RELATIONSHIPS BETWEEN COGNITION AND SENSORIMOTOR ABILITIES IN OLDER AGE IN THE ACTIVE STUDY

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my grandmothers, Ruth Holihan and Mary Maye, who have epitomized graceful aging and inspired my career path in countless ways; and to my grandfathers, Bill Holihan and Bill Maye, who I will forever wish I had the chance to know.

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Sensorimotor variables are strongly related to a variety of cognitive measures in older adults. The current study was a secondary analysis of a ten-year study of the long-term effects of cognitive interventions in older adults from the ACTIVE study. Analyses addressed three aims: (1) description of ten-year change in sensorimotor (vision, balance) and cognitive (memory, reasoning, perceptual speed, visual attention) function; (2) examination of whether participants who experienced the most sensorimotor loss also experienced the most cognitive loss; and (3) investigation of how sensorimotor change might account for cognitive change. The ACTIVE sample consisted of 2,802 adults aged 65-104 (76% female; 26% African American) who were assessed for up to ten years. 1,220 participants from the original sample were present at the ten-year follow-up. Age-related decline was observed in all sensorimotor and cognitive domains over time, with roughly uniform slopes of change. Sensorimotor functioning accounted for approximately half of the age-related individual differences in every cognitive composite, and accounted for between 40% and 80% of ten-year cognitive change. Vision and balance, which are regularly assessed by a wide variety of

health professionals, functioned as potentially useful sentinels of age-related cognitive change; discussion considers whether such sensorimotor variables might also serve as useful multi-disciplinary screening tools to foster early identification of, and appropriate assessment referrals for, late life cognitive declines.

CHAPTER 1
LITERATURE REVIEW

Cognitive Functioning and Decline in Elderly Adults

Human aging is associated with widespread cognitive decline (review: Drag & Bieliauskas, 2010), although cognitive abilities differ in their patterns and rates of change (Singer & Willett, 2003), and not all abilities decline. Horn and Cattell (1966) divided cognitive abilities into two broad categories: “crystallized” abilities and “fluid” abilities. Crystallized, or “pragmatic” (Baltes, 1997) abilities consist of the knowledge and experience accumulated throughout the lifetime, and are often represented in clinic and in research by measures of vocabulary and semantic knowledge. Crystallized abilities, which are highly environmentally and culturally influenced, are believed to remain relatively stable throughout the life span (Park et al., 2002). Fluid abilities, or “mechanics” (Baltes, 1997), on the other hand, are more vulnerable to aging effects, and are associated with poorer performance in older age (Baltes, 1993; Park et al.; Salthouse et al.,1996). These abilities include working memory, attention, reasoning, and speed of processing, among others.

Information obtained from cognitive aging studies regarding age-related changes in fluid cognitive abilities is largely dependent on the study design. Cross-sectionally, there is evidence that working memory, attention, and executive functioning performance are much poorer in older individuals than younger individuals (Park et al., 2002; Zacks, Hasher, & Li, 2000). Poor short-term declarative memory and reasoning performance is common in elderly adults, with evidence existing for accelerated rates of decline past the age of 70 for declarative memory (Drag & Bieliauskas, 2010; Christensen, 2001; Grady & Craik, 2000). Processing speed is thought to be a very age-vulnerable domain, and is among the first to show signs of decline (Salthouse, 1996). Salthouse (1982) suggested that processing speed has decreased by approximately 20% at age 40 and 50-60% at age 80, and later (1996) suggested that other fluid abilities are limited by processing speed. It is largely unknown, however, how deterioration of one process affects, controls, or is directly associated with deterioration of another process. Cross-sectional designs, which compare cognitive performance across individuals of different ages, are sometimes criticized for overestimating cognitive change with age, because, for example, cohort effects favor later-born generations, and may only give the appearance of massive decline (Schaie, 2009; Lindenberger & Poetter, 1998).

Longitudinal findings regarding cognitive aging tend to be more optimistic than cross-sectional, and suggest that both crystallized and fluid abilities increase or remain stable until around the sixth decade of life, and then show moderate decline in every domain except for verbal knowledge (Giambra, Arenberg, Zonderman, Kawas, & Costa, 1995; Singer, Verhaeghen, Ghisletta, Lindenberger, & Baltes, 2003). Longitudinal designs can be criticized for underestimating the actual change that occurs, in part due to practice effects from prior testing and selective attrition (Salthouse, 2010). Those who have the health and resources to remain in a longitudinal study until very late life are often considered to be exemplars of successful aging (Rowe & Kahn, 1987; Rowe & Kahn, 1997; Baltes & Baltes, 1990) that may not truly represent others of their age group.

Sensorimotor Functioning and Decline in Elderly Adults

Another major area of decline in older age is in sensory and sensorimotor functioning. Visual acuity, a measure of spatial resolution, specifically the ability to perceive the fine spatial detail of an object, begins to decline around age 45-50, and accelerates in rate of decline after age 80 (Schneider & Pichora-Fuller, 2000). “Low vision,” commonly defined as corrected visual acuity worse than 20/40 or 20/70, is found in 20% of older adults aged 60 to 69, and in 25-30% of older adults aged 75 and older (Wahl & Heyl, 2003; Schieber, 2006).

Close visual acuity tends to be more affected by age than distance visual acuity, although distance visual acuity also declines significantly with age. Distance visual acuity is poorer than 20/50 in 10% of adults aged 60 to 69, and in 25 to 35% of those over the age of 80 (Anderson & Palmore, 1974; Branch, Horowitz, & Carr, 1989).

Decline in visual acuity with age is likely to be due to a combination of structural changes in the eye and changes within the visual cortex. Only 1/3 of the amount of light that reached the retina at age 10 reaches the retina at age 60, largely due to restricted pupil diameter and yellowing of the lens (Weale, 1961). The numbers of cells in the retina, as well as in the visual cortex, also decrease with advancing age (Meisami, Brown, & Emerle, 2007). fMRI studies have shown that the hemodynamic response to sensory stimuli is significantly reduced in elderly subjects’ visual cortices, relative to younger adults (Buckner, Snyder, Sanders, Raichle, & Morris, 2006; Ross et al., 1997).

Beyond the loss of visual input, there may also be psychosocial and functional consequences to late life vision changes. Impaired vision is associated with high rates of depression (Brody et al., 2001) and reduced quality of life (Mitchell & Bradley, 2006). Low vision is also related to reduced physical mobility and driving status (Decarlo, Scilley, Wells, & Owsley, 2003). Seniors over the age of 70 with poor vision have much more difficulty with activities such as walking and getting into/out of chairs and bed, preparing meals and managing medication, and are less active than those without vision impairment (Campbell, Crews, Moriarty, Zack, & Blackman, 1999). Indeed, impaired vision is also one of the most common causes of hip fractures and disability (Lin et al., 2004). Associations of approximately 0.20 have been found between visual acuity and balance of the elderly (Hofer, Berg, & Era, 2003), and it has been suggested that visual losses actually serve as a precursor to balance/gait problems (Lord, Clark, & Webster, 1991; Manchester, Woollacott, Zederbauer-Hylton, & Marin, 1989).

Balance, the other sensorimotor construct of interest in the present study, severely diminishes after age 60, and the rate of decline accelerates with advancing age (Bohannon, Larkin, Cook, Gear, & Singer, 1984). The most obvious and direct consequence of impaired balance in the elderly is falling and resulting injury. Approximately 1/3 of those over age 65 fall each year (CDC, 2000), with an annual rate of falling that increases from 1/4 of elderly aged 65-74 to 1/3 of elderly aged 75 years and older (Nevitt, Cummings, Kidd, & Black, 1989; Tinetti, Speechley, & Ginter, 1988). Of those who fall once, about 2/3 have another fall within the next 6 months (Perry, 1982). 12-50% of elderly have recurring falls (Blake et al., 1988; Nevitt, Cummings, & Hudes, 1991). While most falls do not result in severe disability, it is estimated that 5% of falls result in a break of the hip, pelvis, humerus, or wrist, and 20-30% of falls result in a general moderate or severe injury (Nevitt et al.,1991; Wild, Nayak, & Isaacs, 1981). Those injuries can impact mobility, independence, and increase the risk of premature death (CDC 2000;Wild et al.).

Balance is closely related to the “big five” senses, and is often termed a “higher order” sense. Balance is achieved when the center of gravity in the body falls within the support base formed by a person’s stance (Hutton, 2000). Even when “balanced,” the body continuously sways back and forth and requires nearly constant minor adjustments to maintain postural stability. This process often requires not just visual information, but also auditory, proprioceptive, and vestibular input, as well as motor coordination. As such, its reliance on the integrity of these systems makes balance-gait a powerful indicator of overall sensorimotor functioning. Balance is often measured by quantifying aspects such as sway and corrections while one attempts to stand still in different positions, or turn in a circle. It has been suggested that an older adult who fears falling because of vision and balance problems is likely to limit his or her physical activities (Arfken, Lach, Birge, & Miller, 1994).

Reduced sensorimotor functioning, in addition to being associated with injury and impairment in activities of daily living and quality of life, has also been linked in aging literature to reduced cognitive functioning. It is indeed intuitive that sensory impairment, such as in the case of reduced vision, might impact neuropsychological test performance at the level of performance factors. However, previous research also suggests that the relationship is more complex than this type of simple performance effect. As discussed by Wahl (2013), vision-related cognitive abilities (e.g. visual speed of processing, visual attention) are highly linked to central nervous system functioning, and are not dependent on the integrity of the eye (Fozard, 1990; Weale, 1987). Impaired cognitive performance in the face of sensorimotor impairment could be due in part to long-term sensory deprivation that produces neural change (Sekuler & Blake, 1987). Cognitive performance could also be hampered by the diversion of limited and shared attentional resources toward sensorimotor functioning, in a compensatory fashion following sensory decline, as suggested by past dual task studies (e.g. Verghese et al., 2007; Lindenberger, Marsiske, & Baltes, 2000). The relationship could also reflect the idea that decline in both sensorimotor and cognitive function are due to common factors (Lindenberger & Baltes, 1994) that will be explained in greater detail later in this document.

Relationship Between Sensorimotor Functioning and Cognitive Functioning in Older Age

Sensorimotor function seems to be strongly associated with late life cognitive functioning. In a seminal 1994 report, researchers from the Berlin Aging Study (BASE) suggested that almost all (93%) of the age-related variance in a composite measure of cognitive functioning (a general intelligence construct made up of processing speed, reasoning, memory, and fluency) could be explained by sensory and sensorimotor variables such as vision, hearing, and balance (Lindenberger & Baltes, 1994). The same authors later observed similar results in a much larger group of older BASE adults (n=516), as well as with a younger group of adults (25-69 years old). In the latter study, authors observed that the variance shared by sensory and cognitive factors increased from younger adulthood to older adulthood (Baltes & Lindenberger, 1997).

Since the Berlin Aging Study, other research groups have also reported close sensorimotor-cognition relationships cross-sectionally, although the associations have been more modest. For example, in the Maastricht Aging Study, vision was moderately associated with performance on cognitive measures (Valentijn et al., 2005). Correlation coefficients that were calculated from published results suggested that baseline vision was moderately associated with measures of verbal memory (r= 0.30), selective attention/processing speed (r=0.28), simple speed/cognitive flexibility (r=0.40), and processing speed (*r*=0.38). The Australian Longitudinal Study of Ageing (ALSA), observed evidence that visual and auditory acuity could account for the majority (80%) of age-related variance in cognitive functioning, specifically, verbal skills and memory (Anstey, Luszcz, & Sanchez, 2001). In a prospective cohort study, The Hispanic Populations for Epidemiological Studies of the Elderly (H-EPESE; N=2140, aged 65+) found that near vision impairment at baseline, but not distance vision or hearing impairment, was associated with decline in mental status (MMSE) at 2, 5, and 7 years of follow-up (Reyes-Ortiz et al., 2005), and found that those with near vision impairment had a steeper slope of cognitive decline than those with adequate near vision. In another prospective cohort study, Lin and colleagues (2004), studying 6,112 women aged 69 and older, discovered that baseline visual impairment, as well as combined vision and hearing impairment, could predict decline in mental status (MMSE) over a period of two years. Participants with vision impairment at baseline had significantly increased odds of experiencing cognitive decline (OR=1.78, 95% CI=1.21-2.61) and those with combined vision and hearing impairment had even greater odds of cognitive decline (OR=2.19, 95% CI=1.26-3.81).

More recently, indicators of balance have been linked to cognitive function. For example, slower gait speed has been associated with poorer speed/executive attention and memory performance (Holtzer, Verghese, Xue, & Lipton, 2006), and has been shown to predict cognitive impairment and decline (Verghese et al., 2002; 2007, 2008). Increased rates of falling and recurrent falling have also been associated with impairment in executive function and speed of processing (Chen, Peronto, & Edwards, 2012; Herman, Mirelman, Giladi, Schweiger, & Hausdorff, 2010). Some evidence also exists that balance-gait is even more powerful than vision and hearing in accounting for age-related variance in cognition and everyday functioning (Lindenberger & Baltes, 1994; Marsiske, Klumb, & Baltes, 1997; Marsiske et al., 1999).

Longitudinal studies, which do not confound age-related individual differences with other cohort-related differences, have only rarely reported sensorimotor-cognition relationships. Additionally, perhaps partly because of the relatively brief intervals studied in most previous work, only modest associations between rates of change in sensorimotor and cognitive functioning have been reported. ALSA established shared variance in the decline of vision and (episodic) memory (r=0.36), and to a lesser extent, the decline of hearing and memory (r= .14) in a sample of 1,540 non-demented elderly adults (Anstey, Hofer, & Luszcz, 2003). In ALSA, with covariates included in the model, no significant associations between processing speed and vision or hearing existed. Ghisletta and Lindenberger (2005) extended the findings of BASE (N=516, age range 70-103) and found 6-year longitudinal relationships of intellectual and sensory domains, such that overall (mean/level in MLM), close and distance visual acuity were correlated at r=0.45 and r=0.44 with processing speed, respectively, and close and distance visual acuity were correlated at 0.38 and 0.32 with verbal knowledge, respectively. Additionally, in BASE, decline in both close and distance visual acuity within persons was significantly associated with decline in processing speed (r=0.33 and r=0.49). The Maastricht Aging Study observed modest associations between rate of change in visual acuity and change in memory (r=0.26), simple speed/cognitive flexibility (r=0.18), and information processing speed (r=0.23) (Valentijn et al., 2005). Prior to the current investigation, to our knowledge, no studies of the longitudinal coupling of balance/gait and cognition have appeared in the literature.

The question of whether the association between sensorimotor and cognitive functioning is *causal* is unresolved, in part because the mediators of the relationship between sensorimotor and cognitive functioning are not yet fully understood. The next section considers some of these potential mediators.

Potential Mechanisms of Association Between Sensory/Sensorimotor Functioning and Cognitive Functioning

From a theoretical perspective, it is important to understand why sensorimotor and cognitive functioning might be related. Lindenberger & Baltes (1994) proposed a number of conceptual possibilities.

The “direct effects” hypothesis speculates that cognitive performance deficits are a direct result of sensory impairment. In this hypothesis, a clear measure of actual ability is not observed because performance data are obscured by the impairment. In this scenario, a person who is visually impaired will be disadvantaged in testing simply because perception of words/figures is compromised and he/she misinterprets visual stimuli. This scenario argues that elderly adults should be briefly screened for sensory/sensorimotor impairment at the time of cognitive testing so that cognitive performance is not accidentally interpreted as a deficit/decline. Lindenberger, Scherer, and Baltes (2001) argued against the direct effects hypothesis with evidence that simulated sensory deprivation (e.g. visual occlusion filters, noise protectors) did not affect cognitive performance, and the report concluded that common factors were more likely to explain the relationship between sensory and cognitive function.

The “common cause” hypothesis (Lindenberger & Baltes, 1994) postulates that both sensory impairment and cognitive decline are due to a third, unknown, common factor. The idea is that if certain aspects of cognition and of sensory/sensorimotor function share common brain regions or pathways/circuits, this overlapping infrastructure, if declining, degrades both systems and will manifest in observable testing decline. Baltes & Lindenberger (1997) argued that their findings of greater shared variance between sensory and cognitive abilities in older adulthood (relative to younger adulthood) support the common cause hypothesis, as the age-related increase could reflect underlying neurological aging. To the author’s knowledge, no neuroimaging studies have directly tested the common cause hypothesis. However, Salat and colleagues (2004), scanning nondemented 18-to 93- year old participants, described finding widespread age-related thinning of the cortex by middle age, particularly in the prefrontal cortex, and also reported unexpected age-related atrophy in an area very close to the primary visual cortex, the calcarine cortex. This finding of age-related thinning in visual areas, as well as frontal areas, lends some support to the idea of a common-cause connection between sensorimotor and cognitive decline.

The “sensory deprivation” hypothesis suggests that a long-term lack of sensory input can lead to underuse (and possible atrophy) of particular parts of the brain, causing deterioration in related cognitive ability. Sekuler and Blake (1987) suggested that chronic sensory underload can severely limit a person’s level of intellectual interaction with the environment, which may ultimately lead to cognitive deterioration. This deprivation and deconditioning effect can be thought of as the ‘opposite’ of the effect created by enriched, stimulating environments in animal models: increased neural activity and wiring (Speisman et al., 2013; Fan, Liu, Weinstein, Fike, & Liu, 2007). Few studies have directly evaluated the sensory deprivation hypothesis, although it has been repeatedly shown that correction of ‘end-organ’ sensory deprivation, for example through cataract surgery or hearing aids, does not immediately result in cognitive improvement (Valentijn et al., 2005; Hall, McGwin, & Owsley, 2005), which draws support away from this hypothesis.

The “resource allocation” hypothesis is based on the idea that humans have a finite amount of attentional resources, and sensory decline leads to less resource allocation toward cognitive tasks (Baltes & Lindenberger, 1997). In the case of a visual spatial reasoning task, for example, reduced vision may require increased attentional allocation to resolve percepts, thereby diverting attentional resources from reasoning performance. Consistent with this hypothesis, Cabeza and colleagues (2004) discovered increased frontal and decreased sensory (occipital) fMRI activation in old (mean age 70.3) compared to young (mean age 22.6) adults when completing working memory, visual attention, and episodic retrieval tasks. Davis et al. (2007) reinforced these findings and postulated that increased frontal activation with age occurs in reaction to deficient ventral visual and sensory activations,

In the case of the link between balance and cognitive functioning, dual task studies suggest that the two constructs may both be adversely affected if shared attentional resources are degraded, or under conditions of competing attentional demands. For example, walking speed in older adults tends to slow, and the adult becomes less steady, when challenged with a concurrent cognitively demanding task such as talking while walking (Verghese et al., 2007). Dual task studies have also suggested that cognitive performance suffers during concurrent balance-gait challenges, more so at older ages, indicating that dual task costs increase with older age (Lindenberger et al., 2000), and that older adults prioritize motor functioning over cognitive performance (Li, Krampe, & Bondar, 2005; Li, Lindenberger, Freund, & Baltes, 2001).

Contributions of the Current Study

Given the promise of sensorimotor functioning as a predictor of cognitive functioning, and the relative rarity of longitudinal studies that have investigated that relationship, the authors believe that the length of the ten-year ACTIVE dataset provides a unique opportunity to examine both inter-individual differences and intra-individual change in sensorimotor and cognitive functioning. The ACTIVE study is rare in its large, racially and geographically diverse sample, and in the unique combination of vision, balance/gait, and cognition data that were collected from the sample. The inclusion of balance in this study was particularly promising, as it allowed the opportunity to explore longitudinal coupling relationships of balance/gait and cognition, which have not previously been reported. Additionally, the application of relatively new strategies that allow for the analysis of coupled longitudinal change between measures furthered the potential for ACTIVE to provide innovative information about the nature of sensorimotor-cognition relationships.

Summary

As discussed in this literature review, age-related declines in vision, balance, and cognitive functioning are all well documented in the literature. Research groups throughout the United States, Europe, and Australia have investigated whether sensory and sensorimotor variables could serve as functional biomarkers of cognitive aging, with mixed results. Overall, these studies suggest moderate- to-strong sensorimotor-cognition relationships cross-sectionally, yet modest associations longitudinally.

The current investigation focuses not only on the nature of the association between sensorimotor and cognitive functioning, but also tries to determine whether the domains “travel together” over time, in other words, whether they demonstrate evidence of coupled change over the 10 years of the ACTIVE study. The next chapter will discuss the specific aims of the study.

CHAPTER 2
STATEMENT OF PROBLEM

Overview

Cognitive decline and sensory/sensorimotor decline both occur in the final decades of life, and substantial evidence exists to suggest that sensorimotor function is associated with cognitive function in older adults (Anstey et al., 2003; Anstey, Lord, & Williams, 1997; Baltes & Lindenberger, 1997; Dulay & Murphy, 2002; Li & Lindenberger, 2002; Lindenberger & Baltes, 1994; Salthouse, Hambrick, & McGuthry, 1998; Salthouse, Hancock, Meinz, & Hambrick, 1996). Moderate-to-strong sensorimotor-cognitive associations, however, have been found primarily in cross-sectional studies, while there is less evidence regarding shared associations over time. One reason for this is that there are relatively few longitudinal studies of aging of significant length that have collected both sensorimotor and cognitive data.

As previously mentioned, the ACTIVE study followed a large (N=2,802) sample of cognitively normal elderly adults over a period of ten years. The study collected measures of visual acuity and balance, along with numerous measures of cognitive functioning. The current investigation attempted to characterize sensorimotor and cognitive function and ten-year change in the ACTIVE sample. It also aimed to determine whether the two areas of function were related, both overall and in rate of decline. There were three specific aims of the study.

Description and Comparison of Change in Sensorimotor and Cognitive Measures

Aim 1

The purpose of the first aim was to describe ten-year change in sensorimotor and cognitive functioning, by comparing rates of change for sensorimotor and cognitive variables.

Hypothesis 1

Both age-related sensorimotor and cognitive decline over the 10 years of ACTIVE was expected, and it was also expected that adults of older age would have poorer cognitive and sensorimotor functioning, as well as steeper rates of decline as the study progressed, relative to their younger counterparts. This hypothesis was driven by previous reports of age-related decline in vision (Schneider & Pichora-Fuller, 2000), balance (Bohannon et al., 1984), and fluid cognitive abilities included in this study (Drag & Bieliauskas, 2010, Christensen, 2001; Grady & Craik, 2000; Salthouse, 1982) .

Associations Between Sensorimotor and Cognitive Variables

Aim 2

The second aim was to determine whether sensorimotor functioning was related to cognitive functioning at both the between- and within-subjects levels. Specifically, the aim was to determine whether sensorimotor functioning was related to cognitive functioning at the interindividual level, and whether change in sensorimotor functioning over the ten years of ACTIVE was related to change in cognitive functioning at the within-subjects level.

Hypothesis 2

Based on previous studies in which strong age-cognition associations were reported between subjects (Lindenberger & Baltes, 1994; Valentijn et al., 2005; Anstey et al., 2001), and to a lesser extent within-subjects (Anstey et al., 2003; Ghisletta & Lindenberger, 2005; Valentijn et al.) it was expected that those with poorer levels of sensorimotor functioning (on average) would also have poorer cognition, and that those who experienced more sensorimotor decline over time would also experience more cognitive decline. Associations were expected to be stronger at the between-subjects level than the within-subjects level.

Baseline and Longitudinal Mediation

Aim 3

Aim 3 was to investigate whether sensorimotor change might account, at least in part, for cognitive change. At baseline, the aim was to determine whether individual differences in vision and balance/gait would mediate age-related variance in cognition. An illustration of this relationship can be found in Figure 2-1. We also aimed to determine whether mediation would occur longitudinally, in other words, whether 10-year cognitive change variance could be accounted for by concurrent balance and vision changes.

Hypothesis 3

Based on previous cross-sectional research, it was expected that changes in vision and balance would either partially or fully account for the age-related variance in cognitive variables (Lindenberger & Baltes, 1994). It was also expected that age-related change in cognition over 10 years would be somewhat accounted for by concurrent balance and vision changes, although to our knowledge this has never been investigated before.

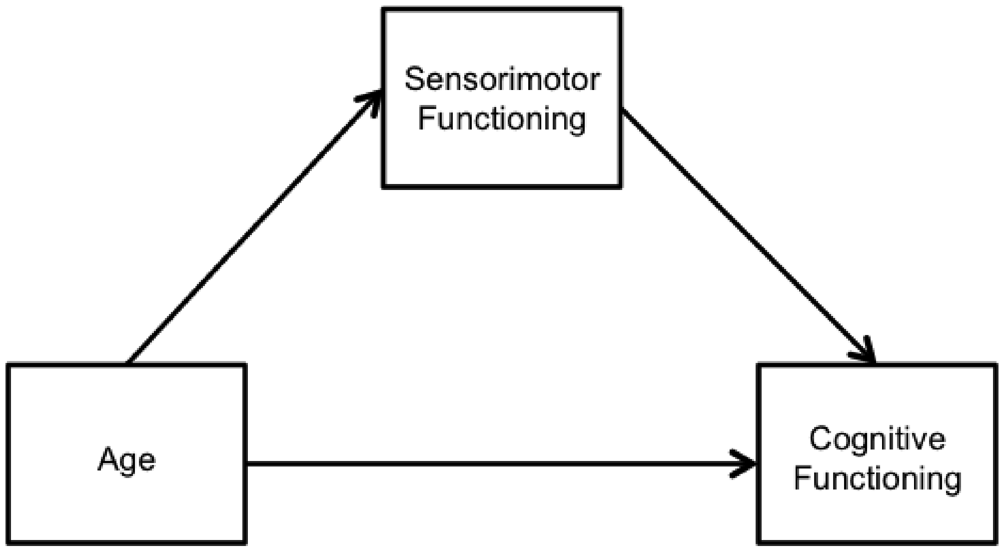

Figure 2-1. Hypothesized mediation relationships.

CHAPTER 3
RESEARCH DESIGN AND METHODS

Overview

The Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) is a recently completed 10-year longitudinal study of cognition and general functioning in elderly adults. The present study utilized data from ACTIVE in an attempt to explore relationships between sensorimotor and cognitive functioning in the elderly. In the following sections, an overview of the ACTIVE study is presented, followed by a description of the present study sample, procedures, measures, and proposed statistical analyses for exploring sensorimotor-cognitive associations.

ACTIVE Study

Design

ACTIVE was a randomized, controlled, single-blind trial of the elderly that evaluated the effects of three cognitive training interventions on cognitive abilities and daily functioning. The interventions consisted of training in memory, reasoning, or speed of processing, all of which are empirically supported for improving their targeted cognitive ability. Briefly, assessment of cognitive functioning was conducted at baseline, 1 month post-training, and at 1, 2, 3, 5, and 10 years post-initial training. The full ACTIVE study and design is described in detail by Jobe and colleagues (2001), Ball and colleagues (2002), Willis and colleagues (2006), and Rebok and colleagues (2014).

Recruitment

Recruitment occurred between March 1998 and October 1999 at six different field sites in the United States. Recruitment strategies and sources varied by site; strategies included on-site presentations, advertisements in the newspaper, introductory letters and follow-up telephone calls. The University of Alabama (UAB) recruited participants through the Alabama Department of Public Safety and UAB eye clinics. The Hebrew Rehabilitation Center for Aged recruited from congregate and senior housing sites, senior centers, and a research volunteer registry. Indiana University recruited through a network of facilities providing activities and social services to seniors, in addition to local churches and senior citizens' organizations. Johns Hopkins University recruited from senior community organizations and centers, churches, senior housing, and programs offering or coordinating wellness or service programs for seniors. Pennsylvania State University recruited through a state-funded pharmaceutical assistance program for low-income elders. Wayne State University recruited from a range of community organizations, churches, hospital-based senior assessment centers, senior-housing sites, and driver registration lists.

Eligibility

In an effort to yield a sample of healthy and stable older adults, potential participants were excluded from the study if they a) were <65 years of age at screening; b) had existing cognitive deterioration (measured by a score of 23 or less on the Mini-Mental State Examination Exam (MMSE; Folstein, Folstein & McHugh, 1975) or if they self-reported that they had dementia or Alzheimer's Disease; c) experienced trouble completing activities of daily living (ADL) (Morris et al., 1997); d) had severe medical conditions that would likely result in participants exiting study before the end of 2-year assessment period, e) experienced severe sensory losses (self-reported difficulties when reading print media or performance-based vision test scores exceeding 20/50) (Mangione et al., 1992); f) had severe communication difficulties that would prohibit them from completing the study protocol (interviewer-rated); g) had recent cognitive training or h) had scheduling difficulties that would prohibit them from completing all phases of the study.

Participants

ACTIVE Sample

The ACTIVE study sample at baseline consisted of 2,802 adults between the ages of 65-94. Following baseline assessment, participants were randomly assigned to one of four training conditions: memory training (n=703), reasoning training (n=699), speed training (n=702), or no-contact control (n=698). The no-contact control group allowed for observation of natural rates of change in sensorimotor functioning and cognitive functioning. 11 months post-completion of cognitive training, participants who completed at least 80% of their training were randomly selected to take part in four booster training sessions in their intervention. Psychometric testing was conducted at baseline, post 10-session cognitive intervention (or no contact control), and one, two, three, five, and ten- years post-intervention. Testing included measures of memory, reasoning, perceptual speed, attention, and language, which are described above.

Of the original 2,802 study participants, 1,220 participated in the 10-year follow-up visit. The data collected from this visit was used in the present study's longitudinal analyses. Demographic information for the baseline sample, as well as for the sample at the 10- year post-intervention extension can be found in table 3-1. As determined by comparison to a large (N=10,487) survey sample of retirees, the baseline ACTIVE sample was slightly younger, more educated, more female, and included more African Americans than average, but overall was nationally representative of elderly adults (Prindle & McArdle, 2013).

Attrition

The ACTIVE sample, along with most longitudinal trials of cognitive aging, was prone to attrition because of the elderly sample and the lengthy follow-up period. The longitudinal retention pattern of the study sample is presented in Figure 3-1. Age of participants, loss of functional independence, change in residence, disability and institutionalization were predictors of dropout in the larger ACTIVE study, as were having a close family member suffering from serious illness, and death. To characterize selectivity of longitudinal attrition, participants still present at year 10 were compared to those who were not present at year 10. Results from these analyses are presented in table 3-3. Relative to those who were present at year 10, participants who were not present had, on average, slightly but significantly less education, lower MMSE scores, and were older at baseline ($p<.001$). A weak but significant association between gender and study presence also existed, with females being more likely to attend the year 10 follow-up visit than males. Worse performance on cognitive outcomes was also a predictor of attrition at year 10 follow-up (Rebok et al., 2014).

Measures

Cognitive Measures

The cognitive measures used in the present study were influenced by previous ACTIVE literature (e.g. Ball et al., 2002), which demonstrated that the measures contained sufficient variance for the present analyses. These measures are listed below in table 3-2, and are described in greater detail later in this section.

For the needs of the present study, composite values of individual cognitive measures were calculated to represent the cognitive domains of Memory, Reasoning, and Perceptual Speed/Attention. Composite values were calculated by standardizing and averaging individual measures, for example, the Memory domain score for an individual participant at a given visit was calculated by averaging their HVLT, AVLT, and RBMT-PR scores as listed below in table 3-2.The Reasoning domain consisted of an average of Letter Series, Letter Sets, and Word Series. Perceptual speed and attention were represented by an average of Useful Field of View Tasks 1-4. The individual measure of Digit-Symbol Substitution was used to roughly represent the domains of Processing Speed and Attention.

Memory

Memory was included as a domain because it has been shown to decline with advancing age (Schaie, 1996). In ACTIVE, basic memory was assessed with three main measures: Hopkins Verbal Learning Test, Related Word Lists (HVLT; Brandt, 1991); Rey Auditory-Verbal Learning Test, Unrelated Word Lists (AVLT; Rey, 1941); and the Rivermead Behavioral Memory Test, Paragraph Recall task (RBMT-PR; Wilson, Cockburn, & Baddeley, 1985).

For the HVLT, participants were asked to learn and recall a list of 12 words that could be grouped into three semantic categories (e.g. precious stones, animals). The lists were read and recalled three times. A recognition task challenged participants to distinguish between words from the target list, new words from the same semantic categories, and semantically unrelated words. Scores were tallied across the three trials and ranged from 0-36. The HVLT has a test-retest reliability of 0.73 (Ball et al., 2002).

The AVLT consisted of a 15-item word list that was read aloud with an 8-second pause between each word. Following word presentation, participants were asked to write down as many of the words as they could remember in two minutes, in any order. List reading and recall writing was repeated five times, and scores (0-15 on each trial) were summed for a total possible raw score range of 0 to 75. The AVLT has a test-retest reliability of 0.78 (Ball et al., 2002).

The RBMT-PR evaluated story memory. Participants were directed to listen to an audiotaped story, then write down everything that they could remember from the story. The story consisted of 21 idea units, or individual lexical items, that participants could receive up to 1 point each for (0=not recalled, 0.5=approximately accurate, 1=completely accurate). The RBMT-PR has a test-retest reliability of 0.60 (Ball et al., 2002).

Reasoning ability

Reasoning was assessed in ACTIVE with the Letter Sets (Gonda & Schaie, 1985), Letter Series (Thurstone & Thurstone, 1949), and Word Series (Ekstrom, French, Harman, & Derman, 1976) tasks, which are standardized paper and pencil measures.

The Letter Sets task consisted of five sets of four letters each, and participants were asked to determine which set of letters within the five was different from the rest.

The participant was given 15 of these items to complete within 7 minutes. Possible scores ranged from 0-15, with one point given for each correct item, and higher scores indicating better performance. Letter sets has a test-retest reliability of 0.69 (Ball et al., 2002).

The Letter Series task consisted of a sequence of letters with an identifiable pattern, and participants were asked to choose the letter that should go next in the series from a choice of five letters. 30 sequences were given to complete within 6 minutes. Possible scores ranged from 0-30, with one point given for each correct item, and higher scores indicating better performance. The Letter Series task has a test-retest reliability of 0.86 (Ball et al., 2002).

The Word Series task consisted of a series of words (days of the week, months of the year) with a pattern, and participants were asked to choose the next day/month that should come in the series, from a choice of five words. The participant was given 30 sequences to complete within 6 minutes. Possible scores ranged from 0-30, with one point given for each correct item, and higher scores indicating better performance. The Word Series task has a test-retest reliability of 0.84 (Ball et al., 2002).

Perceptual Speed

Basic visuospatial perceptual speed was measured with the UFOV Task 2 and Task 3. UFOV Task 2 measured divided attention with a computer task in which a car or truck was presented in the center of the computer screen (central stimulus), while concurrently a picture of a car was presented at one of eight locations on the computer screen (peripheral stimulus). Participants were scored on the accuracy of their judgment of whether the central stimulus was a car or truck, and also scored on the judgment of the location of the peripheral stimulus on the computer screen. UFOV Task 3 measured selective attention and was very similar to Task 2, with the addition of greater distraction in the form of visual clutter (numerous small triangles between the central and peripheral stimuli). For both Tasks 2 and 3, the score reflected the minimum stimulus duration that the participant needed in order to respond correctly 75% of the time. Higher scores represented worse performance, as they represented more time needed (longer latency) to produce correct responses. A composite measure of Tasks 2 and 3 was computed for this study. The test-retest reliability of Tasks 2 and 3, plus a third not used in this study, was 0.80 (Ball et al., 2002).

Processing Speed and Attention

These domains were evaluated with the Digit-Symbol Substitution task, which required the participant to use a key to match numbers to symbols, filling in empty boxes located beneath numbers with the corresponding symbol. The participant was given 90 seconds to complete the task, and higher scores indicated better performance.

Sensorimotor Measures

The two independent variables available in ACTIVE to represent sensorimotor functioning were visual acuity and balance/gait. As described in the Literature Review, these two sensory/sensorimotor domains decline have been shown to decline with age in an exponential fashion, and are indicators of broader sensorimotor functioning.

Visual acuity

Visual acuity was measured at screening and at every post-test from years 2-10 with a GOOD-LITE LD-10 Chart inside a GOOD-LITE Model 600A light box. The chart was located at a standard 10-foot distance from the participant’s eye. The participant was asked to read rows of letters, and distance visual acuity scores ranged from 0-90, with higher scores indicating better vision. Those with scores of 39 or below were ineligible for the study.

Balance/Gait

Balance-gait was assessed at baseline and at every post-test from years 2-10 with the Turn-360 test. Participants were directed to turn in a complete circle, and the number of steps that were required for them successfully complete the fastest, safest 360-degree turn was recorded. Fewer steps indicated better balance.

Additional Covariates for Statistical Modeling

Baseline predictors of selective dropout (age, education, race, general health, gender, depression, MMSE) were included in models to adjust for attrition over time. Retest and training effects were also controlled for. General health was measured with the General Health subscale of the MOS Short Form Health Survey (SF-36; Ware & Sherbourne, 1992). The Center for Epidemiological Studies-Depression-12 scale (CES-D) was used to assess depressive symptom severity (Radloff, 1977). The Mini-Mental State Examination (MMSE; Folstein et al., 1975) was used to measure global functioning.

Statistical Analyses

This study addressed three primary experimental hypotheses. First, we aimed to describe change in participants' sensorimotor and cognitive functioning over the ten years of enrollment in the ACTIVE study (Aim 1). Next, we attempted to determine whether, on average, sensorimotor functioning of ACTIVE participants was related to their cognitive functioning, and whether these abilities declined together over time (Aim 2). Finally, we attempted to determine whether there was evidence in the ACTIVE study of sensorimotor mediation of the relationship between age and cognitive functioning (Aim 3).

Multilevel modeling (MLM), a statistical approach that is also known as mixed effects modeling or hierarchical linear modeling (Bryk & Raudenbush, 1992), was chosen as a primary method of analysis for the present study. MLM is an extension of the linear model and allows for the estimation of interindividual (between-person) differences in intraindividual (within-person) change. In other words, it allows for the measurement of individual differences in patterns of performance over time.

MLM was chosen for the present study in part because it models longitudinal change without using case-wise exclusion in the face of missing data, which is common in multiple-occasion studies. Instead, assuming that absent data is missing at random, MLM includes all available data points (Singer & Willett, 2003) using a full information likelihood approach. Attrition-related bias of results is minimized with the MLM approach. As mentioned previously, about half of ACTIVE's participants were lost to attrition between baseline and the year 10 follow-up visit. Attrition-related, in addition to training-related, covariates were adjusted for appropriately in analyses that follow.

All data were blom-normalized to make them appropriate for modeling and SPSS Version 21 was used to conduct all analyses. Detailed information about statistical analyses for Aims 1-3 is presented below.

Aim 1

To address the descriptive Aim 1, two types of MLMs were employed. First, an unconditional means model was run for each individual sensorimotor [Visual acuity; Balance (steps)] and cognitive composite (Memory; Reasoning; UFOV; Digit-Symbol Substitution) to determine the total variance that was available to be explained in each variable. In these unconditional means models, there were no predictors, and only the fixed and random effects of the intercept were estimated. The intraclass correlation (ICC) was calculated to determine the amount of variance in each cognitive composite that was due to between person differences versus within-person changes.

A second set of MLMs, unconditional latent change models, were designed to determine between- and within- person associations of age and functioning in the six sensorimotor and cognitive domains. MLM has the ability to estimate both fixed effects, or “average effects” that apply to all participants, and random effects, which vary across participants, simultaneously. One MLM was run for each dependent variable domain, and estimated the fixed effects of linear and quadratic age (age squared), along with the random effects of linear age, on each. These MLMs covaried training as well as predictors of selective attrition (education, mental status, gender, race, depression, and self-rated health). One consolidated “age basis” graph was created to present, in common metric, the relative age-related differences and longitudinal rates of change in the six domains. The equation for the MLM modeling was:

$$Memory_{ij} = \pi_{0i} + \pi_{1i}(Age) + \pi_{2i}(Age^2) + \pi_{3i}(Retest) + \varepsilon_{ij}$$

$$\pi_{0i} = \gamma_{00} + \gamma_{01}Intervention + \gamma_{02}Education + \gamma_{03}MMSE + \gamma_{04}Gender + \gamma_{05}White + \gamma_{06}SF36GH + \gamma_{07}CESD$$

$$\pi_{1i} = \gamma_{10} + \gamma_{11}(Age*Intervention) + \zeta_{1i}$$

$$\pi_{2i} = \gamma_{20}$$

$$\pi_{3i} = \gamma_{30}$$

This model was repeated identically for dependent variables $Reasoning_{ij}$, $UFOV_{ij}$, and Digit Symbol $Substitution_{ij}$

Aim 2

The first goal of Aim 2 was to determine whether sensorimotor functioning was related to cognitive functioning on average, in other words, whether participants who had the poorest sensorimotor functioning also had the poorest cognitive functioning. The second goal was to determine whether individuals who experienced the greatest amount of sensorimotor decline over time also experienced the greatest amount of cognitive change, in other words, whether rates of decline over ten years were associated in the two areas.

Aim 2 drew heavily on a multivariate MLM approach, particularly its ability to test and hypotheses at both the within- and between person levels separately (Sliwinski & Hofer, 1999). An unconditional growth model produced both a “G” (between-persons) random effect covariance structure matrix and an “R” (within-persons) residual covariance matrix. The values produced by the two covariance matrices were rescaled into correlations in Microsoft Excel, using the following formula:

$$\text{Correlation}_{x,y} = \text{covariance term}_{x,y} / \sqrt{\text{var}\,iance_x} * \sqrt{\text{var}\,iance_y}$$

Bivariate correlational coupling between sensorimotor and cognitive variables was evaluated to determine the mean overall associations between domains, as well as the association of within-person changes over time between domains. Statistical significance of correlations was determined from the MLM estimates of covariance parameter values.

The equation for Aim 2 MLM modeling was:

$$Values = \pi_{0i} + \pi_{1i}*Measure_{ij} + \varepsilon_{ij}$$
$$\pi_{0i} = \gamma_{00} + \zeta_{0i}$$
$$\pi_{1i} = \gamma_{10} + \zeta_{2i}$$

The between-subject variance in the model (ζ_{0i}) addressed how individual differences across the cognitive measures were related (i.e., “Were persons higher in reasoning also higher in vision?”). The within-subject variance in the model (ζ_{2i}) addressed how within-person changes were related (i.e., “On those occasions where participants’ were higher in reasoning, were they also higher in vision?”)

Aim 3

The third aim was to determine whether evidence existed of sensorimotor mediation of age-related variance in cognitive functioning. Two analyses were performed for Aim 3.

Cross-sectionally, the authors examined whether individual differences in baseline vision and balance/gait would mediate age-related individual differences in each cognitive domain. Direct and indirect effects of age on cognition were tested using a bootstrapped mediation approach [MEDIATE dialog for SPSS, 1000 bootstrapped samples, Hayes & Preacher (in press)]. Regardless of normality in variables, estimates of indirect effects tend to be positively skewed and kurtotic, rendering z-test and p-values unreliable. Therefore, in this study, the creation of bootstrapped estimates, standard errors, and confidence intervals was necessary to accurately measure and interpret mediation effects. Pedhazur’s Communality Analysis (Pedhazur, 1997), which partitions variance into unique and common effects, was subsequently used to determine the amount of age-related variance in cognitive composites that could be accounted for by vision and balance.

Longitudinally, the authors examined whether any of the age-related linear change in cognition over 10 years could be accounted for by concurrent balance and vision changes. Initial unconditional growth models estimated the fixed effects of linear and quadratic age, as well as the random effect of linear age. Initial models were compared to a second set of models that included time-varying visual acuity and balance. These models were used to approximate "longitudinal mediation" of age-related cognitive decline by sensorimotor decline. Significant reduction in random variance of linear change would indicate that, at least to some extent, individual differences in participants' rates of change would be accounted for by time-varying sensorimotor functioning.

The equations for Aim 3 MLM modeling were:

Model 1:

$$Memory_{ij} = \pi_{0i} + \pi_{1i}(Age) + \pi_{2i}(Age^2) + \varepsilon_{ij}$$

$$\pi_{0i} = \gamma_{00} + \zeta_{0i}$$

$$\pi_{1i} = \gamma_{10} + \zeta_{1i}$$

$$\pi_{2i} = \gamma_{20}$$

Model 2:

$$Memory_{ij} = \pi_{0i} + \pi_{1i}(Age) + \pi_{2i}(Age^2) + \pi 3iVision_{ij} + \pi 4iSteps_{ij} + \varepsilon_{ij}$$

$$\pi_{0i} = \gamma_{00} + \pi_{01}Vision_{mean} + \pi_{02}Steps_{mean} + \zeta_{0i}$$

$$\pi_{1i} = \gamma_{10} + \zeta_{1i}$$

$$\pi_{2i} = \gamma_{20}$$

$$\pi_{3i} = \gamma_{30}$$

$$\pi_{4i} = \gamma_{40}$$

These two-stage models (unconditional growth, followed by conditional growth with Level 1 & 2 steps and vision added as predictors) were also repeated identically for dependent variables $Reasoning_{ij}$, $UFOV_{ij}$, and Digit Symbol $Substitution_{ij}$

Table 3-1. Sociodemographic characteristics of the ACTIVE sample at baseline and at Year 10

	Baseline Sample (N=2,802)			Sample at Year 10 (N=1,220)		
	Mean	S.D.	Range	Mean	S.D.	Range
Baseline Age, years	73.63	5.91	65-94	72.31	4.90	65-94
Years of Education	13.53	2.70	4-20	13.78	2.60	6-20
Baseline MMSE	27.31	2.01	23-30	27.70	1.89	23-30
Gender	%			%		
Women	75.9			79.8		
Men	24.1			20.2		
Race						
White	73.1			75.6		
African American	25.9			23.5		
Other/Unknown	0.8			0.4		

MMSE: Mini-Mental State Examination

Table 3-2. Table 3-2. Cognitive measures utilized in the present study, listed by cognitive domain represented.

Domain	Test	Published Source	Reliability
Memory	HVLT	Brandt, 1991	0.73[a]
	AVLT	Rey, 1941	Recall: 0.78[a] Recognition: 0.36[b]
	RBMT-PR	Wilson et al., 1985	0.60[a]
Reasoning	Letter Series	Thurstone & Thurstone, 1949	0.86[a]
	Letter Sets	Ekstrom et al., 1976	0.69[a]
	Word Series	Gonda & Schaie, 1985	0.84[a]
Perceptual Speed	UFOV Tasks 1-4	Ball et al., 1993	Task 1: 0.69[c] Tasks 2&3 Composite:0.78[d]
Processing Speed/Attention	Digit-Symbol Substitution	Wechsler, 1981	0.82[e]

Note. HVLT=Hopkins Verbal Learning Test; AVLT= Rey Auditory Verbal Learning Test; RBMT-PR=Rivermead Behavioural Memory Test- Paragraph Recall; UFOV=Useful Field of View; MMSE=Mini-Mental State Examination. *Reliabilities are all test-retest correlations; [a]Ball et al., 2002; [b]Schmidt, 2004, one year interval; [c]Edwards et al., 2005; [d]Calculated using ACTIVE control group, 12 week interval; [e]Wechsler, 1981

Table 3-3. Sample attrition, comparing participants assessed at Year 10 to those not assessed at Year 10

Characteristic	Assessed at Year 10 (N=1,220)	Not Assessed at Year 10 (N=1,582)	*t*	*d*	χ^2	*p*
Baseline Age, years	72.31	75.52	15.27	0.58		0.000
Education, years	13.78	13.34	-4.24	0.16		0.000
MMSE	27.70	27.01	-9.18	0.35		0.000
Sex, %Female	79.8				18.53	0.000
Race, %White	75.6				5.60	0.018

MMSE: Mini-Mental State Examination

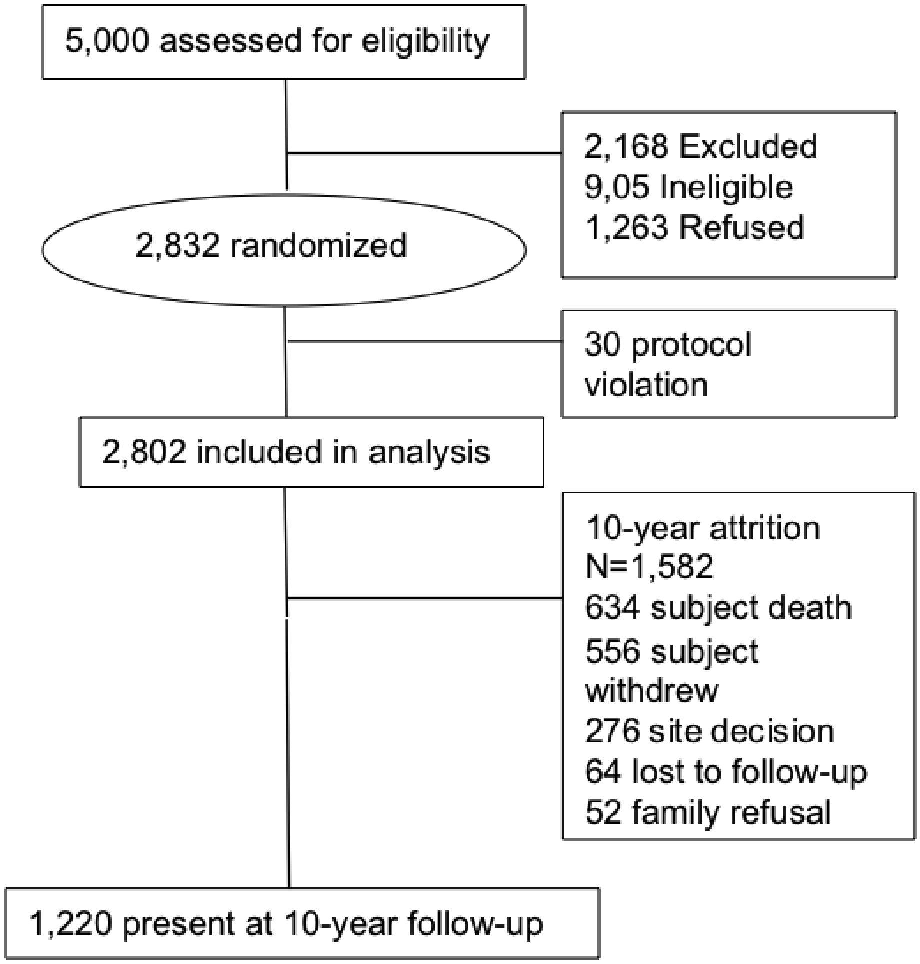

Figure 3-1. Profile of the full ACTIVE trial.

CHAPTER 4
RESULTS

Aim 1: Descriptive Aim

The first aim was to describe change in participants' sensorimotor and cognitive functioning over the ten years that they were enrolled in the ACTIVE study. MLM was utilized, first with an unconditional means model with no predictors, and then with an unconditional growth model that included both linear and quadratic age.

Unconditional Means Model and Intraclass Correlation

To determine the total variance to be explained in each cognitive variable, as well as to determine the percentage of between-person vs. within person-variance in each, we ran an MLM unconditional means model with no predictors and calculated the intraclass correlation (ICC).

As shown in Table 4-1, the null model with no predictors suggests that there are significant differences between persons on all cognitive and sensorimotor measures ($p<.001$), and significant within-person variation (change over time, occasion-to-occasion fluctuation) in performance on each cognitive and sensorimotor measure across study visits ($p<.001$). The intercept and residual variance in Table 4-1 provide estimates of the total between- and within-person variance, respectively, that exists. Future models including sensorimotor predictors will be evaluated, in part, by their ability to reduce this amount of unexplained variability.

To calculate the intraclass correlation (ICC) for cognitive composites, which gives the amount of variance due to between person differences versus within-person changes, the following equation was used: ICC = BPvar/ (BPvar + WPvar).

Over 80% of the variance to be explained in Digit-Symbol Substitution task and Reasoning composite performance was determined to be at the between-subjects level, as was over 70% of the variance in Memory composite performance and over 60% of the variance in UFOV composite performance. Calculations immediately follow.

Memory composite ICC: 0.504217/ (0.5042 + 0.2116) = 0.7043

Reasoning composite ICC: 0.701030/ (.7010 + 0.1232)= 0.8505

UFOV composite ICC: 0.647369/ (0.6473 + 0.3839)= 0.6277

Digit-Symbol Substitution ICC: 0.822789/ (0.8229 + 0.186379) = 0.8153

These calculations alerted the authors to the fact that among all of the variability in cognitive performance over the ten years of ACTIVE, the majority of the variance to be explained in each cognitive domain was due to performance differences between individuals. The within-person change, therefore, constituted the minority of the variance for all four domains, with approximate values of 30%, 15%, 37%, and 18% for Memory, Reasoning, UFOV, and Digit-Symbol Substitution, respectively. Nevertheless, these calculations revealed that there was sufficient variability to be explained at the both between- and within-person levels. The relative proportions of variance to be explained based on the null model are depicted in Figure 4-1.

Unconditional Change Model

Unconditional latent change models were utilized to determine any age-related differences and/or decline in areas of sensorimotor and cognitive functioning that occurred in participants during the ten years of ACTIVE. The unconditional change models included both linear and quadratic age, and covaried for training and predictors of selective attrition (education, mental status, gender, race, depression, and self-rated health). Results from these models can be found in Table 4-2 below.

As described in Table 4-2, and illustrated in Figure 4-2, a negative linear relationship between age and vision suggested that vision had a fairly constant rate of decline across the age range studied. For all other sensorimotor and cognitive variables, in addition to linear decline with age, significant quadratic trends indicated that the rate of decline accelerated as participants aged.

Depicted in Figure 4-2 is an “age basis” graph of change (McArdle & Epstein, 1987; McArdle, Fisher, & Kadlec, 2007), in which each person’s performance is represented at each age in which they are represented in the study. For example, if a participant was tested at ages 67, 68, 69, 70, 72, and 77, then the curve would include data points from each of these visits. Visual comparison of rates of change suggest roughly uniform slopes across domains, although judging from visual inspection, UFOV was the most sensitive to age effects and had the steepest decline, followed by Digit-Symbol Substitution, Balance, Memory, and Reasoning. Visual acuity appeared to have been the least age-affected domain across the ten years of ACTIVE data collection.

Aim 2: Mean (Between-Participants) and Longitudinal Associations Between Sensorimotor and Cognitive Variables

Aim 2 examined bivariate associations between our sensorimotor and cognitive variables both at the between- and within-subjects levels, using a multivariate unconditional means MLM model (all variables serve as DVs) and calculating correlations from the resulting residual (R) and random (G) covariance matrices.

Between-Subject Associations

In absolute size, small but significant between-person correlations between variables ranged from 0.08 (visual acuity with Memory) to 0.46 (UFOV with Reasoning). In terms of sensorimotor-cognition pairings, on the whole, both better visual acuity and balance were associated with better performance in all cognitive areas. Visual acuity was positively correlated with scores for Digit-Symbol Substitution ($r = 0.11$, $p<.001$), Memory ($r=0.08$, $p<.001$), and Reasoning ($r=.08$, $p<.001$), such that persons with vision were more likely to have higher cognitive measure scores, and was negatively correlated with UFOV, such that persons with better vision evinced faster UFOV performance ($r=-0.15$, $p<.001$). Balance (steps) was negatively correlated with scores for Digit-Symbol Substitution ($r=-0.19$, $p<.001$), Memory($r=-0.17$, $p<.001$), and Reasoning ($r=-0.20$, $p<.001$), and positively correlated with UFOV performance ($r=0.32$, $p<.001$) such that persons who had better balance (required fewer steps) had better performance in all cognitive domains. Table 4-3 displays between-person bivariate correlational associations between these measures of sensorimotor and cognitive function.

Within-Subject Correlational Coupling

At the within-subjects level, very small but significant absolute couplings in rates of change were found between each sensorimotor-cognitive pair, suggesting that change in sensorimotor functioning over the ten years of ACTIVE was related to change in cognitive functioning. In terms of absolute values, significant within-person correlations between variables were more modest than those found at the between-subjects level. Change in visual acuity was associated with change in Digit-Symbol Substitution ($r= 0.04$, $p<.001$), Memory($r=0.03$, $p<.001$), Reasoning ($r=.01$, $p<.05$), and

UFOV performance (r=-0.03, p<.001). Change in balance (steps) was associated with change in Digit-Symbol Substitution (r=-0.11, p<.001), Memory (r=-0.12, p<.001), Reasoning (r=-0.06, p<.001), and UFOV performance (r=0.03, p<.001). Taken together, these findings suggest that pairs of sensorimotor and cognitive abilities decline together within subjects over time. Table 4-4 displays within-person bivariate coupling coefficients between measures of sensorimotor and cognitive function.

Aim 3: Baseline and Longitudinal Mediation

Baseline Mediation

The first part of Aim 3 examined, in baseline data, whether Lindenberger & Baltes' 1994 BASE findings that sensorimotor variables mediate age related individual differences in cognition could be replicated in ACTIVE. Lindenberger & Baltes found that sensorimotor variables explained 50% of the variance in a general composite of intelligence, and almost 100% of the age-related variance (full mediation). Using the SPSS Preacher and Hayes MEDIATE dialog (Hayes & Preacher, in press) with 1000 bootstrap samples, and Pedhazur's Communality Analysis (Pedhazur, 1997), we found consistent but more modest findings than those observed in BASE.

Reasoning. Together, visual acuity and balance (steps) explained 6.7% of the overall variance in Reasoning, and accounted for (.046/.085) 54% of the age-related variance. This represented a significant indirect mediation effect. This was only partial mediation, because the residual effect of cross-sectional age, while small (.039), and reduced from its initial bivariate effect (.085), was still significantly greater than zero (p<.05).

Memory. Together, visual acuity and balance (steps) explained 6.1% of the variance in Memory, and accounted for (.049/.105) 47% of the age-related variance in

Memory. This represented a significant indirect mediation effect. This was only partial mediation, because the residual effect of cross-sectional age, while small (.056), and reduced from its initial bivariate effect (.105), was still significantly greater than zero ($p<.05$).

UFOV. Together, visual acuity and balance (steps) explained 7.5% of the variance in UFOV, and accounted for (.056/.132) 42% of the age-related variance in UFOV. This represented a significant indirect mediation effect. This was only partial mediation, because the residual effect of cross-sectional age, while small (.076), and reduced from its initial bivariate effect (.132), was still significantly greater than zero ($p<.05$).

Digit-Symbol Substitution. Together, visual acuity and balance (steps) explained 8.8% of the variance in Digit-Symbol Substitution, and accounted for (.055/.091) 60% of the age-related variance in DSS. This represented a significant indirect mediation effect. This was only partial mediation, because the residual effect of cross-sectional age, while small (.036), and reduced from its initial bivariate effect (.091), was still significantly greater than zero ($p<.05$).

Overall, approximately half of the age-related variance in each cognitive composite at baseline was accounted for by vision and balance. In other words, significant ($p<.05$) indirect effects of age on each cognitive composite were observed, through vision and balance. Figure 4-5 illustrates this mediation of age-related individual differences in cognition by sensorimotor factors, and tables 4-5 and 4-6 provide statistical information regarding mediation.

Longitudinal Mediation

Aim 3 also examined, in longitudinal data, whether 10-year cognitive change variance in participants could be accounted for by concurrent balance and vision changes. Unconditional growth models were used to observe differences in random variance in linear age between two models with and without time-varying visual acuity and balance (steps). Reduction in this age-related variance in cognitive variables after the inclusion of sensorimotor variables was considered to represent "longitudinal mediation," although no formal mediation tests were run.

"Partial mediation" occurred in Memory, and "full mediation" occurred in the Reasoning, UFOV, and Digit-Symbol Substitution domains. Full mediation was defined as significant unexplained variance in the first model that was no longer significant after inclusion of vision and balance in the second model. As shown in Table 4-7, reduction in the random variance in linear age was observed in all four cognitive composites after the inclusion of vision and balance in the model. In terms of percentage of reduction of age-related variance, Reasoning had the greatest percentage reduction (81%), followed by UFOV (63%), Digit-Symbol Substitution (52%), and Memory (45%). These results are depicted in bar graphs in Figure 4-6.

Table 4-1. Estimates of fixed and random effects of the intercept for the unconditional means model (no predictors) for each cognitive and sensorimotor variable

				Between person (intercept)		Within person (residual)	
Dependent Variable	-2LL	AIC	BIC	Variance	p	Varian ce	p
Memory Composite	20522.31	20528.31	20550.26	0.5042	0.000	0.2116	0.000
Reasoning Composite	16697.72	16703.72	16725.67	0.7010	0.000	0.1232	0.000
UFOV Composite	26413.54	26419.54	26441.50	0.6474	0.000	0.3839	0.000
Digit-Symbol Substitution	20351.49	20357.49	20379.39	0.8228	0.000	0.1864	0.000
Visual Acuity (Snellen Chart)	22510.28	22516.28	22537.58	0.5300	0.000	0.4600	0.000
Balance (Turn-360 Test Steps)	21861.45	21867.45	21888.52	0.4540	0.000	0.5500	0.000

Table 4-2. Estimates of fixed and random effects from unconditional change model including linear and quadratic age. Covariates include training, age x training interaction, restest, education, gender, race, and baseline values of MMSE, CES-D, and self-reported health

Dependent Variable	Fixed Effect	Estimate	S.E	df	*t*	*p*	Random Effect	Estimate	S.E	Wald *Z*	*p*
Memory Composite	Intercept	-0.17	0.02	2707.10	-7.04	0.000	Intercept	0.30	0.01	25.80	0.000
	Linear age	-0.40	0.02	2016.93	-22.69	0.000	Linear age	0.02	0.01	2.29	0.022
	Quad. age	-0.09	0.01	2759.97	-14.15	0.000	Quad. age	0.01	0.00	2.50	0.012
Reasoning Composite	Intercept	-0.26	0.02	2849.40	-10.28	0.000	Intercept	0.38	0.01	29.78	0.000
	Linear age	-0.28	0.02	1908.76	-17.72	0.000	Linear age	0.03	0.01	4.96	0.000
	Quad. age	-0.05	0.01	2695.16	-9.21	0.000	Quad. age	0.00	0.00	1.59	0.112
UFOV Composite	Intercept	0.21	0.03	2628.54	7.39	0.000	Intercept	0.40	0.02	25.30	0.000
	Linear age	0.45	0.02	1959.66	18.82	0.000	Linear age	0.03	0.01	2.77	0.006
	Quad. age	0.07	0.01	2812.21	7.24	0.000	Quad. age				
Digit Symbol Substitution	Intercept	-0.18	0.03	2748.59	-5.84	0.000	Intercept	0.60	0.02	29.74	0.000
	Linear age	-0.43	0.02	1955.97	-21.44	0.000	Linear age	0.04	0.01	4.50	0.000
	Quad. age	-0.06	0.01	2808.28	-8.58	0.000	Quad. age	0.01	0.00	3.62	0.000
Visual Acuity (Snellen Chart)	Intercept	-0.11	0.03	2906.86	-3.36	0.001	Intercept	0.43	0.02	23.46	0.000
	Linear age	-0.27	0.03	2138.20	-9.41	0.000	Linear age	0.16	0.02	8.31	0.000
	Quad. age	-0.01	0.01	3044.64	-0.57	0.569	Quad. age	0.02	0.01	2.09	0.037
Balance (Turn-360 Test Steps)	Intercept	0.07	0.03	2696.58	2.04	0.041	Intercept	0.44	0.02	18.89	0.000
	Linear age	0.41	0.03	2015.10	14.14	0.000	Linear age	0.11	0.03	4.08	0.000
	Quad. age	0.03	0.01	2817.70	2.89	0.004	Quad. age	0.01	0.01	1.30	0.193

Table 4-3. Between-person correlations between measures of sensorimotor function and cognitive function.

Measure	1	2	3	4	5	6
1. Digit-Symbol Substitution	1					
2. Memory	0.2519*	1				
3. Reasoning	0.4035*	0.3798*	1			
4. Balance (Steps)	**-0.1919***	**-0.1693***	**-0.2019***	1		
5. UFOV	-0.4233*	-0.3657*	-0.4630*	**0.3194***	1	
6. Vision	**0.1077***	**0.0810***	**0.0839***	-0.1069*	**-0.1461***	1

Bold: Sensorimotor-Cognitive Pairings. *p<.001

Table 4-4. Within-person (longitudinal) correlational coupling coefficients between measures of sensorimotor function and cognitive function

Measure	1	2	3	4	5	6
1. Digit-Symbol Substitution	1					
2. Memory	0.0735*	1				
3. Reasoning	0.0408*	0.0343*	1			
4. Balance (Steps)	**-0.1068***	**-0.1171***	**-0.0579***	1		
5. UFOV	-0.0933*	-0.0851*	-0.1095*	**0.0282***	1	
6. Vision	**0.0418***	**0.0288***	**0.0130****	-0.0155**	**-0.0275***	1

Bold: Sensorimotor-Cognitive Pairings. *p<.001; **p<.05

Table 4-5. Prediction of sensorimotor variables by age.

Sensorimotor Domain		Unstandardized Coefficients		Standardized Coefficents	t	Sig
		B	SE	Beta		
Visual Acuity	Constant	-.073	.019		-3.854	.000
	Age	-.315	.019	-.309	-16.892	.000
Balance (Steps)	Constant	.129	.020		6.368	.000
	Age	.342	.020	.312	17.071	.000

Table 4-6. Prediction of cognitive functioning by age and sensorimotor functioning.

Cognitive Domain	Model		Unstandardized Coefficients		Standardized Coefficents	t	Sig
			B	SE	Beta		
Memory	1	Constant	-.164	.015		-10.587	.000
		Age	-.275	.015	-.324	-18.067	.000
	2	Constant	-.043	.014		-3.005	.003
		Vision	.122	.016	.146	7.754	.000
		Steps	-.136	.015	-.175	-9.291	.000
	3	Constant	-.137	.016		-8.718	.000
		Vision	.065	.016	.078	4.077	.000
		Steps	-.082	.015	-.106	-5.547	.000
		Age	-.221	.017	-.259	-13.098	.000
Reasoning	1	Constant	-.397	.017		-22.946	.000
		Age	-.274	.017	-.292	-16.107	.000
	2	Constant	-.281	.016		-17.513	.000
		Vision	.155	.017	.168	8.897	.000
		Steps	-.132	.016	-.153	-8.113	.000
	3	Constant	-.370	.018		-21.034	.000
		Vision	.101	.018	.109	5.668	.000
		Steps	-.080	.017	-.093	-4.851	.000
		Age	-.210	.019	-.223	-11.177	.000
UFOV	1	Constant	.480	.018		27.074	.000
		Age	.353	.017	.363	20.585	.000
	2	Constant	.334	.017		19.690	.000
		Vision	-.222	.018	-.226	-12.005	.000
		Steps	.113	.017	.123	6.562	.000
	3	Constant	.465	.018		25.376	.000
		Vision	-.143	.018	-.145	-7.760	.000
		Steps	.039	.017	.043	2.285	.022
		Age	.304	.020	.302	15.525	.000
Digit-Symbol Substitution	1	Constant	-.278	.019		-14.407	.000
		Age	-.315	.019	-.301	-16.609	.000
	2	Constant	-.145	.018		-8.280	.000
		Vision	.179	.019	.175	9.373	.000
		Steps	-.203	.018	-.213	-11.455	.000
	3	Constant	-.238	.019		-12.309	.000
		Vision	.123	.019	.120	6.320	.000
		Steps	-.150	.018	-.158	-8.310	.000
		Age	-.217	.021	-.207	-10.499	.000

Model 1: Prediction of cognitive functioning by age. Model 2: Prediction of cognitive functioning by sensorimotor functioning measures. Model 3: Prediction of cognitive functioning by age and sensorimotor functioning measures

Table 4-7. Reduction in unexplained change-related variance when comparing random linear age only model vs. after including time-varying balance and vision in the model.

Model	-2LL	Δ-2LL	df	Δdf	AIC	BIC	Random Variance Intercept		Random Variance Linear Age	
							Variance	p	Variance	p
1. Linear Age Only										
Memory Composite	17842.27		12		17866.27	17954.08	0.47	0.000	0.000263	0.108
Reasoning Composite	15543.68		12		15567.68	15655.48	0.64	0.000	0.000426	0.005
UFOV Composite	24875.22		12		24899.22	24987.05	0.56	0.000	0.000614	0.028
Digit-Symbol Substitution	18283.35		12		18307.35	18394.94	0.76	0.000	0.000804	0.000
2. Linear Age with Fixed level 1 (person centered) Vision and Steps										
Memory Composite	14039.68	3802.592	15	3	14069.68	14174.73	0.46	0.000	.000144	0.461
Reasoning Composite*	12683.50	2860.178	15	3	12713.50	12818.55	0.61	0.000	.000079	0.645
UFOV Composite*	18339.24	6535.977	15	3	18369.24	18474.10	0.49	0.000	.000230	0.521
Digit-Symbol Substitution*	14538.32	3745.027	15	3	14568.32	14673.30	0.71	0.000	.000385	0.092

*Indicates cognitive domains in which complete mediation occurred after the inclusion of vision and balance in the model. In these domains, unexplained change-related variance was no longer significant after including sensorimotor variables. Partial mediation occurred in the Memory domain.

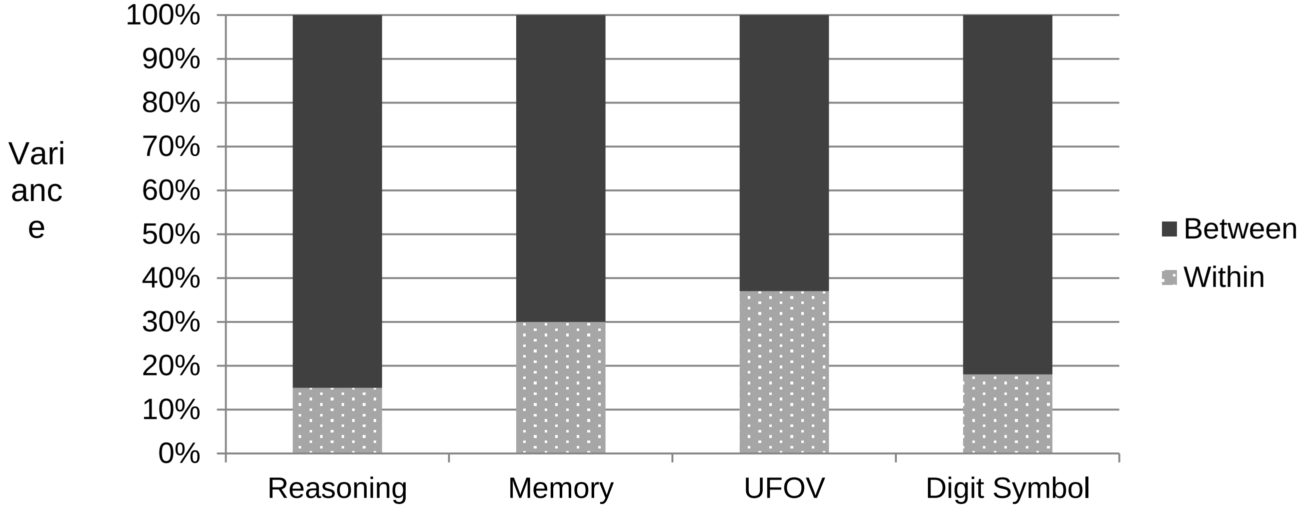

Figure 4-1. Most of the variance to be explained in each cognitive composite was due to between person differences (70-85%) rather than to within-person changes (15-37%)

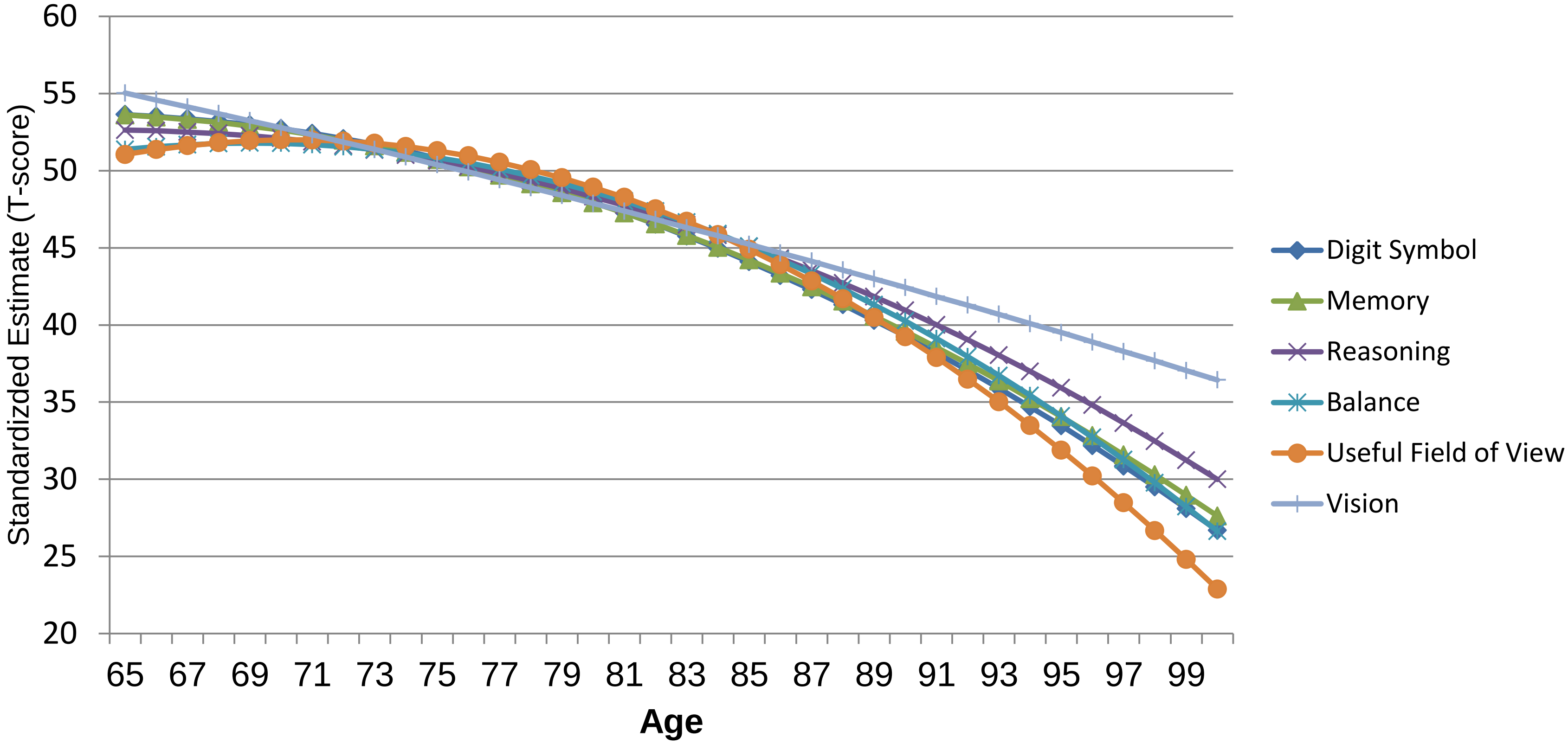

Figure 4-2. Age basis model of sensorimotor and cognitive performance. Age-related decline was observed in all sensorimotor and cognitive variables, with roughly uniform slopes. Quadratic function for all measures except vision indicated steeper rate of decline at older ages. Results from the entire ACTIVE sample (n=2,802). Data were collected at baseline and at 1, 2, 3, 5, and 10 years post-baseline

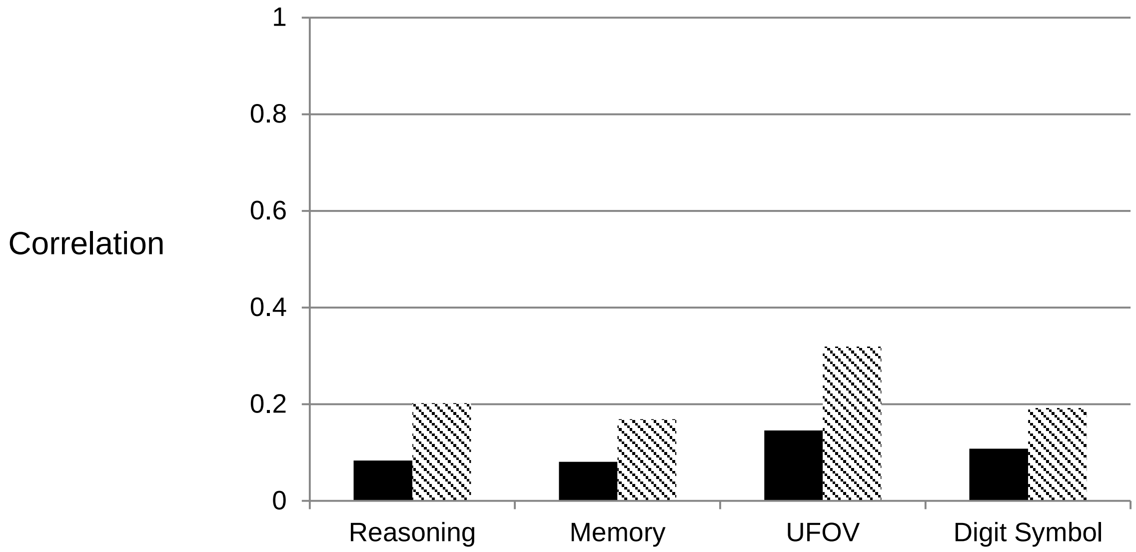

Figure 4-3. Representation of between-person correlations between measures of sensorimotor function and cognitive function. Solid black bars represent visual acuity; striped bars represent balance performance

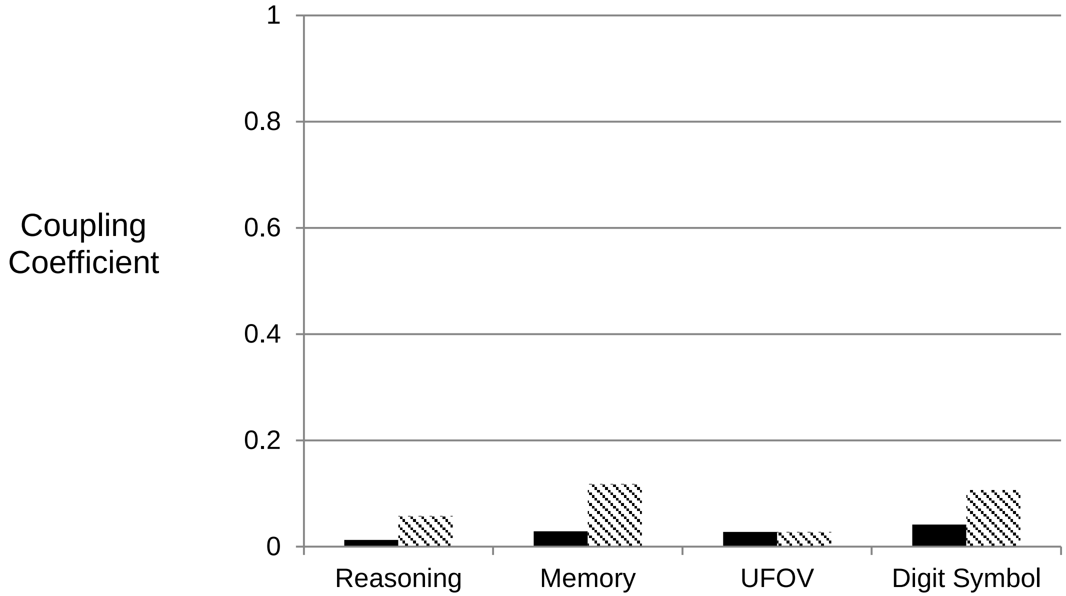

Figure 4-4. Representation of within-person correlations between measures of sensorimotor function and cognitive function. Solid black bars represent visual acuity; striped bars represent balance performance. Absolute association depicted

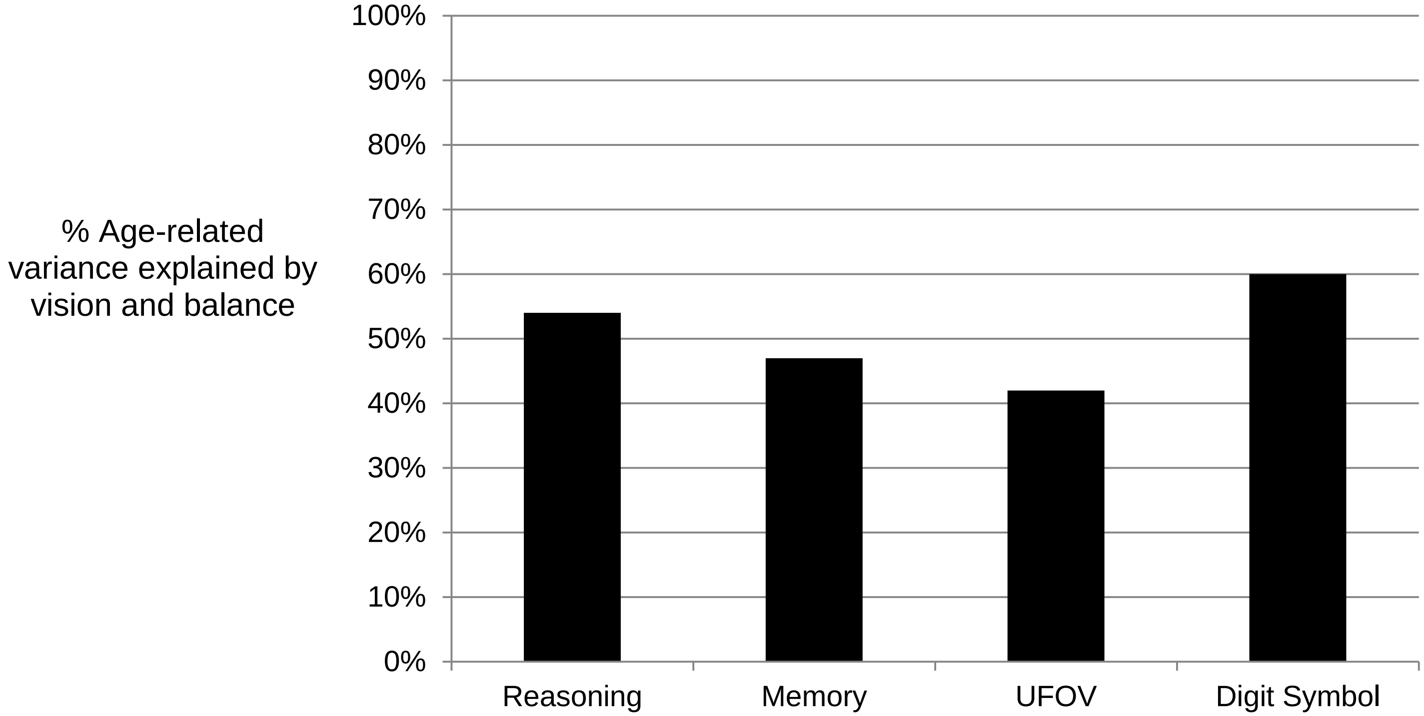

Figure 4-5. Mediation of age-related variance in cognitive composites by vision and balance at baseline. The Y-axis represents the percentage of original age-related variance that was mediated by sensorimotor measures in each cognitive composite

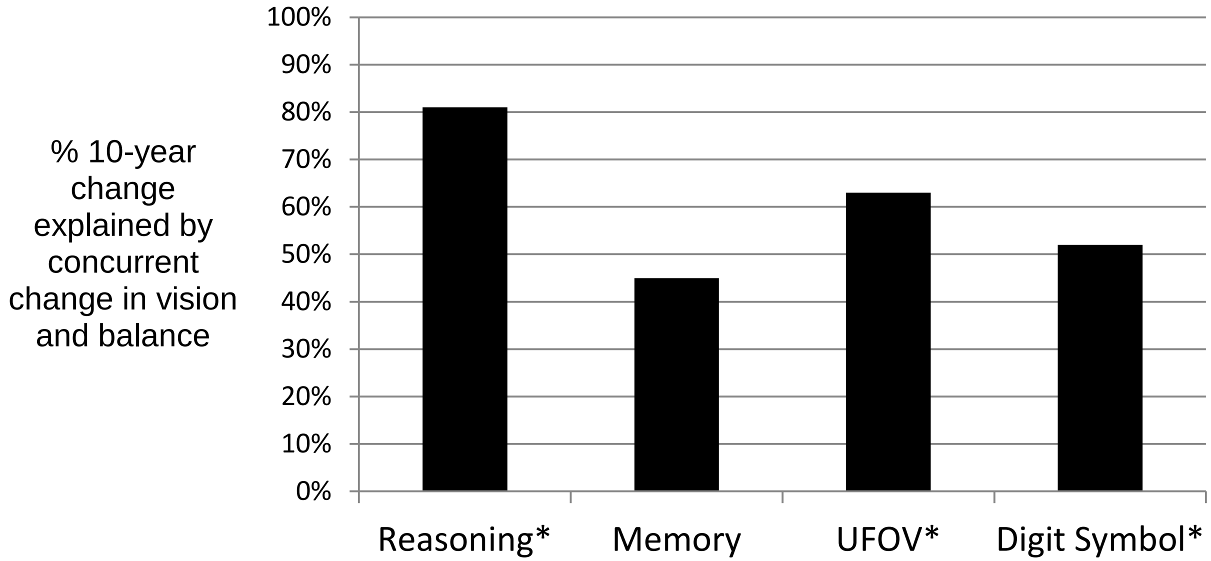

Figure 4-6. Including time-varying vision and balance accounted for 40-80% of the 10-year age-related change in each cognitive outcome. * Indicates complete mediation; after controlling for vision and balance, remaining age-related variance was not significantly greater than zero

CHAPTER 5
DISCUSSION

Overview of Findings

Description and Comparison of Change in Sensorimotor and Cognitive Measures

The first aim of this study was to describe change in participants' sensorimotor and cognitive functioning over the ten years that they were enrolled in the ACTIVE study. Overall, age-related decline was observed in all sensorimotor and cognitive domains. An inverse linear relationship existed between age and visual acuity, such that there was a fairly constant rate of decline in vision across the age range studied. For balance, Memory, Reasoning, UFOV, and Digit-Symbol Substitution, in addition to linear decline with age, significant quadratic trends indicated that rates of decline accelerated with age. These aging patterns are consistent with previous published reports regarding age-associated decline in vision (Schneider & Pichora-Fuller, 2000), balance (Bohannon et al., 1984), and cognitive measures in the present study (Drag & Bieliauskas, 2010, Christensen, 2001; Grady & Craik, 2000; Salthouse, 1982). Based on the visual impression formed by Figure 4-2, cognitive abilities declined at relatively uniform rates, although UFOV appeared to have steeper decline in older age than the other variables. This impression is consistent with prior studies that have reported that processing speed is highly sensitive to age and may eventually limit other fluid abilities (Salthouse, 1996).

Significant age-related variance existed both between and within participants on all cognitive and sensorimotor measures ($p<.001$), with most variance in each cognitive composite being due to between person differences (70-85%) rather than to within-person changes (15-37%). These findings are particularly relevant to the results of Aim

2, as the amount of covariance between two measures will always be limited by their variances.

Associations Between Sensorimotor and Cognitive Variables

The second aim was to determine whether sensorimotor functioning was related to cognitive functioning at the between- and within-subjects levels.

At the between-subjects level, small but significant associations were found between vision and each cognitive composite, and between balance and each cognitive composite. The significant individual correlations suggest that participants of a higher level of a given sensorimotor ability also performed better in the corresponding correlated cognitive measure, and that those lower in the sensorimotor domain were also lower in the cognitive domain.

At the between-subjects level, balance consistently had stronger associations with each cognitive measure than vision did, and the differences were statistically significant ($p<.05$). This finding aligns with previous reports that balance/gait is more strongly associated with cognition and everyday functioning than hearing and vision are (Marsiske et al., 1997; Lindenberger & Baltes, 1994). Based on visual inspection of Figure 4-2, balance had the strongest association with UFOV, followed by Reasoning, Digit-Symbol Substitution, and Memory. Based on visual inspection, again, out of all cognitive measures, vision seemed to be the highest correlated with UFOV, followed by Reasoning, Digit-Symbol Substitution, and Memory. No particular domain-specific hypotheses existed with regard to sensorimotor-cognitive correlations.

At the within-subjects level, very small but still significant absolute couplings in rates of change were found between each sensorimotor-cognitive pair, suggesting that change in sensorimotor functioning over the ten years of ACTIVE was at least somewhat related to change in cognitive functioning. Judging by visual inspection, associations between sensorimotor and cognitive functioning were less robust at the within-subjects level than at the between-subjects level, possibly reflecting the Aim 1 finding that there was more variability between persons than within persons. The relative modesty of within-subject sensorimotor-cognitive relationships relative to between subjects was an expected phenomenon, given this trend in past studies (e.g. Valentijn et al., 2005).

Within persons, the strongest associations, again, tended to be between balance and cognitive composites rather than vision and cognitive composites. Associations between change in balance and change in cognitive composites were statistically stronger than associations between vision and cognitive composites in all cognitive measures except UFOV. Judging from visual inspection of Figure 4-3, change in Balance displayed the strongest association with change in Memory, followed by change in Digit-Symbol Substitution, change in Reasoning, and change in UFOV. Change in Vision appeared to be associated the most with change in Digit-Symbol Substitution, change in Memory, and change in UFOV, and was very modestly, though statistically significantly, associated with change in Reasoning. Again, although no hypotheses specifically addressed the relative strengths of sensorimotor-cognitive domain correlations, it is interesting that Memory, one of the weaker associated cognitive measures between subjects, was the variable that appeared to have the strongest within-person association with balance, while UFOV, which appeared to have the strongest between-person associations with sensorimotor variables, had relatively weak within-person sensorimotor associations.

Overall, findings from Aim 2 support previous between-subjects (e.g., Anstey et al., 2001; Baltes & Lindenberger, 1997; Salthouse et al., 1996) and longitudinal (e.g. Lindenberger & Ghisletta, 2009; Anstey et al., 2003; Valentijn et al., 2005) work that has indicated a moderate-to-strong positive association between sensory and cognitive functioning. However, it is challenging to draw specific comparisons between the present findings and the findings of other studies, because in addition to design and methodological differences, nearly every study defines “cognitive functioning” with different variables or composites of variables. For instance, even within the same study (BASE), Lindenberger and Baltes (1994) used a “general intelligence” outcome that was constructed from a number of cognitive measures, while Ghisletta and Lindenberger (2005) later used processing speed and verbal fluency as longitudinal cognitive outcomes.

Nevertheless, some relative comparisons can be made. At the between-subjects level, Aim 2 associations between vision and Memory (r= 0.08), and vision and UFOV (r=0.15) were more modest than those found in similar pairings in the Maastricht Aging Study (vision and verbal memory: r= 0.30; vision and processing speed: r= 0.38; Valentijn et al., 2005). Moderate within-person associations between a) distance visual acuity and processing speed (r=0.44) (Ghisletta & Lindenberger, 2005) in BASE relative to present study pairings (r= 0.04), and b) vision and memory in ALSA (r=0.36) (Anstey et al., 2003) relative to the present study (r=0.03) further suggest that ACTIVE sensorimotor-cognitive associations are weaker than those observed in previous studies. In ACTIVE, associations between vision and speed of processing (r=.03) were weaker than in ALSA (r=.11), but still reached significance, undoubtedly due to the greater sample size and related statistical power in ACTIVE.

Baseline and Longitudinal Mediation

The purpose of Aim 3 was to investigate whether interindividual differences in sensorimotor functioning could account for interindividual age-related differences in cognitive functioning, and to determine whether 10-year cognitive change variance could be accounted for, at least in part, by concurrent balance and vision changes.

Cross-sectionally, although generally 15% or less of the individual differences in cognitive performance were age-related, about half (42-60%) of the age-related variance in each cognitive measure was accounted for by sensorimotor functioning. In other words, at baseline, there was a significant indirect effect of age, through vision and through balance, on cognition. A smaller proportion of age-related variance in cognition was mediated by sensorimotor variables in ACTIVE than in previous studies (BASE: Lindenberger & Baltes, 1994). A major contrast between BASE and the current study is that BASE investigators demonstrated sensorimotor-cognition relationships using a global cognitive construct, general intelligence. The current study chose to model this relationship at the level of distinct cognitive constructs, so that variations in the strength of the relationship could be explored by domain. It is possible that modeling differences partially contributed to the relatively weaker mediation in the present study, as large latent variables such as the one used by Lindenberger and Baltes (1994) tend to be more reliable and more sensitive to predictor effects.

The third aim also attempted to determine whether individual differences in rates of 10-year cognitive change variance could be accounted for by concurrent individual rates of change in balance and vision. Indeed, to the extent that there was age-related cognitive change in each cognitive composite over 10 years, most of that change (40-80%) was shared with concurrent intraindividual change in vision and balance. Individual differences in 10-year rates of change in Reasoning, UFOV, and Digit-Symbol Substitution were fully explained, and in Memory partially explained, by concurrent rates of change in vision and balance. To our knowledge, this is the first time that evidence of “mediation” of cognitive decline by sensorimotor decline has been found.

Limitations

A number of limitations exist with regard to both the design and interpretation of the findings of the present study. First, ACTIVE was designed as an intervention trial, and consequently approximately 75% of the present sample received some type of cognitive intervention. This training could have affected the present study’s overall pattern of longitudinal results, although we attempted to minimize the potential effect by covarying for training effects in appropriate analyses. Second, as a result of ACTIVE’s rigorous inclusion/exclusion criteria, and the fact that adequate vision was a prerequisite for participation in the study, it was necessary to exclude any potential participant who had visual acuity worse than 20/50. Similarly, in order to maintain a cognitively normal sample, those with an MMSE score below 23 were excluded from the study. Both of those cutoffs were, in a way, unfortunate for the present study’s purposes, as restricted variance of these variables could have led to restricted covariance in our findings. The previous statement assumed that those with low MMSE scores would have also had low performance in cognitive measures in this study.

Another major limitation of ACTIVE is that it did not include measures of either close visual acuity or auditory acuity, which were collected in many previous studies. Some evidence does exist to suggest that both vision and balance-gait are more powerful predictors of cognition than hearing (Marsiske et al., 1997; Lindenberger & Baltes, 1994), so auditory acuity may not have provided significant additional information beyond the present findings. Close visual acuity, on the other hand, tends to be more affected by age than distance visual acuity, and there is reason to believe that close visual impairment predicts decline in mental status better than distance visual impairment (Reyes-Ortiz et al., 2005).

When considering the contributions of the current study it is important to consider that very few longitudinal studies of sensorimotor-cognitive functioning exist, especially of ACTIVE's length. Adding to the increased challenge of interpreting and applying the current results to the broader literature is the fact that, as mentioned previously, there has been very little consistency among studies in the measures used to represent cognitive and sensorimotor functioning.

A final limitation is that our sample may have over-represented the young-old relative to previous studies (e.g. Lindenberger & Baltes, 1994). This may also partially account for attenuated amounts of change observed in cognition at earlier ages, and may hinder direct comparison to other studies such as BASE, the findings of which were drawn from an older sample (mean age 84.9 years).

Future Directions

The scope of the present study is limited in that it only considers concurrent change in sensorimotor and cognitive functioning. Future longitudinal research could involve more dynamic approaches for the measurement of change, such as dual change score modeling (DSCM) (McArdle & Hamagami, 2001; McArdle, 2001). DSCM, as described by Ghisletta and Lindenberger (2003), measures the effect of level and rate of change in given variables on the rate of change in other variables in a crosslagged manner. DSCM could be utilized to explore whether sensorimotor changes precede cognitive changes, or vice versa.

Additionally, while our study and others before it suggest that sensorimotor and cognitive functioning are linked in their decline in older age, it is exceptionally difficult to directly evaluate the underlying reasoning for the connection between the two areas. As mentioned in the Literature Review, a number of theoretical hypotheses regarding the relationship have been proposed. Evidence from the present study cannot directly support any particular hypothesis, however in a very broad sense, the relatively uniform rates of decline among sensorimotor and cognitive variables (Aim 1, Figure 4-3), along with limited coupled sensorimotor-cognitive decline (Aim 2), are most closely aligned with the idea of common cause aging (Lindenberger & Baltes, 1994). If true, the common cause hypothesis would suggest that sensory and cognitive declines observed in this study were related through a third, unknown common factor.

As part of the common cause hypothesis, Lindenberger & Baltes (1994) suggested that sensory, motor, and cognitive abilities dedifferentiate with age, and that changes in all could result from degradation of shared brain areas, pathways, or circuits. To further explore the common cause hypothesis as it relates to sensorimotor-cognitive relationships, the use of neuroimaging is a logical next step. To the author's knowledge, no imaging studies have directly evaluated the common cause hypothesis, although Salat and colleagues (2004) documented age-related atrophy of both visual and frontal areas of the brain, in one study of non-demented 18-93 year old participants. In terms of functional imaging, it may be possible to administer, for example, scanner-based recognition-based vision tasks and cognitive tasks, and evaluate whether the tasks share overlapping functional regions of activation. Structural imaging and/or diffusion tensor imaging could possibly be used to investigate whether atrophy or fiber tract breakdowns in such shared regions predict sensorimotor and/or cognitive decline. Another study could assess whether individual differences in volume or integrity of known sensory areas of the brain, such as the visual cortex, predict later cognitive decline.

Important practical reasons exist for furthering the study of sensorimotor-cognition relationships, and developing a more complete understanding of the nature of these associations. Clinically, for example, if research finds that sensorimotor change is meaningfully indicative of cognitive change, sensorimotor functioning could be used in the future by a wide range of professionals as a screening tool for more thorough assessment of cognitive decline.

Final Conclusions

This study determined that the ACTIVE sample experienced age-related decline in all sensorimotor and cognitive domains over ten years, and found evidence of interindividual sensorimotor-cognitive associations, as well as longitudinal evidence of coupled sensorimotor/cognitive decline. Sensorimotor functioning also mediated the relationship between age and cognitive functioning at baseline, as well as longitudinally, such that ten-year change could be accounted for by concurrent change in sensorimotor functioning. Future research is needed to test whether decline in one area of function actually precedes the other, and to further explore the underlying mechanisms behind these associations.

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BIOGRAPHICAL SKETCH

Jacqueline Maye graduated from Trinity College in 2008 with a Bachelor's degree in Neuroscience. Following graduation, she worked for 3.5 years as a Research Assistant/Coordinator at Massachusetts General Hospital on studies of beta-amyloid pathology and memory functioning in elderly adults with normal cognition, Mild Cognitive Impairment, and Alzheimer's disease. Ms. Maye was accepted into the doctoral program in Clinical and Health Psychology at the University of Florida in 2012. She is currently working toward her doctorate in clinical psychology with a specialization in neuropsychology. Her research interests involve cognitive aging and interventions that are targeted toward delaying cognitive and functional decline in older adults.