristics that relate to health status and aging, including formal education, occupational status, behavioral risk and health factors, and, perhaps, genetic risk factors for cardiovascular and other diseases.

That common factor models fit data of this type is not necessarily indicative of common cause or common outcome. Indeed, whether common factors will represent the data depends less on the magnitude of associations among outcome variables than on the relative homogeneity of correlations. In general, moderate (e.g., $r = .40$) or strong (e.g., $r = .90$) magnitudes of association among indicators may appear to be accounted for by a common factor but must be interpreted in significantly different ways. Clearly, that a common factor is found to account for data that correlate on average .50 (factor loadings of .70) cannot be interpreted as processes that are highly coupled within individuals. The common and specific factor models fit to the data relate more to the relative homogeneity of the correlations than to the magnitude of association. We have shown how such associations arise, at least in part, from average between-individual, age-related differences. These "mean trends" are, therefore, also an aspect of these common/specific factor models in that dissimilar magnitudes of age-related differences may lead to findings of direct age effects that are not accounted for by common factor models. For example, Salthouse et al. (1998) reported that visual acuity exhibits the largest relation with chronological age of all the noncognitive variables. They found that an additional direct association with chronological age is necessary in addition to the common factor pathway. Based on the multiple confounds present in age-heterogeneous studies, a common factor model of age-related variables provides little evidence for the underlying causal processes producing changes in such outcomes, however, perhaps telling us little more than the fact that all of these outcomes exhibit similar average age-related differences in samples varying broadly in age. While mean differences are important for understanding aging-related changes, such cross-sectional, age-related trends confound results emphasizing individual differences in aging.

What is missing in many of these studies is an evaluation of other "markers" that exhibit changes with age but are known to not be part of the same system. In this study, we have attempted to demonstrate that other age-related markers can predict individual differences in cognitive functioning, in some instances, better than theoretically more proximal markers. Many of these age-related markers, such as number of teeth and forced expiratory volume, have been shown to be associated with SES (education, income) and concomitant nutritional and health-related factors (Cook et al., 1991; Griep et al., 2000) that may accelerate age-related declines in these functions (e.g., Abrahams, 1976). It would be useful to bring health-related factors into analyses of the interdependence of aging-related change as an explanatory pathway for accelerated declines. Such processes will be related to mortality and sample attrition and reflect processes associated with population aging.

In summary, our analysis of the limitations of age-heterogeneous designs and results from a single age-cohort sample does not support the notion that broad sensory, motor, and muscle strength are strong predictors of cognitive performance and, thus, are indicators of the physiological integrity of the aging brain. Rather, the results of this study suggest that individual differences in functioning are largely due to independent aging influences. We have discussed the merits of a single-age cohort design and statistical analysis based on SNACs as an alternative and potentially superior approach for understanding associations among rates of aging in which cross-sectional data are used. The reliance on age-heterogeneous, cross-sectional studies for examination of correlated rates of aging should be carefully considered. Indeed, the confounding feature of average age-related trends in typical cross-sectional studies makes, in our opinion, the finding of common cause all too common.

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