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WASHINGTON UNIVERSITY

Department of Psychology

Sensory and Cognitive Declines in Older Adults: A Longitudinal Study

by

Melanie Storm Bauer

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Abstract

In a recent cross-sectional study, as has been found in numerous previous studies, Sommers et al. (2011) found that age-related declines in hearing, as assessed by pure-tone thresholds, begin around age 20 and continue across the lifespan. In another article published from the same cross-sectional dataset, Hale et al. (2011) found that working memory ability also begins declining around age 20 and continues throughout life. The present study is a longitudinal follow-up of these two studies in which a sub-sample of older adults (≥65 years old at the time of original testing approximately four years ago) were re-tested on sensory and cognitive measures. The goal was to examine the extent to which older adults experience longitudinal declines on sensory and cognitive abilities over a relatively short period of time, and whether declines in one domain accompany declines in the other. In reference to sensory abilities, participants experienced declines for pure-tone thresholds and speech perception in noise. Additionally, they experienced declines for most cognitive abilities. They did not experience declines on the two simple verbal working memory tasks or on the two visuospatial processing speed tasks. Despite extensive longitudinal sensory and cognitive declines, there was only partial evidence for a common cause underlying these declines. Given the paucity of longitudinal studies investigating these abilities, the present results provide important information about the sensory-cognitive profile of aging.

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In a recent cross-sectional study on hearing ability, as has been found in numerous previous studies (Agrawal, Platz, & Niparko, 2008; Brant & Fozard, 1990; Cruickshanks et al., 1998), Sommers et al. (2011) found that age-related declines in hearing, as assessed by pure-tone thresholds, begin around age 20 and continue across the lifespan. Age-related hearing loss is especially pronounced for high-frequency pure tones, which show steeper rates of decline than low-frequency pure tones across the lifespan. In another article published from the same cross-sectional dataset, Hale et al. (2011) found that working memory ability also begins declining around age 20 and continues throughout life. Specifically, they found that spatial working memory declines more rapidly with age than verbal working memory, regardless of task complexity (i.e., simple or complex). The present study is a longitudinal follow-up of these two studies in which a sub-sample of older adults (≥65 years old at the time of original testing approximately four years ago) were re-tested on sensory and cognitive measures. The goal was to examine the extent to which older adults experience longitudinal declines on sensory and cognitive abilities over a relatively short period of time, and whether declines in one domain accompany declines in the other.

Age-Related Sensory Declines

Age affects all sensory systems (Hoffman, Ishii, & Macturk, 1998; Humes, Busey, Craig, & Kewley-Port, 2009; Stevens, Cruz, Marks, & Lakatos, 1998). For example, declines in visual acuity occur with age, but corrected vision (e.g., with glasses) remains fair into the 80s (20/40 or better visual acuity; Fozard, 1990; Gittings & Fozard, 1986). Unfortunately this same level of correction is not available for age-related hearing declines (e.g., with hearing aids). This fact is especially evident in a survey conducted in

2001 that assessed people's satisfaction with their prosthetic devices . The researchers found that nearly 100% of respondents were satisfied with their glasses, but less than 50% of respondents were satisfied with their hearing aids. Given that vision can be satisfactorily corrected in older adults, and so the role of age-related declines in vision in experimental tasks can be minimized, the focus of the present study (and the below review of the literature) in reference to sensory abilities in older adults is on hearing ability.

Older adults experience decreased auditory sensitivity and difficulty perceiving speech, especially in noisy environments (CHABA, 1988). Age-related hearing loss (presbycusis) begins primarily with higher frequencies, and progressively and systematically encompasses lower frequencies as individuals age (CHABA, 1988; Corso, 1959; Sommers et al., 2011; see Figure 1). Specifically, decreased sensitivity to pure-tone thresholds for 2000 Hz-, 4000 Hz-, and 8000 Hz-tones begins at age 20 and continues throughout life (Sommers et al., 2011). While multiple factors—"physiological, pathological, and environmental"—likely contribute (CHABA, 1988, p. 861), this age-related high-frequency hearing loss is primarily due to degradation of the inner ear, specifically loss of hair cells at the basal end of the basilar membrane in the cochlea responsible for high-frequency information detection (Liu & Yan, 2007). The rate of high-frequency decline accelerates across each decade of life (Sommers et al., 2011). Fortunately, decreased sensitivity for these high-frequency tones does not fall below "normal" hearing loss (pure-tone threshold less than 25 dB HL) and noticeably affect everyday listening situations until approximately age 65 (Tye-Murray, 2009). One study found that 33% of older adults aged 70 years and older self report hearing loss

(Campbell, Crews, Moriarty, Zack, & Blackman, 1999). This is an underestimation as nearly 50% of adults over 75 years have clinical hearing loss (pure-tone threshold over 25 dB HL), and 77% of those aged 60-69 years have high-frequency hearing loss (Agrawal et al., 2008; National Institute on Deafness and Other Communication Disorders, 2010).

Beyond difficulties detecting tones, numerous studies have found that age-related declines in hearing occur across many levels of speech: identifying spoken phonemes, syllables, words, and sentences (Humes, 1996; Nittrouer & Boothroyd, 1990; Sommers & Danielson, 1999). Older adults experience a particular deficit in perceiving speech presented in noisy backgrounds, even those with normal hearing ability (Akeroyd, 2008; CHABA, 1988; Gosselin & Gagné, 2011). These speech perception deficits are not entirely explained by age-related hearing loss. Given the importance of hearing to speech comprehension, it is not surprising that older adults with better hearing perform better than those with poor hearing on speech comprehension tasks (Wingfield, McCoy, Peelle, Tun, & Cox, 2006). What *is* surprising, is that poor-hearing older adults also perform worse on speech comprehension tasks than young adults with equally poor hearing (Wingfield et al., 2006). Comparing two age groups with similar hearing, we can effectively control for the contribution of hearing impairment. Since we still find age group differences in understanding speech, these results suggest important contributions from another ability that experiences age-related declines, such as cognition. Unfortunately cognitive abilities were not measured in the above cited study, so the direct relationship between hearing and cognition could not be assessed, as it will be in the present study.

Age-Related Cognitive Declines

Older adults experience declines in memory and other cognitive abilities (Park et al., 2002). Working memory, short-term memory, and long-term memory decline progressively beginning in the early 20s through old age (Kaufman & Horn, 1996; Park et al., 2002). These memory tasks often show differential age-related declines: working memory and long-term memory decline more rapidly than short-term memory (Bopp & Verhaeghen, 2005; Park et al., 2002, see Figure 2). In addition, other research highlights the importance of the relationship between the type of information to be remembered (verbal or spatial) and relative declines with age; showing faster rates of age-related decline for spatial than verbal information, regardless of the type of memory being assessed (Hale et al., 2011, see Figure 3; Myerson, Hale, Rhee, & Jenkins, 1999). Hale et al. (2011) assessed working memory with a range of tasks, both in the verbal and spatial domains. Working memory ability was tested by both simple and complex tasks. Simple working memory tasks require participants to remember a series of items, while complex tasks require participants to perform a secondary distractor task (either interleaved between or simultaneous with target item presentation) in addition to remembering a series of target items. Simple working memory tasks are sometimes referred to as "short-term" or "primary" memory tasks, while complex working memory tasks are more traditional measures of "working memory." In the Hale et al. study, simple and complex versions of tasks were included within each content domain, and their rates of age-related decline examined. As mentioned above, spatial working memory declined more rapidly than verbal, regardless of whether the task was simple or complex. Additionally, the simple and complex tasks within each domain did not show differential age-related declines. Therefore, this study suggests that the magnitude of age-related declines in working memory is primarily driven by the distinction between verbal and spatial working memory abilities. However, Park et al. (2002) did not find this distinction between the two content domains in working memory, but rather between tasks with varying complexity: complex working memory tasks declined more than twice as rapidly as simple working memory tasks (called "short-term memory" tasks in Park et al.). They included measures of short-term and working memory as well. Specifically, they included two verbal (Digit Span, forward and backward) and two spatial (Corsi Block, forward and backward) short-term memory tasks along with two verbal (Reading Span and Computation Span) and two visuospatial (Line Span and Letter Rotation) working memory tasks.

An explanation for these differing results is that Park et al. (2002) did not match the type of target item in the simple and complex working memory tasks as Hale et al. (2011) did. For example, in Hale et al., one simple (i.e., short-term memory) verbal working memory task asked participants to remember a series of words (Word Span), and the complex version (i.e., working memory) of that task used the same target item content (i.e., words) in addition to a secondary distractor task, which in this case was to solve a mathematical problem (Operation Span). Therefore, in both tasks, the to-be-remembered items were the same, words. Hale et al. used this same system of matching pairs of simple and complex working memory tasks for all 12 of the tasks they included (6 verbal, 6 spatial). In Park et al.'s study, half of the short-term memory tasks tested memory for digits, while only one-quarter of their working memory tasks tested memory for digits. In this way, target items that are easier to remember and do not tend to decline as rapidly with age (i.e., digits; Botwinick, Storandt, & Berg, 1986) were confounded with task complexity, perhaps masking the age-related distinction between content domains found by Hale et al.

Evidence for an exaggerated age-related deficit for spatial processing can also be found in research examining age-related changes in processing speed. In a meta-analysis performed by Lima, Hale, and Myerson (1991), they found that non-lexical (i.e., visuospatial) processing speed tasks showed greater age-related slowing than lexical (i.e., verbal) tasks, using an extreme-groups design. These meta-analytic findings were corroborated by a cross-sectional study that included adults 18-90 years in which participants were tested on four verbal and four visuospatial processing speed tasks (Lawrence, Myerson, & Hale, 1998). Over the adult lifespan, both in group- and individual-level analyses, visuospatial processing speed declined more rapidly than verbal processing speed. Moreover, this decline in visuospatial processing speed was non-linear and accelerated with age, while verbal decline maintained a more linear decline. This was evidenced by a positively accelerated, steeper regression slope for the visuospatial tasks than for the verbal tasks when examining age-related declines. This common deficit for spatial processing across the domains of working memory and processing speed is in line with the notion that processing speed is a basic cognitive ability that supports working memory (Salthouse, 1996).

Relationship between Sensory and Cognitive Declines

Given the age-related declines that occur for both sensory and cognitive declines, is there a correlation between these age-related declines that can be attributed to a common source? This relationship is described by the “common cause” hypothesis

(Lindenberger & Baltes, 1994). According to this hypothesis, the age-related declines in sensory and cognitive abilities are both caused by age-related degradation of "anatomical, chemical, and functional" aspects of the brain (Lindenberger & Ghisletta, 2009, p. 10). Therefore, one should expect to find both cross-sectional and longitudinal evidence for a relationship between age-related sensory and cognitive declines.

With data from the ongoing longitudinal Berlin Aging Study (BASE), Lindenberger and Baltes (1994) drew a sample of older adults aged 70-103 years (N = 156). In this sample, they found moderate to strong correlations (.29-.61) of hearing (low- and high-frequency pure-tone thresholds) and vision (close and distance visual acuity) with cognition (termed "intelligence" in their paper; including speed, reasoning, memory, knowledge, and fluency). Next, they constructed a latent variable model that examined the relationship between age and sensory and cognitive abilities. They assumed that hearing and vision were more direct, reliable measures of age-related brain degradations, so these abilities should fully mediate the relationship between age and cognition; and they found exactly that. While there were moderate to strong correlations between age and the two sensory factors (-.75 for vision and -.45 for hearing), there was no significant, direct path from age to the cognitive factor. All of age's relationship with cognition was mediated by sensory ability, with a strong correlation between the vision and cognition factors (.56) and a weak correlation between the hearing and cognition factors (.28). Therefore, all of the age-related changes that occur in cognition seem to be attributed to a common source that also accounts for age-related changes in sensory abilities.

Evidence is also available that challenges the validity of the common cause hypothesis. Specifically, data from the Australian Longitudinal Study of Aging (ALSA) from older adults aged 70-85+ years (*N* = 1,823) were used to assess the longitudinal relationship between sensory and cognitive abilities (Anstey, Hofer, & Luszcz, 2003). Latent growth modeling, a longitudinal analysis technique, was used to assess growth (i.e., decline) for these abilities over the course of 8 years, assessed at three points in time. Comparing the rates of change of these abilities, they found that changes in vision were moderately associated with changes in memory, while changes in hearing were only weakly associated with changes in memory. Therefore, contrary to the common cause hypothesis, the majority of age-related declines that occur for vision and hearing are independent of those that account for age-related memory declines.

The primary goal of the present study was to characterize the sensory and cognitive declines that occur longitudinally for older adults, and to determine whether these age-related declines are comparable to those found by cross-sectional studies, namely Hale et al.(2011) and Sommers et al. (2011). Sensory measures included pure-tone and babble detection thresholds (measures of absolute sensitivity) as well as speech identification in noise. Cognitive measures included working memory (both spatial and verbal) and processing speed (both spatial and visual). As a secondary goal, evidence for the common cause hypothesis (Lindenberger & Baltes, 1994) was examined by comparing the current simple (zero-order correlations) and age-related (partial correlations) relationships between sensory and cognitive tasks, which would be consistent with a common cause producing age-related declines. In summary, we addressed the following research questions to provide one of the first longitudinal studies of the effects of age on a select set of sensory and cognitive abilities:

1. Are longitudinal age-related declines for detecting high-frequency tones greater than for low-frequency tones, and are there longitudinal age-related declines for identifying speech in noise?
2. Are longitudinal age-related declines for spatial cognitive tasks (both processing speed and working memory) greater than for verbal ones?
3. Are longitudinal age-related declines greater for complex working memory tasks than for simple ones?
4. Are age-related sensory and cognitive declines correlated? (common cause hypothesis)

Method

Participants

Forty-three older adults (female = 30), ranging in age from 67 to 92 years old (*M* = 79.49, *SD* = 7.07), were recruited from the Sommers et al. (2011) adult lifespan study. The recruitment pool included those participants who were 65 years or older at the time of original testing (referred to as "Time 1" in this article; present study referred to as "Time 2"). These participants were first tested 3.90-5.69 years ago (*M* = 4.41, *SD* = 0.42). All were native English speakers and none reported wearing hearing aids. They had on average 14.95 years (*SD* = 2.48) of education and a Wechsler Adult Intelligence Scale vocabulary score of 50.40 (*SD* = 8.04; WAIS III; Wechsler, 1997), both assessed at the time of original testing. Participants were screened for cognitive impairment using the Telephone Interview for Cognitive Status (Brandt et al., 1988) when contacted for recruitment for the present study. All individuals scored above 26 (the recommended cutoff for cognitive impairment), comparable to a score of 28 on the Mini-Mental State Examination (de Jager, Budge, Clarke, 2003). To assess whether those who participated in the present follow-up study ("returners") differed from those who did not participate in the follow-up ("non-returners"), we compared performance at the original time of testing for these two groups. Importantly, on average, those who returned for the present study (n = 43) did not show significant differences on any of the measures included in the present study—demographic, screening, sensory, or cognitive—from the rest of the original older-adult sample (n=114) at the time of original testing (see Table 1).

Sensory Measures

Thresholds. The first threshold measure included in the present study assessed auditory sensitivity for pure tones for octave frequencies ranging from 250-8000 Hz. Thresholds were assessed using a standard adaptive tracking procedure for clinical assessment ("up 5 dB, down 10 dB"; Carhart, 1959; Guthrie & Mackersie, 2010). In this procedure, thresholds are assessed in an adaptive staircase manner, in which a correct tone detection results in continuing the series in 10-dB HL amplitude decrements until the participant can no longer hear the tone. Then, when no response is given (i.e., the tone can no longer be heard), the experimenter increases the total amplitude in 5-dB HL increments until the tone can again be heard. At this point, the amplitude is noted and the adaptive procedure is again performed as described twice more, or until the participant detects the tone at the same amplitude three times in a row. The same procedure was used to measure thresholds for a babble of multiple talkers, our second hearing measure. This "babble" noise (a six-talker babble) sounds similar to a noisy cafeteria, in which no individual conversations are discernible, but the cumulative noise sounds like a crowd of people talking. Thresholds were assessed for each ear separately, and performance for the best ear on each task was used in subsequent analyses.

Speech in noise. Identification of speech in a noisy background was assessed with an adaptation of the Speech Perception in Noise task (SPIN; Kalikow, 1977; Gordon & Allen, 2009). In the SPIN task participants listened to sentences presented in noise (the same multi-talker babble mentioned previously) and were asked to identify and repeat aloud the terminal word in each sentence. Sentences were "low-predictability" (e.g., *Ruth couldn't know about the shrimp.*) such that the sentence beginning did not help the participant to predict the terminal word. Twenty-five sentences were presented to each ear separately, and performance for the best ear was used in subsequent analyses.

Cognitive Measures

Working memory. Eight measures of working memory were assessed, a subset of those used in the original study: two simple spatial, two complex spatial, two simple verbal, and two complex verbal. Figures 4 and 5 present screenshots for four sample tasks used in the current study (see Hale et al., 2011 for screenshots of all tasks). The simple tasks assessed memory for a series of items of either verbal or spatial content. The complex versions of the simple tasks included memory for a series of items, along with a same-domain secondary distractor task that participants had to perform. For all working memory tasks, participants were allowed as much time as they desired to recall the target items at the end of each trial. Two trials were presented for each series length (series lengths specified below for each task) in a predetermined pseudo-random order, which was the same for all participants, such that no series length was repeated before the others had been presented once.

Spatial domain. Two pairs of spatial working memory tasks were assessed. The simple spatial tasks were Grid Span and Dot Span, along with their complex versions Alignment Span and Position Span, respectively. In Grid and Alignment Span, participants had to remember a series of locations of an “X” on a grid, and in Dot and Position Span (see Figure 4) they remembered a series of dots in a cloud of dots. For all spatial tasks, participants recalled the target items by touching with a finger their locations on a touchscreen monitor. In addition to remembering a series of locations, for the complex tasks participants had to make a decision about a secondary task that occurred along with—on the same screen as—the target item. For Alignment Span, participants determined whether a set of three circles (one circle is the target circle) were aligned in a straight line, and in Position Span determined whether the target dot was positioned to the left or right of another dot. Participants responded by saying their secondary task decision aloud. For simple tasks, each target item appeared for 1750 ms, followed by an empty grid (Grid Span) or cloud (Dot Span) for 500 ms. For complex tasks, the target item (along with the secondary task) was displayed for 1750 ms (Position Span) or 2000 ms (Alignment Span), and again followed by an empty grid/cloud for 500 ms. Series lengths were 2-11 items for Grid and Dot Span, and 2-8 items for Alignment and Position Span.

Verbal domain. Two pairs of verbal working memory tasks were assessed. The simple verbal tasks were Letter Span and Word Span, along with their complex versions Counting Span and Operation Span, respectively (complex span tasks were adapted from

Conway, Kane, & Al, 2005). In Letter and Counting Span, participants had to remember a series of letters, and in Word and Operation Span (see Figure 5) they remembered a series of words. For all verbal tasks, participants repeated the target items aloud as they appeared on the screen, and then recalled the items aloud at the end of each series. In addition to remembering a series of items, for the complex tasks participants had to make a decision about a secondary task that occurred on a separate screen between the presentation of each target item. For Counting Span, participants counted the blue circles in an array of shapes (always 7 or 8 blue circles), and in Operation Span participants judged the correctness of a solution to a mathematical problem. Participants repeated the secondary task aloud as it was presented and responded by pressing one of two keys on a keyboard to indicate their secondary task decision. For simple tasks, each target item appeared for 1500 ms, followed by a blank screen for 500 ms. For complex tasks, the secondary task was displayed for 10,000 ms. Following a response (or completion of the 10,000 ms response period) the next trial was initiated following a 250 ms delay. Target item presentation was the same as the simple tasks. Series lengths were 2-11 items for Letter Span, 2-10 items for Word Span, and 2-7 items for Counting and Operation Span.

Scoring. A proportion correct scoring method (Kane et al., 2004) was used for the working memory tasks to provide a more sensitive measure of individual differences than the traditional “longest series length recalled” (i.e., one’s “span”). For this method, participants received credit for the proportion of each trial (two trials per series length) they recalled correctly. The proportion correct for each trial was then averaged across trials to obtain a proportion correct score for each working memory task, for each participant. Specifically, for the spatial tasks participants received one point for each correct item, regardless of the order, and were penalized one point for each extra item they recalled. A limitation of the task programming precluded assessing recall order for the spatial tasks, necessitating the method of scoring just mentioned. For the verbal tasks, participants received 0.5 points per correct item and an additional 0.5 points if it was in the correct position in the series. Participants did not receive any points for items recalled longer than the series length and were not penalized for extra items. Participants were informed by instructions prior to each task whether recall order was required.

Processing speed. Two non-verbal processing speed tasks were assessed: Dot (spatial processing) and Shape (visual processing; see Figure 6). Only visuospatial processing speed tasks were included in the present study because they showed the greatest age-related declines in the original cross-sectional dataset (data unpublished), and so were the best candidate tasks for showing longitudinal declines. In the Dot task, participants made a judgment as to which of two dots was closest to a central dot. In the Shape task, participants made a judgment as to which of two shapes was most similar to a target shape. For both tasks, participants were instructed to respond as quickly and as accurately as possible, by pressing one of two keys on a keyboard. Performance was assessed across trials both by the mean reaction time and the median reaction time. The purpose of including both scoring methods was to account for the biasing effect of outlier trials, such as an especially slow trial, on the mean reaction time scores by also calculating the median.

Procedure

All hearing tasks were completed in a sound-attenuated booth, and all cognitive tasks in a quiet testing room. Stimuli for the hearing tasks were presented through an audiometer over headphones. Volume on the audiometer was adjusted before each test session so that presentation of the babble sound and SPIN sentences were constant across test sessions. Stimuli for the cognitive tasks were presented on a computer screen. An experimenter was present during all testing, recording verbal responses to tasks when necessary. A recording of the verbal responses was also created as a backup. The order of the working memory tasks was always such that a simple working memory task immediately preceded its corresponding complex task. Testing occurred over two sessions, each approximately 90 minutes in length, which occurred on separate days within a week of each other.

Results

Longitudinal Changes in Sensory and Cognitive Abilities

Test-retest reliabilities. The last column in Table 2 presents the correlations between participants' original scores (Time 1) and their current scores (Time 2), the tasks' test-retest reliabilities over approximately four years. A correlation of .70 or greater represents an adequate test-retest reliability (Cicchetti, 1994). Eleven out of the sixteen correlations in the table meet this standard. It should be noted that this .70 standard is considered "adequate" for retests that occur within only days or weeks of the original testing, and considered "excellent" when retests occurs at least a year after the original testing (Hunsley & Mash, 2008). Therefore, all of the test-retest reliabilities can likely be considered at least adequate, and many exceptional, given that the retest occurred approximately four years after the original testing time. The only potential unreliable tests are the two complex verbal working memory tasks, Counting Span and Operation Span, but should be considered sufficient given the long test-retest interval.

Group-level analysis. Longitudinal changes in sensory and cognitive abilities were investigated at both the group and individual level. Table 2 presents the predicted and observed group-level changes for each measure, along with a paired *t*-test comparing participants' Time 1 and Time 2 scores. The predicted mean changes were calculated from the cross-sectional data of all older adults 65 years and older from the original cross-sectional dataset from Time 1 ($N = 158$), and the observed mean changes were calculated by subtracting Time 1 scores from Time 2 scores for the subset of participants from the original cross-sectional study who returned for the present follow-up study ($n = 43$). Due to a computer error (in the case of the processing speed tasks) and to participant inability to complete tasks (in the case of the other tasks), there are fewer than 43 data points for some tasks. Average median changes were calculated in addition to average mean changes for the two processing speed tasks: Dot ($n = 32$) and Shape ($n = 21$). Due to file loss from the original cross-sectional dataset, average median change scores could only be calculated for some participants.

On a group level, older adults experienced declines for most sensory and cognitive abilities, which for the most part were larger in magnitude than those declines predicted by the cross-sectional data. In reference to the sensory measures, there were significant declines for both low- (PTAL) and high-frequency (PTAH) pure-tone thresholds—with PTAH declining numerically more than PTAL—as well as for identifying speech in noise (SPIN). In the case of the two threshold measures, a positive value indicates hearing loss (i.e., increased threshold), and in the case of the SPIN a negative value indicates declines in speech perception (i.e., decreased proportion correct). Specifically, there were the following average declines (in parentheses, units in dB HL) for each pure-tone frequency: 250 Hz (*M* =4.29, *SD*=10.22), 500 Hz (*M* =4.88, *SD*=13.95), 1000 Hz (*M* =3.45, *SD*=6.76), 2000 Hz (*M* =3.93, *SD*=7.20), 4000 Hz (*M* =5.81, *SD*=9.47), and 8000 Hz (*M* =5.60, *SD*=14.02). Therefore, the greatest declines were for the two highest frequencies (4000 Hz and 8000 Hz) and the smallest declines were for the two middle frequencies (1000 Hz and 2000 Hz). However, babble threshold did not show declines from Time 1 like the other sensory measures, but instead showed a significant improvement. A negative value for babble threshold indicates improvement in hearing (i.e., decreased threshold). This result was unexpected given the other sensory declines for participants, and a possible explanation with respect to the component frequencies of the Babble sound file is suggested in the Discussion.

With respect to the cognitive measures, all of the working memory tasks showed significant declines except for the two simple verbal working memory tasks (Letter Span and Word Span). In the case of the working memory tasks, negative values indicate cognitive decline (i.e., decreased proportion correct). Finally, in reference to processing speed when the average mean reaction time score of participants was considered, both tasks showed numerical improvement from Time 1, but only the Shape task showed statistically significant improvement. On the processing speed tasks, a negative value indicates improved speed (i.e., faster reaction times). When the average median reaction time score of participants was used, again only the Shape task showed statistically significant improvement, while the Dot task showed some non-significant numerical decline (i.e., reaction time slowing). Given the consistent spatial working memory task declines, this finding of no significant visuospatial processing speed decline was unexpected and possible reasons, namely practice effects, are considered in the Discussion.

Individual-level analysis. Declines on sensory and cognitive tasks were observed not only at the group level but also across individuals. Figures 7 through 9 present scatter plots of participants' Time 1 scores as a function of their Time 2 scores. For all plots, to the extent that the data points fall below the diagonal dashed line, participants showed declines on these tasks. In the case of the threshold (PTAL, PTAH, and Babble) and processing speed tasks, Time 1 data was plotted on the *y*-axis and Time 2 data on the *x*-axis. Conversely, for the rest of the tasks, the data was flipped such that Time 1 data was plotted on the *x*-axis and Time 2 data on the *y*-axis. In this way, the patterns of decline (i.e., falling below the diagonal) could be easily seen across all plots.

Working memory tasks were plotted as composites. All correlations between pairs of working memory tasks were strong, supporting the decision to combine them into composite scores (see shaded cells in Table 3). In order to plot the working memory tasks, two procedures were performed. First, participants' scores for Time 1 and Time 2 were standardized based on means and standard deviations for the entire group. For Time 1 scores, the mean was subtracted from the raw score, and this value was then divided by the standard deviation to compute the *z*-scores, as is traditionally done. For Time 2 scores, the mean and standard deviation from Time 1 were used to compute the *z*-scores. This procedure was used so that longitudinal declines in scores could be observed from Time 1 to 2 when plotted and would not be lost in the standardization procedure. The second procedure involved creating a composite out of the two working memory tasks for each task type (simple spatial, complex spatial, simple verbal, and complex verbal). Composites were formed by averaging participants' *z*-scores for each pair of tasks. The composite values were then plotted.

As can be seen from the plots, the average changes in sensory and cognitive abilities seen at the group level are echoed on an individual level. Detection of pure tones, both low (PTAL) and high (PTAH) frequencies, along with identifying speech in noise (SPIN) all showed longitudinal declines from Time 1 to Time 2, indicated by more data points below the diagonal dashed line than above (see Figure 7). Babble threshold, however, did not show longitudinal declines, with more data points above the diagonal (see Figure 7). Most working memory tasks showed declines, with most data points falling below the diagonal, except for the simple verbal tasks (see Figure 8). For processing speed, there were more data points above the diagonal than below, indicating improvement on the task, but this was primarily the case for the Shape task (see Figure 9). For the Dot task, data points mostly remained close to the diagonal, indicating no longitudinal changes. For both processing speed tasks, it was those who originally had the slowest performance that showed the most improvement (i.e., faster reaction times).

Individual age-related differences and regression lines were plotted for each task separately for Time 1 and Time 2 scores (see Figures 10-13). For all sensory measures it is the young-old participants (those closer to age 65) who performed the best at Time 1 and Time 2 as compared to the old-old participants (those closer to age 95) for all tasks, as indicated by the positive slopes for the threshold measures (PTAL, PTAH, and Babble) and negative slope for the SPIN (see Figure 10). Similarly, for all of the spatial working memory tasks, young-olds performed better than old-olds at Time 1 and Time 2, as indicated by the negative slopes (see Figure 11). There is some evidence, given the non-parallel regression lines, of faster decline for the old-olds than the young-olds on the Alignment Span task, but also evidence for equivalent decline for both young-olds and old-olds on the Position Span task. For the verbal working memory tasks, there were not strong age-related differences in performance at Time 1 (i.e., horizontal lines) but greater age-related differences at Time 2 for all tasks (i.e., negative slopes) likely due to faster rates of decline for the old-olds (see Figure 12). Finally, for the processing speed tasks, differences in performance were related to age at Time 1, as indicated by a positive slope, and somewhat less so at Time 2 especially for the Dot task.

Evaluation of the Common Cause Hypothesis

The "common cause" hypothesis (Lindenberger & Baltes, 1994) predicts significant correlations between sensory and cognitive abilities, especially in older adults, given their shared source of degradation, the aging brain. We can evaluate evidence for this hypothesis with simple zero-order correlations between the sensory and cognitive abilities in our older adult sample (see zero-order correlations in black box in Table 3). Despite the moderate to strong intra-correlations within each domain (.44-.81), the sensory-cognitive inter-correlations were mostly weak, ranging in magnitude between .01 and .40. Only a few correlations were moderate and significant, and none of them included pure-tone thresholds, which common cause studies usually test for hearing ability. Instead, they were all between babble threshold and spatial working memory tasks and the Shape processing speed task.

Lindenberger and Baltes, however, have argued that stronger evidence for the common cause can be found by examining age-related relationships between sensory and cognitive abilities. Therefore, we computed partial correlations between age and each cognitive ability, controlling for each sensory ability separately. Since, according to the proposal, sensory abilities are relatively direct and reliable measures of age-related brain degradations, controlling for them should significantly reduce the correlation between age and each cognitive ability. Table 4 presents the zero-order correlations between age and performance on each sensory and cognitive measure in the first column, followed by the partial correlations between age and cognitive ability controlling for each sensory ability separately (indicated by the remaining column headings). Evidence to support the common cause hypothesis would occur if attenuations in the correlations were observed from the first column compared to the other columns. Overall, these partial correlations were reduced, but in some cases were increased, by controlling for the low- and high-frequency pure-tone thresholds (PTAL and PTAH, which were the two hearing measures used by Lindenberger and Baltes, 1994). Specifically, for those cognitive abilities that were significantly related to age—Dot Span (Dspan), Grid Span (Gspan), Alignment Span (Aspan), Word Span (Wspan), and the Shape task—pure-tone thresholds partially reduced that relationship for all but one (Wspan). However, for Letter Span (Lspan) and Operation Span (Ospan), controlling for pure-tone threshold resulted in an increased relationship with age. When you consider babble threshold (Babble) and the speech perception in noise task (SPIN), these sensory measures were just as successful as pure-tone thresholds at reducing the larger age by cognition correlations.

Discussion

The present study was a longitudinal (approximately 4-year) investigation of age-related changes in sensory and cognitive abilities. Overall, there were declines on most sensory and cognitive abilities that were tested over this time: pure-tone thresholds, speech perception in noise, and most working memory tasks. There were no observed declines for detection of a babble sound, simple verbal working memory, or processing speed. These results were at times inconsistent with predictions made by previous cross-sectional studies, as discussed below. Importantly, the present study is the first study to examine longitudinal changes in older adults on such a range of sensory and cognitive abilities, especially as it includes working memory tasks assessing both spatial and verbal abilities.

Sensory Declines

High-frequency pure-tone thresholds (PTAH) showed a numerically greater degree of average longitudinal decline across the sample than low-frequency pure-tone thresholds (PTAL). These differential declines for PTAL ($M = 3.69$) and PTAH ($M = 5.11$) are consistent with results from cross-sectional studies. Cross-sectional studies would predict greater age-related declines for high-frequency than low-frequency pure tones (CHABA, 1988; Corso, 1959; Sommers et al., 2011) given the predominance of hair cell loss at the end of the basilar membrane in the cochlea responsible for detection of higher frequencies (Liu & Yan, 2007). In Sommers et al.'s (2011) cross-sectional study, they found that there were nearly equal age-related declines for the three low-frequency pure tones (250 Hz, 500 Hz, 1000 Hz), but greater and progressively steeper age-related declines for each of the three high-frequency pure tones (2000 Hz, 4000 Hz, 8000 Hz). Based on these results, we would have expected the same, relatively small decline for the low frequencies, and progressively greater declines for each higher frequency. Somewhat differently, we found the two lowest frequencies (250 Hz and 500 Hz) and the two highest frequencies (4000 Hz and 8000 Hz) had the numerically greatest longitudinal decline, while the two remaining middle frequencies (1000 Hz and 2000 Hz), which comprise most of human speech showed the least amount of longitudinal decline. Therefore, neither cross-sectional pattern from Sommers et al. (2011) was precisely replicated here.

A potential explanation for these differing results is related to the resolution of the pure-tone threshold tests. Changes in an individual can only be measured to the nearest 5 dB HL, given the constraints of the audiometer and the testing procedure used to evaluate thresholds. Therefore, some changes that may have occurred in individuals' thresholds may not be detectable over this relatively short period of time. Another potential explanation for the relatively small longitudinal declines for the highest frequencies is a "floor" effect, or perhaps more appropriately a "ceiling" effect given the positive sign of this threshold measure. The following average thresholds (in parentheses, units in dB HL) for each pure-tone frequency characterized our older adult sample at the time of original testing: 250 Hz (*M*=18.33, *SD*=11.67), 500 Hz (*M*=17.26, *SD*=10.89), 1000 Hz (*M*=19.05, *SD*=10.08), 2000 Hz (*M*=26.67, *SD*=14.00), 4000 Hz (*M*=42.38, *SD*=18.59), and 8000 Hz (*M*=61.43, *SD*=20.46). The average level of hearing loss for the two highest frequencies is clinically categorized as "moderate" to "moderately severe," with some older adults reaching "severe" hearing loss (Clark, 1981 as cited in ASHA, n.d.). Additionally, two older adults reached the limit of our testing ability at 90 dB HL, considered "profound" hearing loss (the highest rating of hearing loss according to ASHA, n.d.). We examined histograms and normality plots for each frequency and these averages do not appear skewed by outliers. Given the already extensive hearing loss for the highest frequencies, attributable to age-related hair cell loss (Liu & Yan, 2007), it is likely that for many older adults auditory stimulation at these frequencies is not sufficiently registered by the mature, damaged inner ear. Therefore, our reports of average hearing loss may underestimate the true level of longitudinal hearing loss, especially for the highest frequencies.

To address this question more specifically, we computed the regression slopes for predicting change in pure-tone threshold based on participants' original thresholds. If there is a floor/ceiling effect operating on the high-frequency pure-tone thresholds, we would expect the thresholds for these frequencies to have smaller slopes than those of the low-frequency pure tones. This would indicate a slower rate of decline for participants who had the poorest hearing at the time of original testing. The following slopes (in parentheses) were found for each frequency: 250 Hz (-0.39), 500 Hz (-0.68), 1000 Hz (-0.22), 2000 Hz (-0.13), 4000 Hz (-0.19), and 8000 Hz (-0.27). As can be seen, for the most part the higher frequencies do in fact have smaller slopes than the lower frequencies, suggesting age-related damage to the ear may be masking longitudinal decline at the highest frequencies.

Unlike pure-tone thresholds, babble threshold (Babble) did not show longitudinal declines on average. One possibility is that the loudest parts of the Babble sound file were composed of frequencies that decline the least with age, which for the current sample would be around 1000 Hz and 2000 Hz as assessed with pure-tone thresholds. To determine the loudest frequencies in the Babble sound file, a power spectrum analysis was conducted. This analysis produces a plot with loudness (dB) on the *y*-axis and frequency (Hz) on the *x*-axis. The peaks in the line indicate the loudest frequencies, which we found to be around 250 Hz, 1200 Hz, and 1900 Hz. The first peak is an artifact of the analysis, but the next two peaks indicate the loudest frequencies within the sound file. We can see that the two loudest frequencies are within the range of the pure tones that declined least in the current sample, 1000 Hz-2000 Hz. Therefore, this is a plausible explanation for the longitudinal maintenance of older adults' Babble detection threshold in our sample. We do not believe these results are due to technical issues as the audiometer with which the Babble was tested was calibrated prior to the study.

Our final sensory measure, which examined speech perception in noise (SPIN), showed longitudinal declines. The existence of longitudinal declines is consistent with older adults' greater difficulty understanding speech in noisy backgrounds as compared to young adults (Akeroyd, 2008; CHABA, 1988; Gosselin & Gagné, 2011).

Cognitive Declines

Spatial working memory and processing speed tasks did not show the expected exaggerated longitudinal declines as predicted by previous studies (Hale et al., 2011; Lawrence et al., 1998; Lima et al., 1991). In reference to average changes in working memory, simple spatial, complex spatial, and complex verbal tasks showed similar declines. Simple verbal tasks did not show any decline, on average. These results are inconsistent with the cross-sectional study conducted by Park et al. (2002), which found greater age-related declines for complex working memory tasks than for simple ones, regardless of the content domain of the to-be-remembered information. These results are also inconsistent with the cross-sectional study conducted by Hale et al. (2011), which found greater age-related declines for spatial working memory tasks than for verbal ones, regardless of the complexity of the task. In the present study, instead of a simple main effect of content domain (Hale et al., 2011) or task complexity (Park et al., 2002), as would be predicted by the two cross-sectional studies just cited, the present longitudinal study found an interaction such that all tasks but the simple verbal working memory tasks showed longitudinal declines.

One explanation for these results is that the older adults benefited from a practice effect from having been tested a second time on the simple verbal working memory tasks. In fact, in a four-year longitudinal that included healthy older adults, forward digit span (a simple verbal working memory task) did not show decline across the study, and also was the task that showed the least amount of longitudinal decline in a group of older adults with mild Alzheimer's disease (Botwinick et al., 1986). Therefore, this ability seems to be largely maintained with age, perhaps due to practice effects compensating for any age-related declines and/or some maintenance of verbal processing with age.

A related, more specific explanation is that the simple verbal tasks provided the best opportunity for older adults to develop and employ memory strategies. First, older adults tend to implement strategies when performing relatively easy tasks (Lemaire, 2010). Therefore, we would expect them to have this opportunity for the *simple* working memory tasks that do not involve a distracting secondary task, as in the complex working memory tasks. Second, strategies for verbal working memory tasks (e.g., verbal rehearsal) are perhaps more successful than those that can be utilized in spatial working memory tasks (e.g., tracing a path), so even the simple spatial tasks were at a disadvantage for strategy use. While there has not been much prior research investigating spatial working memory strategies, one study found that grouping the target locations and tracing a path between the target locations were two strategies that participants utilized (Ridgeway, 2006). Relatedly, simple spatial working memory tasks may be better measures of executive attention, which has been found to decline with age, because they are not amenable to verbal rehearsal (Kane et al., 2004). Furthermore, spatial grouping/tracing strategies would have been difficult to implement with great accuracy in the present study's tasks as the number of possible locations was very large for the Dot and Position Span tasks (30 dots), and the locations were not very separable for the Grid and Alignment Span tasks (benefits of separability discussed in Ridgeway, 2006). Additionally, the array of locations changed for each new trial in the former tasks (30 dots in each cloud, out of 81 possible locations), so grouping strategies tied to the locations could not be maintained across trials.

Another possible explanation is that the simple and complex working memory tasks in the spatial domain are less separable than in the verbal domain in the abilities they tap. This was the case in the latent-variable analyses conducted by Hale et al. (2011), who found good discriminant validity for the latent constructs of simple and complex tasks in the verbal domain but poor discriminant validity for those in the spatial domain. Similar findings have also been found by Bopp and Verhaeghen (2007); Kane et al. (2004); and Miyake, Friedman, Rettinger, Shah, and Hegarty (2001). As mentioned above, this may be attributed to simple spatial working memory tasks requiring executive attention like the complex spatial and complex verbal tasks, which simple verbal working memory tasks do not.

The two visuospatial processing speed tasks did not show longitudinal declines, which may be due to the benefits of practice effects. Both tasks showed numerical improvements (improvement is a negative number as it is a reaction time measure), but only the visual task (Shape) showed significant improvements from original testing.

While the practice gained from performing these two, very short processing speed tasks is probably minimal, the practice gained from performing many similar computer-based, laboratory cognitive tasks over the course of three or more days at Time 1 and two days at Time 2 may contribute to a practice effect on this simple task. The lack of longitudinal declines in these visuospatial processing speed tasks is contrary to unpublished results from the original cross-sectional study, from which a subsample of older adults were drawn for the present study. They found large age-related declines for processing speed, especially for the visuospatial tasks. These results are also contrary to age-related processing speed effects found by many other studies as well (Hale & Myerson, 1996; Lawrence et al., 1998; Lima et al., 1991). In sum, there does not seem to be a general spatial deficit for cognitive abilities, or at least evidence for this deficit is clouded by practice effects or strategy use associated with the working memory and processing speed tasks used in the present study.

Some Evidence for a Common Cause

While the present study did not have a sufficient sample size to conduct latent variable or latent growth modeling, it evaluated the common cause hypothesis using simple correlations as was done in the initial steps of analysis by Lindenberger and Baltes (1994). The weak zero-order correlations between the various sensory and cognitive abilities of the present study do not provide strong support for a common cause. The magnitude of these correlations ranged from 0.01 to 0.40, with the highest correlations existing with babble threshold. Conversely, Lindenberger and Baltes (1994) found moderate to strong correlations (0.29-0.61) between their pure-tone threshold measures and various cognitive abilities (memory, speed, reasoning, knowledge, and fluency).

While Lindenberger and Baltes did not include a measure of working memory in their study—the memory measure assessed long-term memory—the common cause should apply to all aspects of cognition that experience age-related declines.

Even though the present sample only included older adults, a possible criticism by Lindenberger and Baltes of evaluating the common cause using zero-order correlations is that only *age-related* changes in cognitive ability are related to sensory ability. Therefore, a partial correlation between age and cognitive ability should be significantly reduced by controlling for sensory ability. We found that these partial correlations were mostly reduced by controlling for PTAL or PTAH (as well as by the Babble and SPIN measures). Overall, the common cause hypothesis was partially supported by the present data.

Limitations

One limitation of the present study is the small sample size. This limitation may be especially important in the evaluation of the common cause hypothesis, given the large to very large sample sizes used in previous studies (N = 1,823 in Anstey et al., 2003; N = 156 in Lindenberger & Baltes, 1994). With a large pool of measures and a relatively small pool of participants, the power to detect this sensory-cognitive relationship may have been stinted. This sample size also limited the types of analyses that could be conducted to investigate the common cause. Structural equation modeling, as was done in the previous cited studies for single-assessment and longitudinal data, would be a better method for testing the sensory-cognitive relationship given its ability to specify directional paths between abilities, but could not be performed on this small sample.

Another limitation of the present study, as occurs with any longitudinal study, is the question of the selectivity of those who return for follow-up testing. We were fortunate in our sample to have older adults across a wide range of ages, but certainly our 92-year-old participant, along with the others in the oldest old age group, are a select group of people. However, we did not find evidence for this at least on a group level when we compared those who returned to those who did not on the measures assessed in the present study.

Conclusions and Future Directions

In a relatively short time span of approximately four years, older adults experienced significant declines in many sensory (pure-tone thresholds and speech in noise tasks) and cognitive (working memory) abilities. In fact, the present study is one of the first to measure sensory abilities longitudinally, and the *first* study to measure this range of cognitive abilities longitudinally. Given the paucity of longitudinal studies investigating these abilities, the present results provide important information about the sensory-cognitive profile of aging. While sensory and cognitive abilities were not consistently related (evidence against a common cause), future research should investigate the implications of declines on these basic abilities for higher-level abilities that rely heavily on both, such as understanding a spoken conversation. Older adults frequently report difficulty when engaging in conversations, which leads to anxiety and frustration (CHABA, 1988; Schneider, Daneman, & Pichora-Fuller, 2002). Therefore, determining the relative contributions of sensory and cognitive abilities to understanding speech in various listening situations is clinically important, especially since older adults are largely dissatisfied with their current hearing assistive devices (47% dissatisfaction rate for hearing aids; Mann, Goodall, Justiss, & Tomita, 2002).

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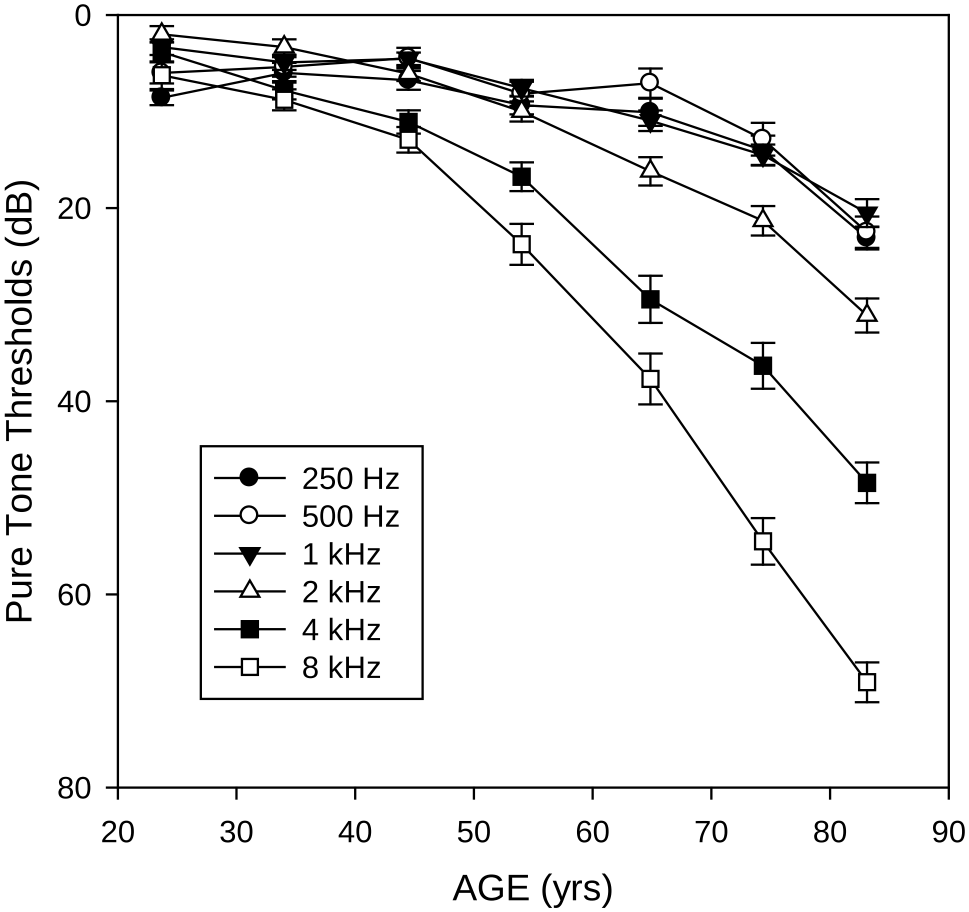
Figure 1

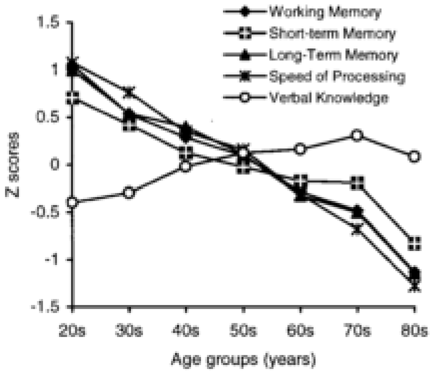
Age-Related Declines in Hearing by Frequency



Note. Reproduced from Sommers et al. (2011).

Figure 2

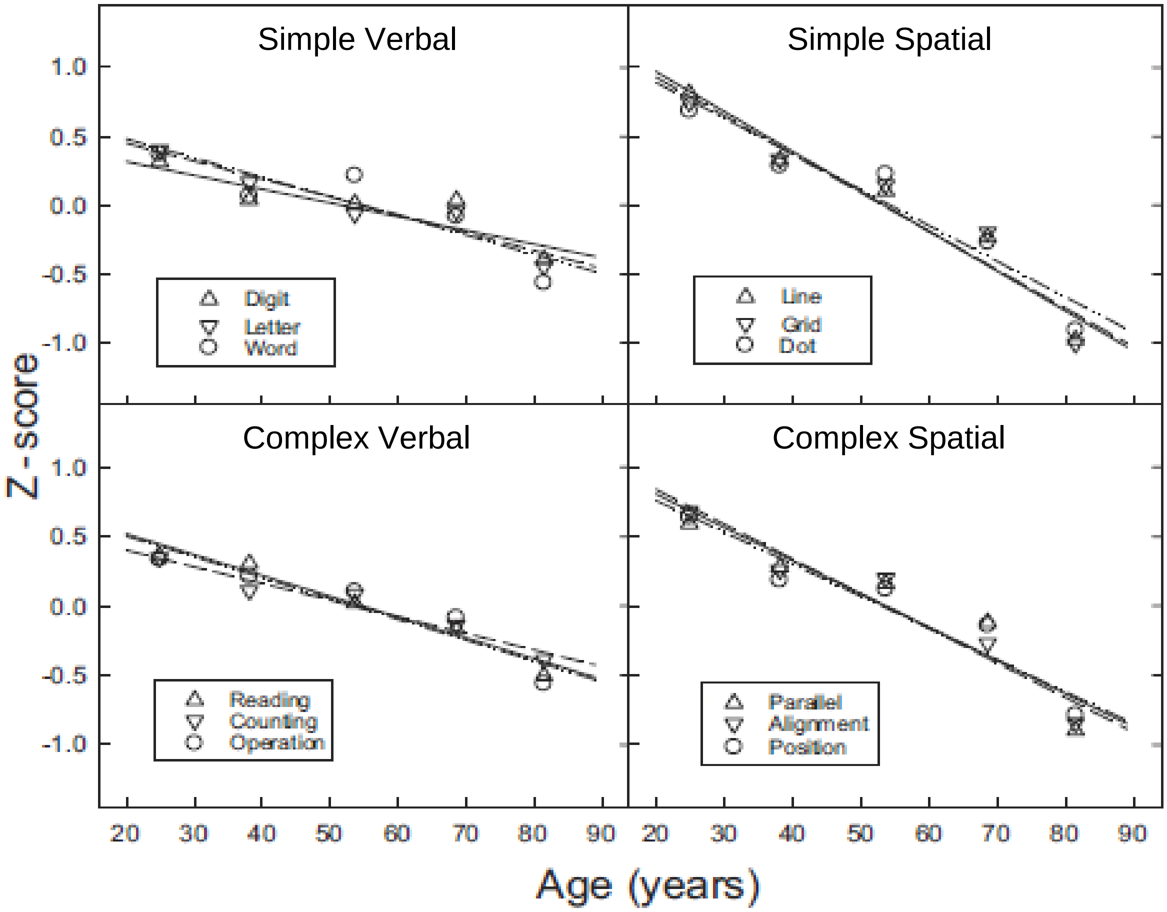
Age-Related Declines in Cognition by Task Domain



Note. Reproduced from Park et al. (2002).

Figure 3

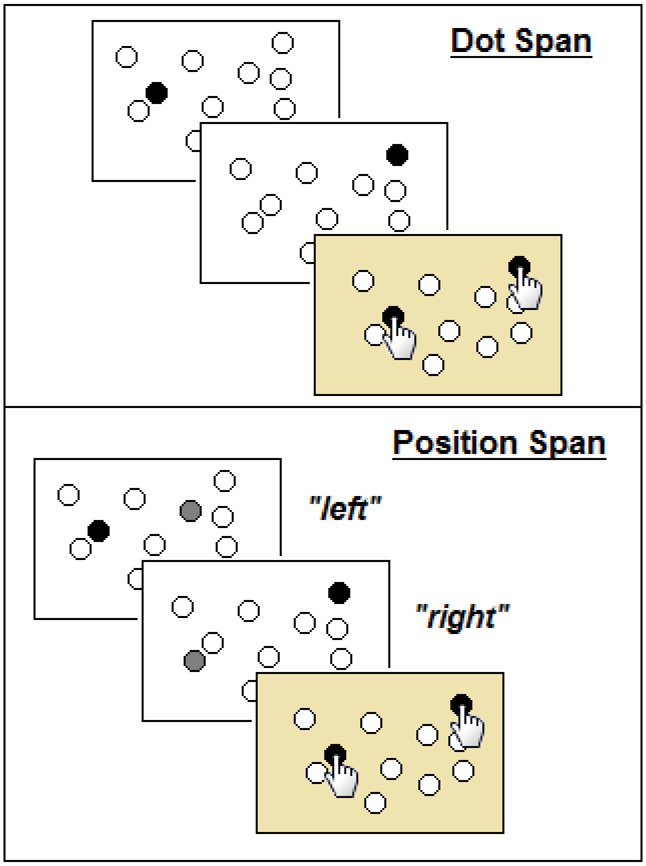
Age- Related Declines in Working Memory by Content Domain



Note. Reproduced from Hale et al. (2011; labels added).

Figure 4

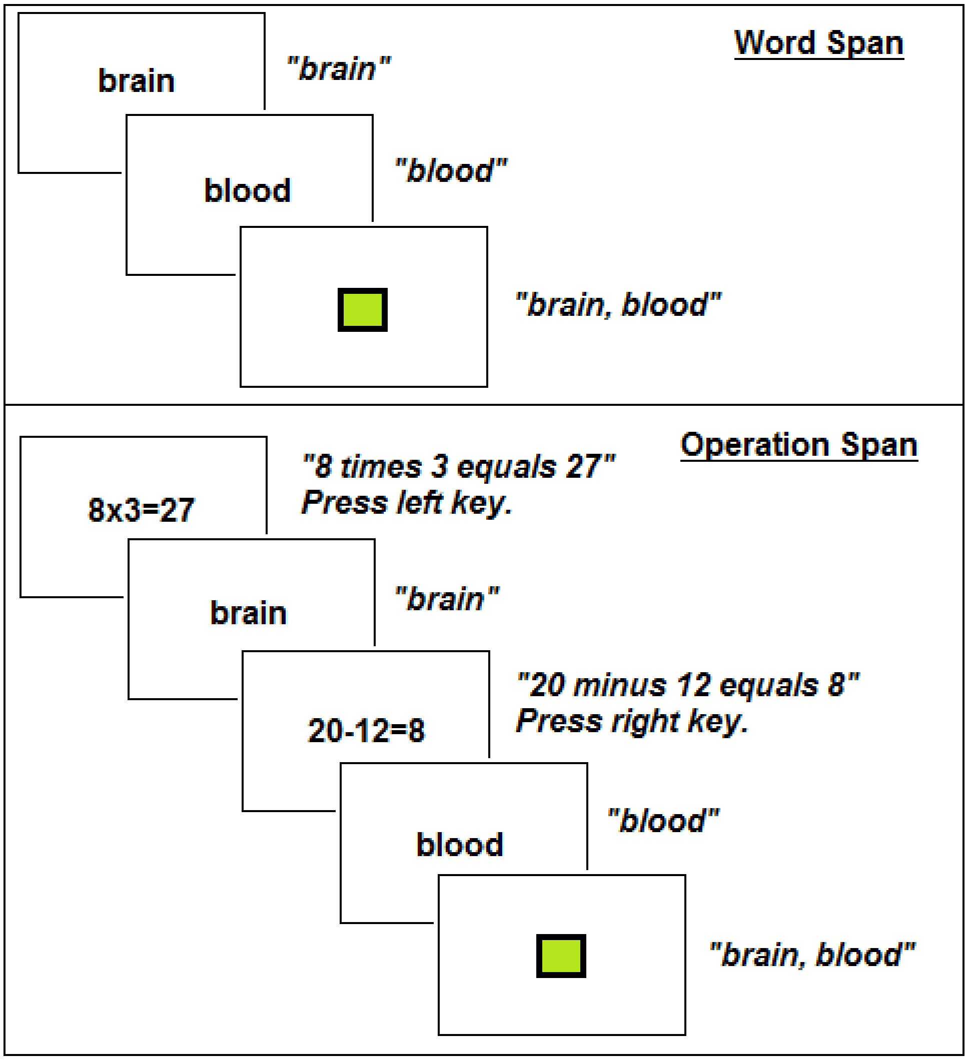
Sample Screenshots from a Simple and Complex Spatial Working Memory Task



Note. Simple (top) and complex (bottom) spatial working memory tasks. In the Dot Span task participants had to remember the locations of a series of dots and touch those dots at the end of the series (indicated by screen's background changing color). In the Position Span task participants had to not only remember a series of locations, but also make judgments about whether the black dot was located to the left or right of the gray dot.

Figure 5

Sample Screenshots from a Simple and Complex Verbal Working Memory Task

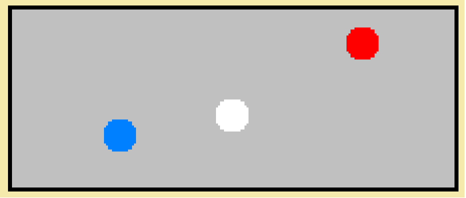


Notes. Simple (top) and complex (bottom) verbal working memory tasks. In the Word Span task participants saw a series of words and had to recall those words at the end of the series (indicated by the appearance of a green square). In the Operation Span task participants had to not only remember a series of words, but also make judgments about the correctness of a math problem between each word. Participants were required to read the words and math problems aloud as they were presented.

Figure 6

Sample Screenshots from the Processing Speed Tasks

Dot Task



Shape Task

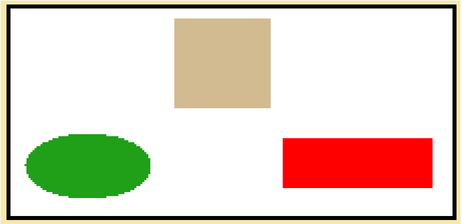


Figure 7

Longitudinal Changes in Sensory Abilities

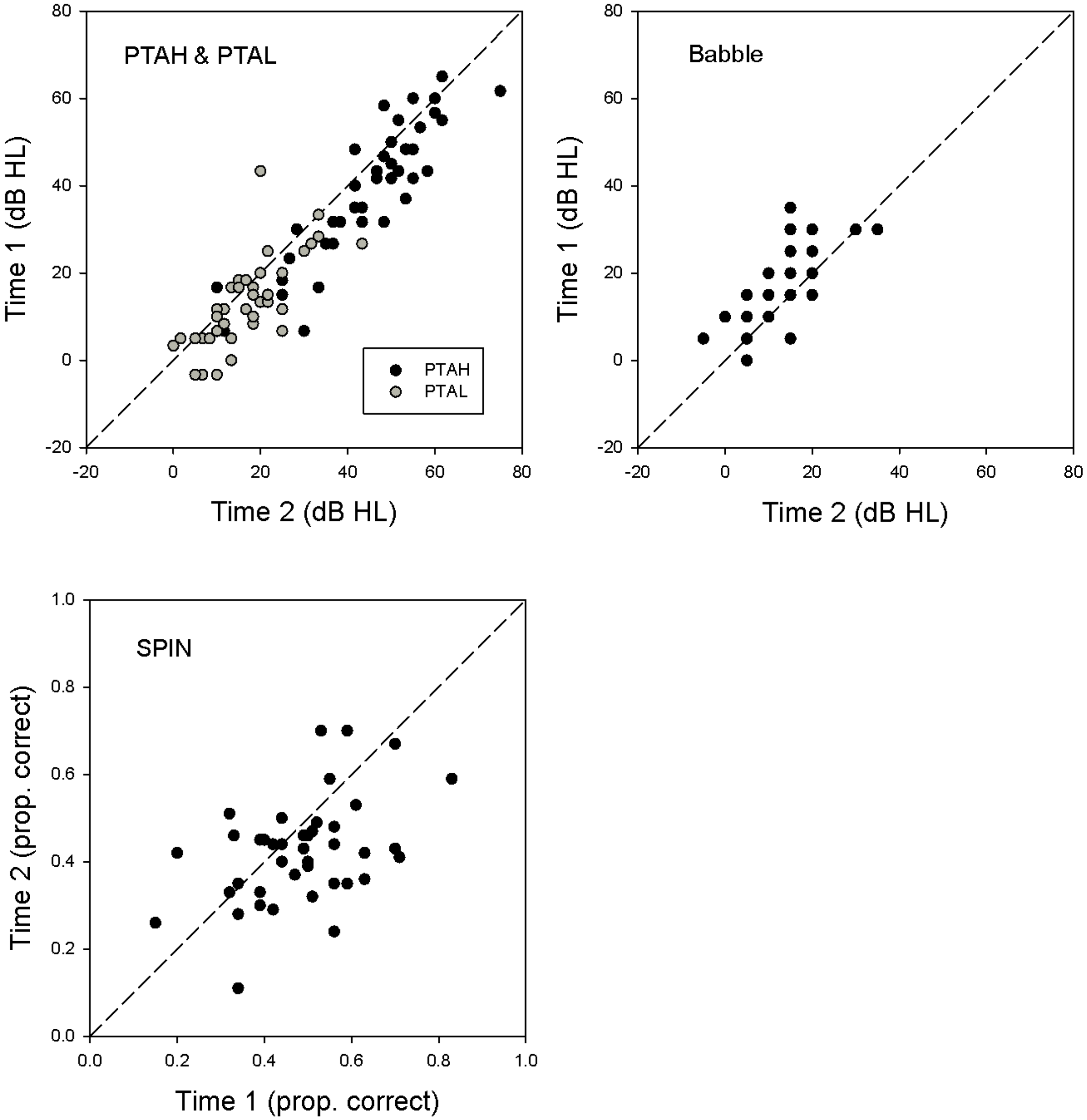


Figure 8

Longitudinal Changes in Working Memory

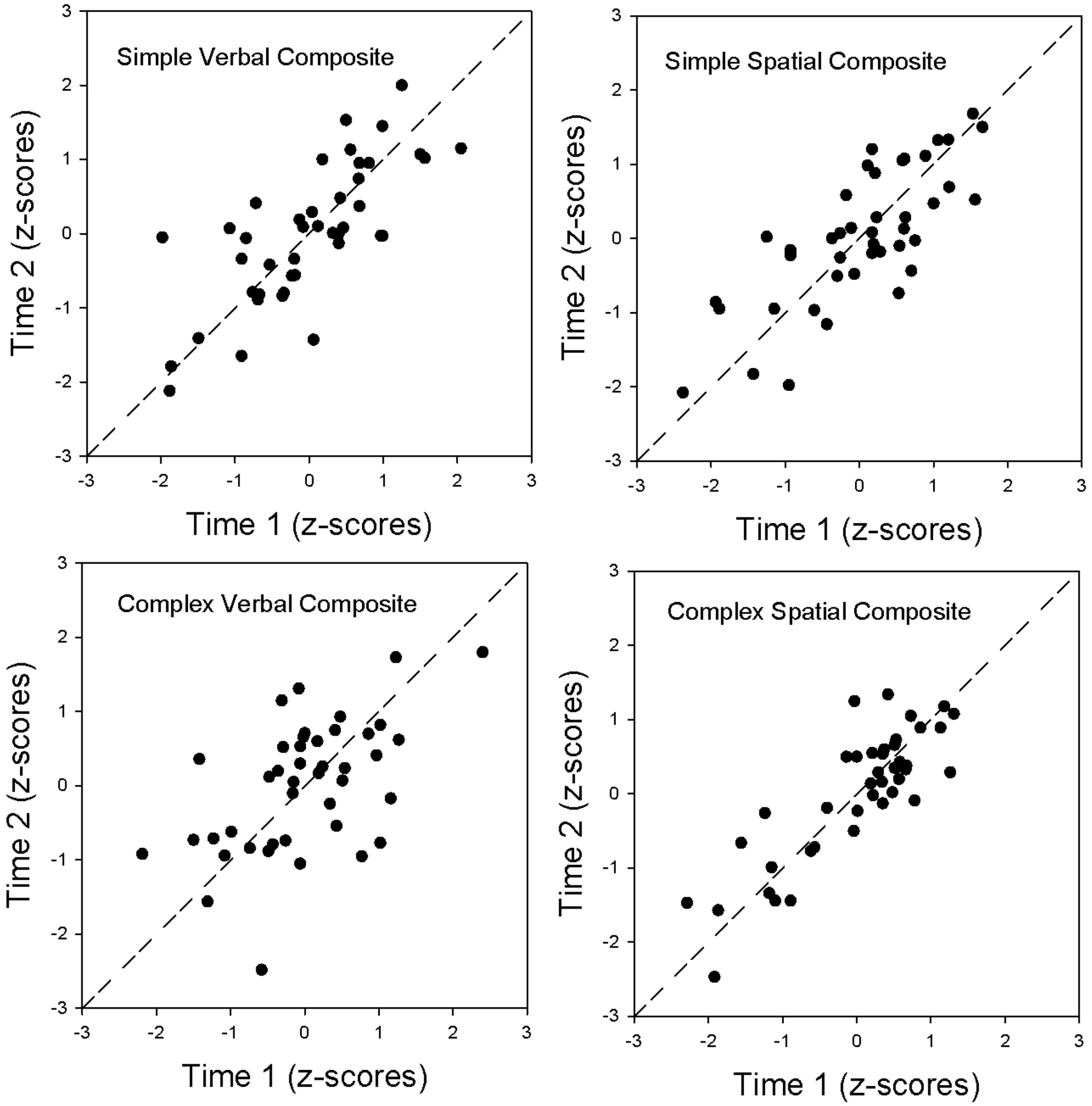


Figure 9

Longitudinal Changes in Processing Speed

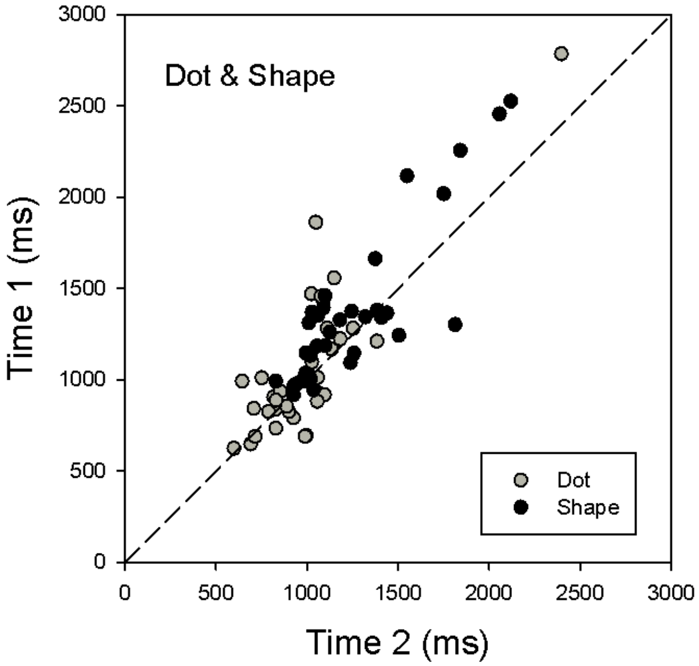


Figure 10

Age-Related Changes in Sensory Abilities

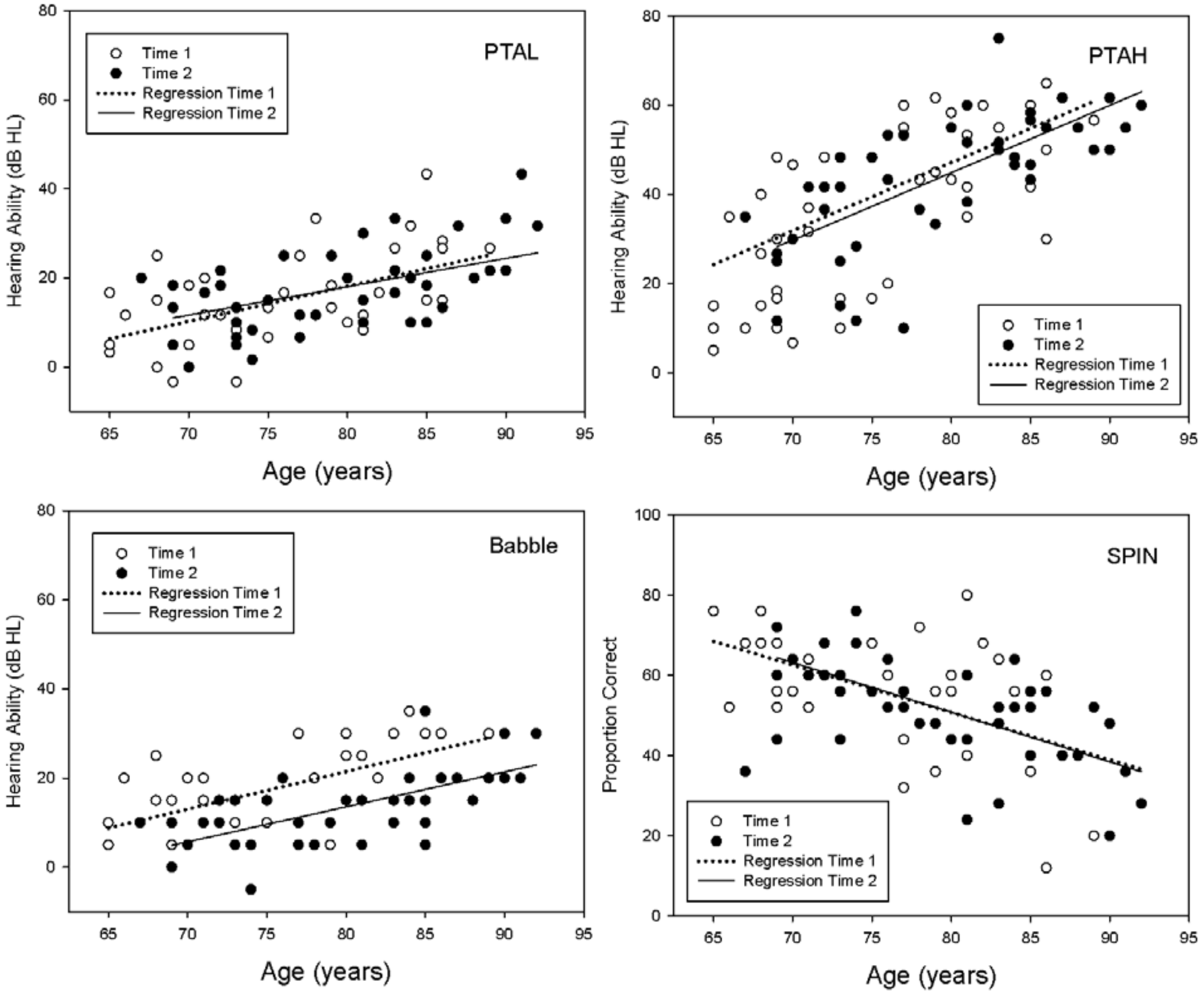


Figure 11

Age-Related Changes in Spatial Working Memory

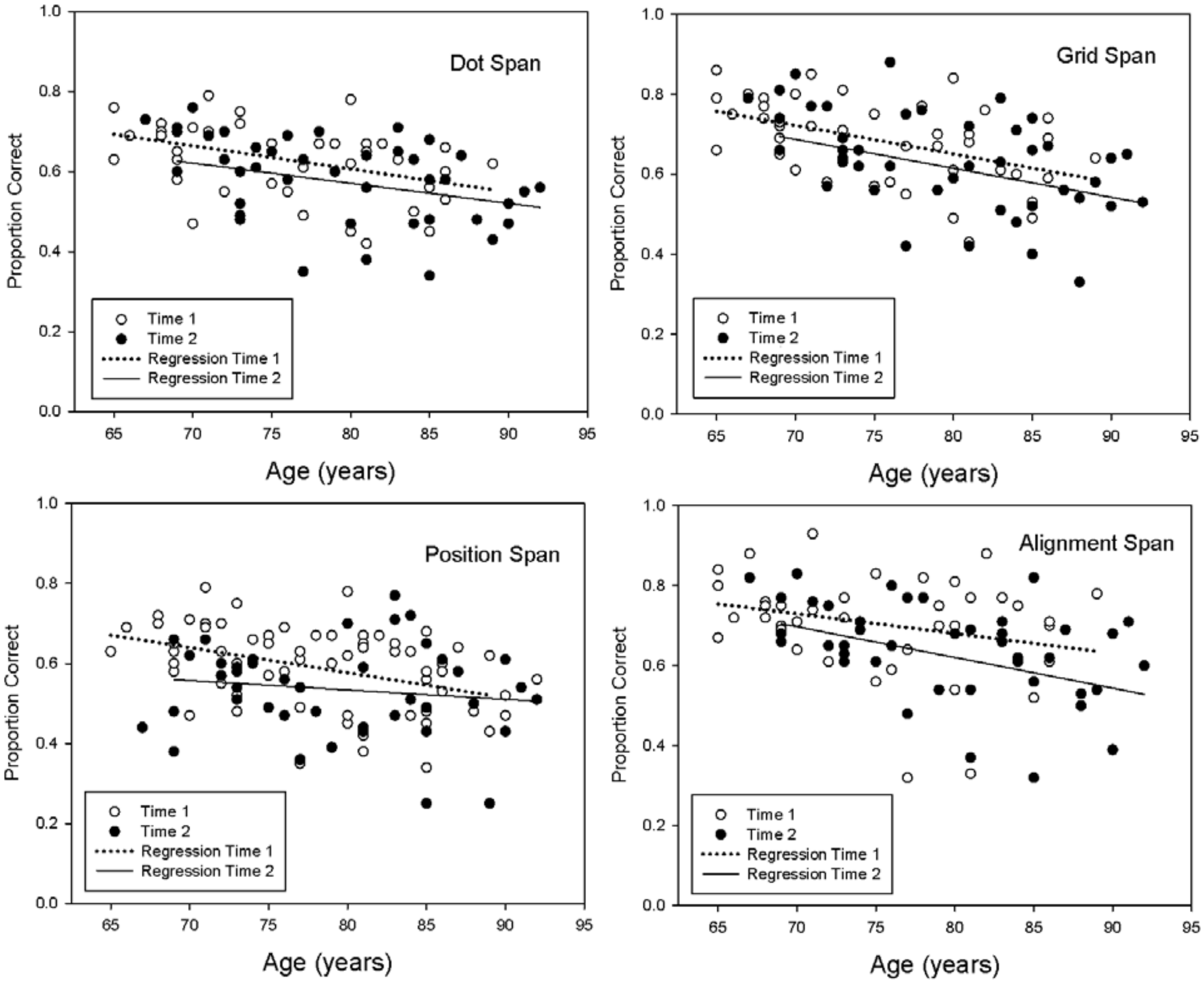


Figure 12

Age-Related Changes in Verbal Working Memory

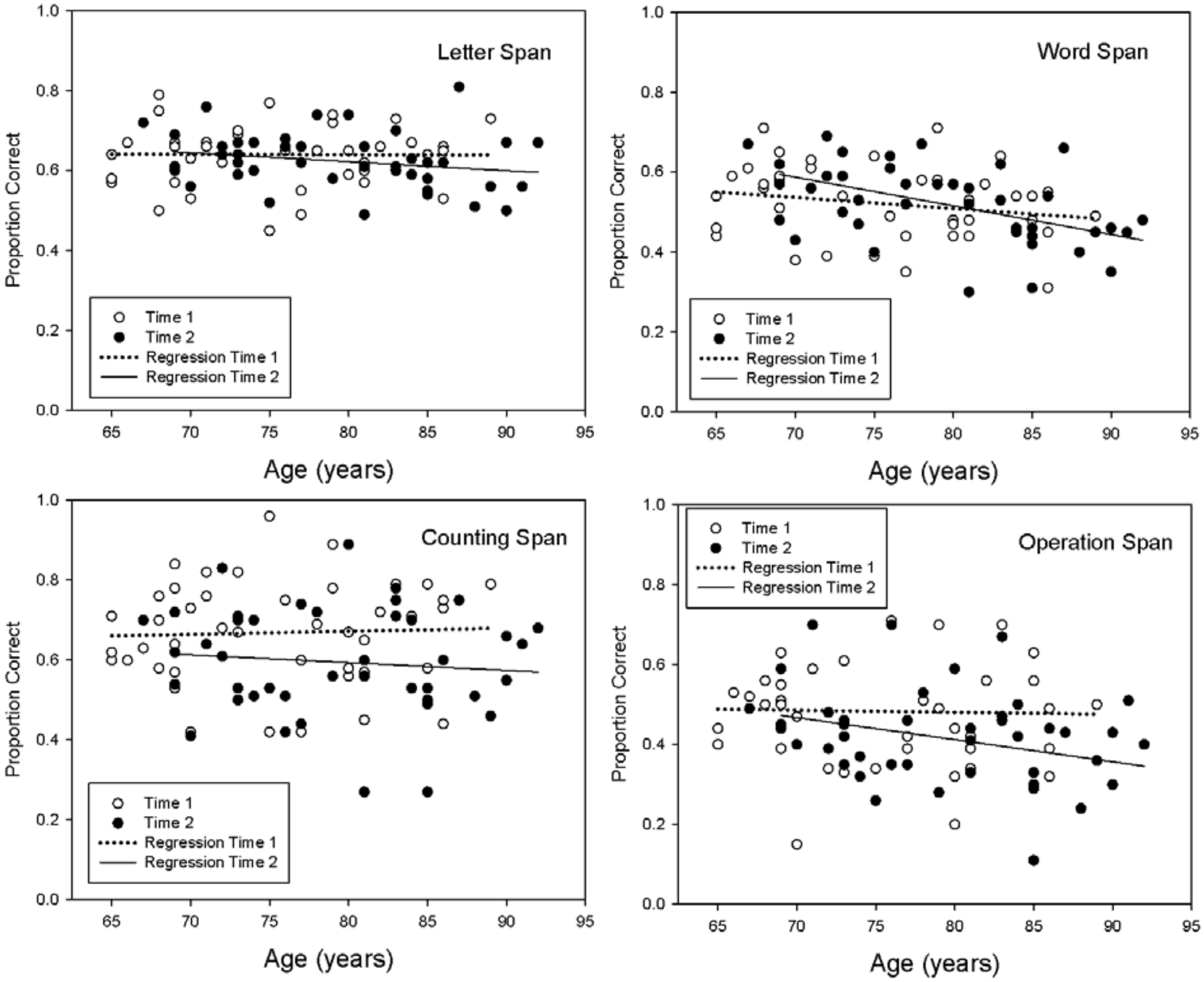


Figure 13

Age-Related Changes in Processing Speed

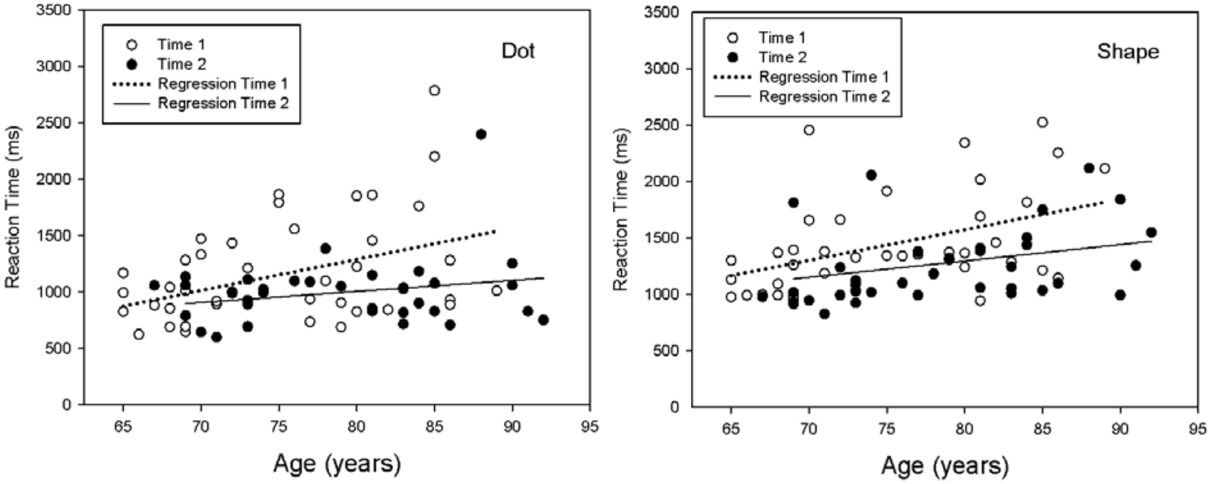


Table 1

Comparison between Returners and Non-Returners at Time 1 (Original Study)

	Returner *M* (*n* = 43)	Non-Returner *M* (*n* = 114)	*F*	*p*
Age (years)	75.40	76.02	.26	.61
Sex (count)	M=13, F=30	M=44, F=70	.95 (χ^2)	.33
Education (years)	14.95	15.10	.09	.77
Vocabulary (points)	50.40	48.24	1.71	.19
Sensory				
PTAL (dB HL)	14.42	16.20	.97	.33
PTAH (dB HL)	38.57	40.87	.68	.41
Babble (dB HL)	17.56	18.86	.49	.48
SPIN (prop. correct)	55.72	50.53	2.97	.09
Simple Spatial WM (prop. correct)				
Dot Span	.63	.64	.01	.94
Grid Span	.68	.67	.43	.52
Complex Spatial WM (prop. correct)				
Position Span	.61	.59	.77	.38
Alignment Span	.70	.68	1.75	.19
Simple Verbal WM (prop. correct)				
Letter Span	.64	.63	.12	.74
Word Span	.52	.52	.04	.85
Complex Verbal WM (prop. correct)				
Counting Span	.67	.65	.31	.58
Operation Span	.48	.48	.00	.99
Processing Speed (ms)				
Dot	1158.60	1147.58	.02	.89
Shape	1416.30	1576.81	2.68	.10

Note. For all variables, units of measurement are specified in parentheses beside each variable name. For Sex, M (male) and F (female) values represent the total number of participants in each sex group. For Vocabulary, the maximum possible score was 66 points.

Table 2

Longitudinal Changes and Test-Retest Reliabilities of Sensory and Cognitive Tasks

	N	Predicted M Δ	Observed M Δ	SD	Paired t	df	p	r
Sensory								
PTAL (dB HL)	42	3.54	3.69	7.02	3.41	41	.001	.74
PTAH (dB HL)	42	5.61	5.11	7.22	4.59	41	<.001	.90
Babble (dB HL)	42	2.87	-4.05	5.96	-4.39	41	<.001	.75
SPIN (prop. correct)	42	-.045	-.050	.127	-2.57	41	.014	.61
Simple Spatial WM (prop. correct)								
Dot Span	42	-.022	-.052	.082	-4.10	41	<.001	.67
Grid Span	43	-.028	-.051	.083	-4.04	42	<.001	.75
Complex Spatial WM (prop. correct)								
Position Span	42	-.033	-.076	.096	-5.12	41	<.001	.71
Alignment Span	43	-.025	-.069	.085	-5.27	42	<.001	.77
Simple Verbal WM (prop. correct)								
Letter Span	42	-.008	-.013	.060	-1.36	41	.181	.67
Word Span	42	-.011	-.000	.071	-.01	41	.993	.72
Complex Verbal WM (prop. correct)								
Counting Span	42	-.008	-.070	.141	-3.25	41	.002	.44
Operation Span	42	-.017	-.062	.135	-3.00	41	.005	.46
Processing Speed (ms)								
Dot	34	74.49	-73.43	237.11	-1.81	33	.080	.83
	32		-11.66 (median)	163.41	-.36	31	.724	.85
Shape	35	123.03	-110.65	216.42	-3.03	34	.005	.86
	21		-102.74 (median)	220.31	-2.84	20	.010	.88

Note. For all variables, units of measurement are specified in parentheses beside each variable name. Predicted mean change values (Predicted M Δ) were calculated from cross-sectional predictions from the Time 1 data regression analyses. Observed mean change values (Observed M Δ) were calculated by subtracting Time 1 scores from Time 2 scores. For low-frequency pure-tone threshold (PTAL), high-frequency pure-tone threshold (PTAH), and babble threshold (Babble), positive values represent declines in hearing ability (db HL). For Speech Perception in Noise (SPIN) and working memory (WM) tasks, negative values represent declines in proportion correct. For processing speed tasks, negative values represent faster reaction time. The last column presents the test-retest reliabilities of the task from Time 1 to Time 2.

Table 3

Zero-Order Correlations between Sensory and Cognitive Tasks

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. PTAL		.60***	.75***	-.61***												
2. PTAH			.66***	-.65***												
3. Babble				-.51***												
4. SPIN																
5. SS Dspan	-.18	-.25	-.33*	.29		.81***	.51***	.79***								
6. SS Gspan	-.25	-.27	-.31*	.28			.44**	.76***								
7. CS Pspan	-.15	.07	-.11	.05				.53***								
8. CS Aspan	-.22	-.26	-.40**	.22												
9. SV Lspan	-.04	-.05	-.11	.05						.77***	.62***	.63***				
10. SV Wspan	-.14	-.22	-.29	.18							.62***	.60***				
11. CV Cspan	.01	-.11	-.09	-.01								.57***				
12. CV Ospan	.05	.01	-.06	.06												
13. Dot (mean)	.07	.03	.07	-.11											.59***	
14. Dot (median)	.10	.09	.08	-.17												.53**
15. Shape (mean)	.28	.18	.35*	-.24												
16. Shape (median)	.29	.19	.39*	-.24												

**p*<.05, ***p*<.01, ****p*<.001. *Note.* PTAL=low-frequency pure-tone threshold, PTAH=high-frequency pure-tone threshold, Babble=babble threshold, and SPIN=Speech Perception in Noise task, SS=Simple Spatial working memory (WM), CS=Complex Spatial WM, SV=Simple Verbal WM, CV=Complex Verbal WM, Dspan=Dot Span, Gspan=Grid Span, Pspan=Position Span, Aspan=Alignment Span, Lspan=Letter Span, Wspan=Word Span, Cspan=Counting Span, and Ospan=Operation Span.

Table 4

Zero-Order and Partial Correlations between Age, Sensory, and Cognitive Tasks

	Age	PTAL	PTAH	Babble	SPIN
PTAL	.57***				
PTAH	.68***				
Babble	.63***				
SPIN	-.54***				
SS Dspan	-.43**	-.41**	-.37*	-.31*	-.34*
SS Gspan	-.49***	-.43**	-.43*	-.40**	-.42**
CS Pspan	-.11	-.03	-.21	-.05	-.10
CS Aspan	-.45**	-.40**	-.38*	-.27	-.40**
SV Lspan	-.26	-.29	-.31*	-.25	-.28
SV Wspan	-.48**	-.49**	-.46**	-.40**	-.46**
CV Cspan	-.08	-.11	-.01	-.03	-.10
CV Ospan	-.26	-.35*	-.37*	-.29	-.27
Dot (mean)	.19	.18	.23	.19	.15
Dot (median)	.21	.19	.21	.21	.14
Shape (mean)	.38*	.28	.36*	.22	.31
Shape (median)	.39*	.28	.36*	.20	.31

**p*<.05, ***p*<.01, ****p*<.001. *Note.* Zero-order correlations between age and each sensory and cognitive ability are presented in the first column. Partial correlations between age and each cognitive ability, controlling for the sensory ability indicated by the column heading, are listed in the remaining columns.