Published in final edited form as:

Hear Res. 2010 June 1; 264(1-2): 21–29. doi:10.1016/j.heares.2009.09.017.

Age-related differences in gap detection: Effects of task difficulty and cognitive ability

Kelly C. Harris, Mark A. Eckert, Jayne B. Ahlstrom, and Judy R. Dubno

Department of Otolaryngology – Head and Neck Surgery, Medical University of South Carolina, 135 Rutledge Ave, MSC 550, Charleston, SC 29425-5500

Abstract

Differences in gap detection for younger and older adults have been shown to vary with the complexity of the task or stimuli, but the factors that contribute to these differences remain unknown. To address this question, we examined the extent to which age-related differences in processing speed and workload predicted age-related differences in gap detection. Gap detection thresholds were measured for 10 younger and 11 older adults in two conditions that varied in task complexity but used identical stimuli: (1) gap location fixed at the beginning, middle, or end of a noise burst and (2) gap location varied randomly from trial to trial from the beginning, middle, or end of the noise. We hypothesized that gap location uncertainty would place increased demands on cognitive and attentional resources and result in significantly higher gap detection thresholds for older but not younger adults. Overall, gap detection thresholds were lower for the middle location as compared to beginning and end locations and were lower for the fixed than the random condition. In general, larger age-related differences in gap detection were observed for more challenging conditions. That is, gap detection thresholds for older adults were significantly larger for the random condition than for the fixed condition when the gap was at the beginning and end locations but not the middle. In contrast, gap detection thresholds for younger adults were not significantly different for the random and fixed condition at any location. Subjective ratings of workload indicated that older adults found the gap-detection task more mentally demanding than younger adults. Consistent with these findings, results of the Purdue Pegboard and Connections tests revealed age-related slowing of processing speed. Moreover, age group differences in workload and processing speed predicted gap detection in younger and older adults when gap location varied from trial to trial; these associations were not observed when gap location remained constant across trials. Taken together, these results suggest that age-related differences in complex measures of auditory temporal processing may be explained, in part, by age-related deficits in processing speed and attention.

Keywords

aging; auditory temporal processing; gap detection; processing speed; workload; cognitive

Corresponding author: Kelly C. Harris, Ph.D., 135 Rutledge Ave, MSC 550, Charleston, SC, 29425-5500, harriskc@musc.edu, (843) 792-7977.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1. Introduction

A common complaint of older adults with and without hearing loss is difficulty understanding speech, especially in complex listening environments (Dubno et al., 1997). A decline in auditory temporal processing has been proposed to account for some of the problems with speech understanding. Numerous psychoacoustic studies have reported age-related declines in auditory temporal processing (Dubno et al., 2003; Gordon-Salant et al., 1993; Schneider et al., 1998; Snell, 1997; Strouse et al., 1998). These deficits may underlie age-related difficulties in speech understanding, given that older adults experience more pronounced word recognition difficulties when the speech signal is temporally distorted, such as by reverberation (Gordon-Salant et al., 1993) or when the background noise is temporally varied (Dubno et al., 2001; Dubno et al., 2003; Duquesnoy, 1983). In addition, psychoacoustic experiments of auditory temporal processing have shown age-related declines in duration discrimination (Abel et al., 1990), gap duration discrimination (Fitzgibbons et al., 1994; Phillips et al., 1994), temporal order determination (Humes et al., 1991; Trainor et al., 1989), and intensity and frequency discrimination (Harris et al., 2007; Harris et al., 2008; He et al., 1998).

A common measure of auditory temporal resolution is gap detection. Gap detection paradigms typically assess an individual's ability to perceive a silent interval in an otherwise continuous stimulus. In general, gap detection thresholds are higher in older than younger adults (He et al., 1999; Humes et al., 2009; Pichora-Fuller et al., 2006b; Schneider et al., 1998; Schneider et al., 1999; Schneider et al., 1994; Snell, 1997), even after controlling for peripheral hearing loss (Fitzgibbons et al., 1994; Grose et al., 2001; He et al., 1999; Lister et al., 2002; Lister et al., 2000; Roberts et al., 2004). With simpler tasks, such as when the gap is located in the middle of a pure tone or broadband noise, gap detection thresholds for older adults tend to be similar to (Alain et al., 2004; Bertoli et al., 2002; He et al., 1999; Lister et al., 2004), or slightly but significantly higher than those of younger adults (Humes et al., 2009; Moore et al., 1992; Strouse et al., 1998). The magnitude of the age-related deficit for gap detection varies with the spectral complexity of the markers surrounding the gap. In comparison to more spectrally stable markers, larger age-related differences are observed both when the markers preceding and following the gap fall into different frequency ranges (Lister et al., 2002; Lister et al., 2000) and when the gap occurs in spectrally dynamic markers (Lister et al., 2004; Pichora-Fuller et al., 2006b). Similarly, robust age-related differences are observed when the markers surrounding the gap are shorter than 10 ms (Schneider et al., 1999) and when the location of the gap falls near the onset or offset of the stimuli or is varied randomly (He et al., 1999).

Age-related differences in gap detection are often attributed to changes in the central nervous system, including age-related changes in recovery from adaptation of eighth-nerve fibers (Schneider and Hamstra, 1999) and declines in neuronal synchrony and inhibition (Alain et al., 2004; Bertoli et al., 2002). Age-related differences in auditory temporal processing are also evident in electrophysiologic studies. Boettcher et al. (1996) observed that in comparison to younger gerbils, older gerbils had prolonged wave-iv latencies following a silent gap. Similarly, increases in ABR wave-V adaptation in older human participants have been associated with poorer behavioral performance on measures of temporal processing (Humes, 2005). Even when older and younger adults have similar gap detection thresholds, or are behaviorally matched for performance, longer gap durations are required to elicit a mismatch negativity response (MMN), a late pre-attentive auditory evoked potential, in older adults compared to younger adults (Alain et al., 2004; Bertoli et al., 2002). The MMN can be elicited in the absence of conscious attention to the stimuli (Naatanen et al., 1993) and indicates whether a rare stimulus occurring among more frequent stimuli has been detected. These results suggest that declines in auditory temporal processing are due to age-related changes in the pre-attentive processing of stimuli in the central auditory system.

To date, investigations of age-related changes in gap detection have focused primarily on behavioral measures and electrophysiologic measures at pre-attentive levels of auditory processing (ABR and MMN). Performance on behavioral tasks may be affected by response criteria, participant fatigue, attentional level, concentration, and motivation. Previous research in both the auditory and visual systems has shown a more pronounced effect of age with increased task difficulty when attention demands are high (Harris et al., 2009; Singh et al., 2008). Similar results are seen in gap detection measures, such that the most consistent and robust effects of age appear with increasing complexity of the task or stimuli (He et al., 1999; Lister et al., 2002; 2005; Pichora-Fuller, et al., 2006). In a complex task with unpredictable stimulus features (varying target location or stimulus markers), the focus of attention must be changed continually. In addition to these continuous changes in the spatial focus of attention, participants must maintain attention to the task over prolonged periods of time. The cost of these additional attention or cognitive components is often slower or more error prone performance (as reviewed in McDowd, 2007). Age-related deficits in various measures of attention and cognition, including information processing speed, divided attention skills, sustained attention, selective attention, and working memory, are well-established (e.g., APA Working Group on the Older Adult, 1998) and may explain the disproportionate problems experienced by older adults during challenging gap detection tasks.

In a recent large-scale study in older adults, Humes et al. (2009) measured visual, auditory, and tactile measures of gap detection and administered the full WAIS-III cognitive assessment. Gap detection was measured using silent gaps inserted in the middle of pure-tone stimuli, for which small but statistically significant effects of age were observed. Few associations were observed between measures of cognitive function and measures of gap detection. However, a modest correlation was observed between auditory and visual gap-detection performance and a subset of the WAIS-III representing general cognitive function. General cognitive performance was negatively correlated with gap detection thresholds. However, these correlations revealed only about 10% of shared variance for performance on these measures, leading the authors to conclude that age-related changes in auditory and visual gap detection and cognitive processing appear largely independent. When confronted with a more challenging task, rather than the simple stimuli used by Humes et al. (2009), additional attention-related or cognitive resources may need to be directed towards the task to maintain performance. Increased demands on cognitive and attentional resources may underlie age-related changes observed during challenging gap detection tasks and reveal associations between cognitive abilities and gap detection.

In the current study, the complexity of the gap detection task was increased in one condition by introducing trial-to-trial uncertainty of the gap location, in contrast to a fixed location. We hypothesized that gap detection thresholds for older adults would be similar to, or slightly higher than thresholds of younger adults during less challenging conditions, including when the location of the gap was fixed (fixed condition) and when the gap was located in the middle of the noise burst. Despite identical stimuli across fixed and random conditions, we predicted a larger effect of gap uncertainty (random condition) for older than younger adults, due to increased demands on cognitive and attentional resources.

A task is typically described as more “challenging” based on specific response criteria, such as increased thresholds or reaction times. However, the degree of difficulty of a task or the amount of workload exerted by a individual to achieve a particular level of performance is dependent on the interaction of several factors, including requirements of the task, task duration, and the skills, behaviors, and perceptions of the participant. Workload is often described as “the degree of processing capacity that is expended during task performance” and is thought to reflect a relationship between available resources and task demands (Haga, 2002; Hart, 1988). Thereby, subjective perception of workload increases with greater amounts

of attentional resources invested and with greater demands on working memory (Yeh and Wickens, 1988). If a person considers the workload of a task to be excessive, they may adopt strategies for a “high-workload” situation, such as ignoring parts of the task, experiencing psychological distress (fatigue, frustration), adopting a lower response criterion, or increasing error rate (Hart, 1988). Subjective ratings of workload were measured to assess the effects of task difficulty in a gap detection measure for younger and older adults. The National Aeronautics and Space Administration (NASA) Task Load Index (TLX) questionnaire (Hart, 1988), a multifaceted tool for evaluating subjective workload, is widely regarded as one of the strongest tools available for reporting perceptions of workload (Young et al., 2008). We predicted that subjective ratings of workload would be associated with gap detection thresholds during conditions when gap location was uncertain and, therefore, when demands on cognitive resources such as attention may be higher.

To examine whether the robust effects of age, observed during challenging tasks, are indeed a result of age-related changes in cognition, we examined the extent to which age-related changes in processing speed accounted for differences in gap detection. Processing speed is one of the strongest predictors of performance across cognitive tasks in older adults (Salthouse et al., 2003). Age-related changes in processing speed are well established (Verhaeghen et al., 1997). Processing speed was assessed in the current study with the Purdue Pegboard test (Tiffin et al., 1948) and the Connections Test (Salthouse, 2000). The Purdue Pegboard test assesses motor speed and dexterity. Scores from the Purdue Pegboard tasks are thought to reflect a complex functional result of different aspects of motor and cognitive speed (Spreen & Spraus, 1998; Streng et al., 2002). Furthermore, several authors have highlighted attentional function as a key factor in pegboard performance (Vingerhoets, et al., 1997; Willder-Willis, et al., 2001). The Connections Test (Salthouse, 2000), a variant of the Trail Making Test (Reitan et al., 1992), is a speeded test of attention, sequencing, mental flexibility, visual search, and motor function. The task changes from a direct speed and sequencing task (Simple) to include a set-shifting component (Complex). Therefore, in addition to perceptual and motor processing, the additional set-shifting component of Connections Complex is described as engaging working memory and/or inhibitory systems (Salthouse, 2000).

2. Materials and Methods

2.1 Participants

Participants included two groups of adults: younger [$n=10$; mean age=25.1 (2.42) years; 6 females] and older [$n=11$; mean age=69.82 (6.95) years; 8 females]. All participants were right-handed native speakers of American English and had not participated in previous listening experiments using the experimental stimuli. Each participant completed the Mini Mental State Examination (Folstein et al., 1983), a screening tool for assessing cognitive mental status, and had three or fewer errors, indicating little or no cognitive impairment (as reviewed in Tombaugh et al., 1992). Pure-tone thresholds at conventional frequencies were measured with a Madsen OB922 clinical audiometer, calibrated to appropriate ANSI standards (ANSI, 2004) and equipped with TDH-39 headphones. All participants had normal hearing (defined as thresholds ≤ 25 dB HL at 250, 500, 1000, 2000, 3000 and 4000 Hz) and differences in thresholds between right and left ears did not exceed 15 dB at each frequency. Mean pure-tone audiometric thresholds for the test ear (right ear) (± 1 S.E.M.) are shown in Figure 1. Individual differences in pure-tone thresholds at each frequency were used to assess associations between pure-tone thresholds, gap detection, workload, and processing speed measures. Participants provided written informed consent before participating in this MUSC Institutional Review Board approved study.

2.2 Gap Detection

2.2.1 Stimuli—Gap detection thresholds were measured under two conditions: (1) gap location fixed at 5%, 50% or 95% of the total noise burst duration for a block of trials and (2) gap location from trial to trial randomly chosen from the same three values: 5%, 50%, or 95% of the total duration. Stimuli were digitally created using custom LABVIEW software (LABVIEW 8.5, National Instruments) and converted to analog using a 16-bit digital-to-analog converter (National Instruments, model 6052E) with a sampling rate of 50 kHz. Stimuli were low-pass filtered (TDT PF1) at a cutoff frequency of 5 kHz, attenuated (TDT PA4), passed through a headphone buffer (TDT HB5), and presented monaurally to the right ear through a TDH-39 headphone. Stimuli were presented at 80 dB SPL. Stimuli were monitored electrically at the input to the earphones (oscilloscope) and acoustically calibrated with the earphone placed in a NBS-9A coupler using a Larson-Davis sound level meter. Noise burst duration was 500 ms. The internal rise/fall time of the gap was 0 ms. The noise on each side of the gap was constrained to start and end at zero amplitude to minimize spectral energy spread. The spectra of the noise with and without a gap were essentially identical, with little to no spectral energy spread into the gap. All gap locations were referenced to the center of the gap, such that a 10-ms gap at the center of the noise burst began at 245 ms and ended at 255 ms. The total duration of the noise burst was kept constant. Gap durations ranged from zero (no gap) to a maximum of either 12 or 20 ms, adjusted for each participant during practice (see later section).

Initially, the maximum gap was set to 12 ms, based on results from the literature (Green, 1985; He et al., 1999) and pilot data from younger and older participants. However, five older adults and two younger adults required longer gaps for some conditions; therefore, the range was extended to a maximum of 20 ms. Note that a gap of 20 ms was the upper limit to prevent the gap from falling close to the rise/fall portion of the noise burst when the gap occurred at the beginning or end of the noise burst.

2.2.2 Procedures—In both fixed and random conditions a single 500-ms noise burst was presented in each trial. Participants pressed a button labeled “yes” if they heard a gap and a button labeled “no” if they did not. In the fixed condition, gap detection was measured with the gap fixed at either 5% (beginning), 50% (middle), or 95% (end) of the total noise duration, for each block of trials. A constant-stimulus method was used and psychometric functions for gap detection were measured separately for each gap location. For each participant the range of the gap durations (0 to 12 ms or 0 to 20 ms) was evenly divided into eleven intervals (e.g., 0 ms, 2 ms, 4 ms, 6 ms, 8 ms, 10 ms, 12 ms, 14 ms, 16 ms, 18 ms, 20 ms). Within each block of trials, each gap duration was presented five times in random order, but at a particular location (55 trials). The measured psychometric functions were recast by a logistic function (Green, 1993). Threshold was calculated as the gap duration corresponding to the 50% point (Yes response) of the psychometric function. Details of this procedure have been reported previously (He et al., 1999). Prior to actual data collection, participants completed several practice sessions. During these practice sessions, psychometric functions were repeatedly measured as already described. Practice ended when ogive-shaped psychometric functions with reasonably steep slopes were obtained. Practice sessions were not designed to improve performance, but instead were used to orient participants to the stimuli and psychophysical procedure.

In the random condition, gap detection thresholds were measured with the location of the gap varying from trial to trial from the beginning, middle, and end of the noise burst within each block of trials. Gap detection thresholds were measured using a maximum likelihood single-interval, yes/no procedure, similar to that described by Green for measuring detection of pure tones (1993) and by Florentine et al. (2000 Florentine et al. (2001) for measuring detection of temporal gaps. The maximum likelihood method is an adaptive psychophysical procedure whereby gap duration is determined using the optimal candidate psychometric function

available based on previous responses. These functions were determined using a logistic function (Green, 1993) and characteristics of these functions, including slope, were extracted from previous gap detection tasks using similar stimuli (He et al., 1999). The “sweet point”, or m (Green, 1993), was calculated based on the estimated midpoint of the psychometric function and the false alarm rate, α , after 24 trials, including eight randomly inserted catch trials. In five of the catch trials, the minimum gap duration (0 ms) was presented. In the remaining three catch trials, the maximum gap duration was presented (either 12 or 20 ms, depending on the participant). Three adaptive tracks, with the gap centered at the beginning, middle, or end of the noise, were interleaved resulting in 72 trials per block. This procedure was performed four times for each participant, resulting in 96 trials per gap location; m was calculated as the geometric mean across the four trial blocks for each gap location and was used to generate psychometric functions using the same logistic function as in the fixed condition (Green, 1993). Threshold was calculated as the gap duration corresponding to the 50% point on the psychometric function.

The 50% point (instead of m values) was used as threshold to facilitate comparisons between the new data and previously reported results that used different methods, such as a two- or three-interval, forced choice (e.g., Snell et al., 1997 e.g., Snell et al., 1999).

2.3 Workload

Participant workload was assessed using a modified version of the NASA TLX self-report questionnaire (<http://humansystems.arc.nasa.gov/groups/TLX/>). Individual scores using a 20-point visual analog scale are generated for six subscales, including mental demands, physical demands, temporal demands, own performance, effort, and frustration. Participants are asked to rate the mental, physical, and temporal demands of the task, their level of frustration, performance, and level of effort exerted to complete the task. The modified NASA TLX consists of nine questions. Questions include: “How hurried or rushed was the task?” (assessing temporal demand) and “How hard did you have to work to accomplish your level of performance?” (assessing effort). The performance subscale consists of three questions and was developed to measure the degree of success or satisfaction felt upon completion of the task. The NASA TLX was administered immediately following the measurement of gap detection.

2.4 Processing Speed

Processing speed was assessed using the Purdue Pegboard (Tiffin et al., 1948) and Connections Test (Salthouse, 2000). For the Purdue Pegboard test, participants completed three time trials, during which they placed as many pegs in the board as possible within 30 s using their right hand, then left hand, then both hands. Participants also completed an assembly task, in which they used both hands, alternately, to construct as many “assemblies,” consisting of a pin, a washer, a collar, and another washer, as possible in 60 s. Performance was averaged across the three time trials for each condition to provide single estimates of processing speed for the right hand (dominant), left hand, both hands, and assembly.

The Connections test consists of two parts, Connections Simple and Connections Complex. The Connections Simple portion of the test requires participants to connect as many circled letters or numbers, in alphabetic and numeric sequence, as possible in 20 s. The letters and/or numbers are pseudorandomly organized in a 7×7 array of circles on a sheet of paper, with the next target located at one of the adjacent locations. Participants completed 2 trials of the letter form and 2 trials of the number form. Performance was averaged across trials to provide the Connections Simple score. Connections Complex requires participants to alternate between drawing a line between a number and a letter (i.e., 1 to A to 2 to B). Participants completed 2

trials starting with a number and 2 trials starting with a letter. Performance was averaged across trials to provide the Connections Complex score.

2.5 Data Analyses

Differences between participant groups, gap location (beginning, middle, end), and gap location uncertainty (fixed, random) were assessed using t-tests and repeated measures analyses of variance (ANOVA); p values of <0.05 were considered statistically significant. Associations among variables were assessed using Pearson correlation analyses and multivariate analysis of covariance (MANCOVA) to determine whether gap detection thresholds were significantly predicted by measures of processing speed and/or workload. Identical results were obtained using ranked data and non-parametric analyses (non-parametric t-tests, and Spearman's correlation analyses).

3. Results

3.1 Effects of gap location, uncertainty, and age

Mean gap detection thresholds and thresholds for individual younger and older adults for the fixed conditions are shown in Figure 2A. In general, gap detection thresholds were higher when the gap was near the beginning or end of the noise than when the gap was in the middle. For the younger adults, gap detection thresholds averaged 5.74 ms for the beginning location, 4.48 ms for the middle location, and 5.47 ms for the end location. For the older adults, gap detection thresholds averaged 8.80 ms, 5.16 ms, and 7.60 ms for the beginning, middle, and end locations, respectively. Gap detection threshold for one older adult exceeded 20 ms when the gap was at the beginning and end of the noise and was assigned the maximum value of 20 ms. Mean gap detection thresholds and thresholds for individual participants for the random conditions are shown in Figure 2B. Similar to results for the fixed conditions, gap detection thresholds were highest when the gap was located near the beginning and end of the noise than when the gap was in the middle; thresholds were also higher for older than younger adults in most conditions. Gap detection thresholds for younger adults averaged 7.24 ms, 4.68 ms, and 5.80 ms for the beginning, middle, and end gap locations, respectively. Gap detection thresholds for older adults averaged 12.17 ms for the beginning location, 5.47 ms for the middle location, and 10.65 ms for the end location. Mean gap detection thresholds for the fixed and random conditions for younger and older adults are shown in Figure 2C. Gap detection thresholds were higher for the random than the fixed condition.

A repeated measures ANOVA, with gap location (beginning, middle, end) and location uncertainty (fixed, random) as repeated measures and age as a grouping factor, revealed a significant three-way interaction of location, uncertainty, and age [$F(2,19)=29.90$, $p=.033$]. Significant main effects of location [$F(2,19)=7.71$, $p=.002$], uncertainty [$F(2,19)=9.00$, $p=.007$], and age [$F(1,19)=7.69$, $p=.012$], and a significant interaction of location and uncertainty [$F(2,19)=13.78$, $p<.001$], were also present.

Paired t-tests indicated that gap detection thresholds were significantly higher when the gap was at the beginning [$t(1,20)=3.51$, $p=.002$] and at the end [$t(1,20)=2.40$, $p=.026$] than in the middle location. For the fixed condition, post-hoc independent samples t-tests indicated that significant age group differences were observed only when the gap was in the beginning location [$t(1,20)=-2.21$, $p=.041$], where thresholds were highest in both younger and older participants (Figure 2A). For the random condition, post-hoc independent t-tests indicated that gap detection thresholds were significantly higher in older adults than younger adults when the gap was at the beginning [$t(1,20)=-2.5$, $p=.024$] and end [$t(1,20)=-2.35$, $p=.030$] locations.

To assess the interaction of age, gap location, and uncertainty, post-hoc paired t-tests were performed to compare gap detection thresholds for fixed and random conditions at each gap location. Results indicated that gap detection thresholds for older adults were affected by both gap location and uncertainty, such that gap detection thresholds for the random condition were significantly higher than for the fixed condition when the gap was located at the beginning [$t(1,10)=2.35$, $p=.041$] and end [$t(1,10)=2.24$, $p=.049$] locations but not the middle ($p>.05$). In contrast, gap detection thresholds for younger adults were not significantly different for the random and fixed condition at any location ($p>.05$) (Figure 2C). These results indicated that gap location uncertainty negatively affected the performance of older adults, but not younger adults.

These group differences were not associated with hearing levels, as individual variation in pure-tone thresholds (250 Hz to 8000 Hz) did not predict gap detection thresholds for any condition in younger or older adults ($r(20)=.08$ to $.31$, ns).

3.2 Effects of age on workload

As noted previously, individual scores were generated for six subscales of the NASA TLX, including mental demands, physical demands, temporal demands, own performance, effort, and frustration. Means and standard deviations for each of the six subscales are provided in Table 1. Analysis of the ratings on the individual NASA TLX dimensions revealed a significant age-related increase in mental demand for gap detection tasks [$t(1,18)=-3.92$, $p=.001$]. These results suggest that older adults found the tasks more mentally demanding than younger adults. Although there was a trend for older participants to report increased effort as compared to younger adults ($p=.052$), subjective ratings of performance, frustration, and physical and temporal demands did not show significant effects of age ($p>.05$). Individual differences in pure-tone thresholds were not predictive of workload ($r(19)=-.401$ to $.200$, ns).

3.3 Effects of age on processing speed

There was a significant age-related slowing of processing speed as measured by the Purdue Pegboard and Connections assessments (Table 1). Several measures of processing speed were assessed, including four measures from the Purdue Pegboard (right hand, left hand, both hands, assembly), and Simple and Complex Connections. Mean scores and standard deviations for younger ($n=10$) and older participants ($n=10$) are provided in Table 1. One older adult did not complete Connections and Pegboard testing. Measures of processing speed across Connections and the Purdue Pegboard were strongly correlated, with Pearson r values ranging from $.74$ to $.86$, $p<.001$. Individual differences in pure-tone thresholds were not predictive of processing speed ($r(19)=-.37$ to $.07$, ns).

3.4 Associations between gap detection and workload

We examined the extent to which gap detection thresholds and subjective assessment of workload were associated. When gap location was fixed, only gap detection at the beginning location and the participants rating of mental demand were significantly correlated (Pearson $r=.47$, $p=.04$). When gap location was randomized, gap detection thresholds for the beginning and end location were significantly associated with mental demand (Pearson $r=.60$, $p=.006$ and Pearson $r=.50$, $p=.025$, respectively) and effort (Pearson $r=.51$, $p=.022$ and Pearson $r=.50$, $p=.047$) and negatively associated with a participant's self evaluation of performance (Pearson $r=-.53$, $p=.01$ and Pearson $r=-.48$, $p=.032$). These results indicated that participants with poorer gap detection thresholds during more challenging conditions tended to judge the task as more mentally demanding and effortful and also reported poorer performance on the task, consistent with increased workload.

3.5 Associations between gap detection and processing speed

Gap detection thresholds in the fixed conditions were not significantly correlated with measures of processing speed ($p > .05$). In contrast, gap detection thresholds in the random conditions were significantly negatively correlated with processing speed (Figure 3, Table 2), such that slower processing speed was associated with higher gap detection thresholds. Pearson correlation coefficients were highest for the random conditions when the gap was located in the beginning of the noise, followed by the end location. As shown in Figure 3, the association with processing speed was due to normal variation across the sample, rather than clusters of results for younger and older adults.

A MANCOVA was performed to determine whether gap detection thresholds in the fixed condition and processing speed measures independently predict gap detection in the more challenging random conditions. To limit the redundancy across measures of processing speed and to maintain an acceptable number of predictor variables for the current sample size, a single measure of processing speed, pegboard assembly, was included as a covariate in the model. Similar results were observed when additional measures of Connections and Pegboard were substituted. Gap detection thresholds for the random condition, beginning or end, was the dependent variable; age was the grouping factor; and pegboard assembly and the gap detection threshold for that location in the fixed condition were entered as covariates. A summary of the MANCOVA results are shown in Table 3. Gap detection for the fixed condition and processing speed accounted for a unique portion of the variance of gap detection in the random condition. Gap detection in the fixed condition and the processing speed variables explained 68% (beginning location) and 64.3% (end location) of the variability of the data, a significant improvement over either variable alone. In addition, as shown in Table 3, age was no longer a significant predictor of gap detection in the random condition after controlling for processing speed and gap detection thresholds in the fixed condition.

4. Discussion

Many studies of gap detection, using different stimuli and psychophysical procedures, report larger age-related differences for complex than more simple listening tasks. However, the factors that contribute to these differences remain unknown. We hypothesized that age-related changes in attention and cognition compound age-related changes in auditory temporal processing, contributing to the robust age effects observed during challenging listening conditions. Consistent with this hypothesis, older adults performed similarly to younger adults during less challenging conditions, such as when the gap was located in the middle of the noise burst, but had significantly higher gap detection thresholds during more challenging conditions, such as when gap location was varied randomly. Importantly, measures of processing speed accounted for a significant amount of the variance in performance during challenging listening conditions and subjective workload ratings indicated that older adults found the task more mentally demanding than younger adults. Taken together, these results suggest that age-related changes in processing speed and attention contribute to poorer gap detection by older adults during challenging listening conditions.

Few studies have examined the effect of gap location and gap location uncertainty on gap detection thresholds. In the current study, gap detection thresholds were lower when the gap was located in the middle of the noise, as compared to the beginning or end of the noise. Although Forrest and Green (1987) found little to no effect of gap location on thresholds, several studies have reported a significant effect of gap location on thresholds (He et al., 1999; Penner, 1977; Snell, 1997). In younger adults, the effect of uncertainty of gap location was previously reported to significantly increase gap detection thresholds (Green et al., 1989). However, similar to the results reported by He et al. (1999), in the current study gap detection thresholds were affected by location uncertainty in older but not younger adults, such

that in older adults thresholds were larger in the random than the fixed conditions when the gap was located at the beginning and end of the noise. In general, the effects of age observed in the current study are consistent with the aging literature. Gap detection thresholds for older adults were similar to those of younger adults when the gap was located in the middle of the noise. As task complexity was increased by moving the gap near the onset or offset of the signal and by adding location uncertainty, more robust age-related differences were observed (He et al., 1999; Lister et al., 2005; Pichora-Fuller et al., 2006b).

In comparison to the fixed conditions, the random conditions increased the complexity of the task by adding gap location uncertainty. Changes in the predictability of target location were hypothesized to place increased demands on cognitive and attentional resources. Consistent with this premise, gap detection thresholds during the random condition were associated with increased workload, particularly for subjective ratings of mental demand, effort, and the participant's self evaluation of performance. Furthermore, older adults reported a significant increase in mental demand as compared to younger adults, consistent with a higher demand on attentional resources to perform the task. In conjunction with higher demands on cognitive processing and attention, older adults demonstrated age-related differences in processing speed. The age-related differences observed in the current study were consistent with previous work demonstrating age-related changes in processing speed (Salthouse, 2000). In the current study, processing speed measures were predictive of gap detection thresholds only when gap location was uncertain. In contrast, Humes et al. (2009) reported that performance on cognitive tasks was not predictive of performance on sensory tasks, including gap detection. This discrepancy may be related to the stimuli and methods employed. In the Humes et al. study (2009), gap location was fixed in the middle of a pure tone, similar to the fixed condition in the current study where processing speed was not associated with gap detection thresholds. In relatively challenging conditions, the effects of age may be driven both by changes in auditory processing and slowed processing speed, which in turn leads to increased mental demands on older participants and poorer performance.

Neurobiological explanations for age-related differences in gap detection have focused largely on the central auditory system. Age-related changes in the structure and function of the central auditory system are well documented (e.g., (Boettcher et al., 1996; Caspary et al., 1995; Harris et al., 2009; Walton et al., 2002; Walton et al., 1997). He et al. (1999) hypothesized that the age effects observed when the gap was located near the beginning and end of the noise were the result of changes in the central auditory system, including changes in eighth nerve adaptation, synchrony, or adaptation to the onset and offset encoding neurons in the ascending auditory pathway. Similar explanations involving the central auditory system have been suggested to explain the robust effects of age when the spectral complexity of the markers surrounding the gap are varied (Lister et al., 2005). Consistent with this premise, higher gap detection thresholds and degraded auditory evoked potentials have been observed in older adults (Alain et al., 2004; Bertoli et al., 2002).

While changes in the central auditory system may account for some of the location effects on gap detection thresholds, they do not explain the additional effect of uncertainty observed in the current study. Alain et al. (2004) assessed the effects of attention on gap detection using an electrophysiologic paradigm. During passive listening, large age effects were observed, such that larger gap durations were needed to evoke a response in older than younger adults. In contrast, when attention was directed to the task, differences between younger and older adults were minimal. These results suggest that older adults may compensate for declines in the central auditory system by increasing attention to the task to perform the task as well as younger adults. The effects of increasing task difficulty and age on a variety of auditory processing tasks have been reported previously (as reviewed in Pichora-Fuller, 2006a). Consistent with these results, using functional neuroimaging, Eckert et al. (2008) observed an

age-related increase in the recruitment of cognitive control systems to maintain normal performance on a listening task. However, as complexity of the task is increased, greater demands are placed on cognitive resources to compensate for changes in auditory processing. With increased task difficulty, cognitive control systems may not be able to compensate for changes in the central auditory system, resulting in declining performance (Harris et al., 2009).

It is still unclear, however, if age-related differences in gap detection during challenging conditions stem from declines in cognitive control systems associated with preserved auditory temporal processing (Alain et al., 2004) and/or exaggerated declines in auditory cortex that limit gap detection. This is not to say that these attention-driven or high-order cognitive effects occur independently of sensory processing. In fact, several studies have shown support for modality and task-specific attentional processing and that brain processes supporting attention can occur even at very early sensory levels (Gazzaley et al., 2005; Gazzaley et al., 2008; Mesulam, 2000; Roland, 1982). Neuroimaging and electrophysiologic studies with larger sample sizes are needed to determine the extent to which changes in the functional and structural integrity of auditory and attention-related systems account for age-related differences in gap detection. The association between gap detection, processing speed, and mental demand observed in the current study suggests that age-related differences in gap detection during challenging conditions may be related to changes in both auditory and cognitive processing.

4.1 Conclusions

The results of this study are consistent with previous studies of gap detection in that age-related differences in gap detection were greatest during challenging listening conditions and occurred independently of hearing loss. Both gap location and uncertainty of the gap location, factors relevant to speech understanding, contributed significantly to gap detection thresholds of older participants. The primary factor believed to contribute to age-related differences in gap detection is changes in the central auditory system. However, results from the current study suggest that age-related differences in cognitive processing, including processing speed, contribute to an age-related decrease in gap detection. The associations between workload and processing speed and gap detection during random but not fixed conditions suggest that these associations are a result of increased task difficulty and may not be specific to gap detection. In fact, several authors have reported similar associations between cognitive processing and speech recognition in effortful listening conditions (as reviewed in Pichora-Fuller et al. 2006a). Knowledge of auditory and cognitive factors contributing to declines in auditory temporal processing may be important for understanding communication difficulties of older adults.

Acknowledgments

We thank the participants of this study and Ning-Ji He for her assistance with stimulus generation. This work was supported (in part) by grants from the NIDCD (P50 DC00422 and K23 DC008787). This investigation was conducted in a facility constructed with support from Research Facilities Improvement Program Grant Number C06 RR14516 from the National Center for Research Resources, National Institutes of Health.

References

- Abel SM, Krever EM, Alberti PW. Auditory detection, discrimination and speech processing in ageing, noise-sensitive and hearing-impaired listeners. *Scand Audiol* 1990;19:43–54. [PubMed: 2336540]
- Alain C, McDonald KL, Ostroff JM, Schneider B. Aging: a switch from automatic to controlled processing of sounds? *Psychol Aging* 2004;19:125–33. [PubMed: 15065936]
- American Psychological Association working group on the older adult. What practitioners should know about working with older adults. *Professional Psychology: Research and Practice* 1998;29(5):413–427.

- American National Standards Institute. American National Standard Specifications for Audiometers (ANSI S3-2004). American National Standards Institute; New York: 2004.
- Bertoli S, Smurzynski J, Probst R. Temporal resolution in young and elderly subjects as measured by mismatch negativity and a psychoacoustic gap detection task. *Clin Neurophysiol* 2002;113:396–406. [PubMed: 11897540]
- Boettcher FA, Mills JH, Swerdloff JL, Holley BL. Auditory evoked potentials in aged gerbils: responses elicited by noises separated by a silent gap. *Hear Res* 1996;102:167–78. [PubMed: 8951460]
- Caspary DM, Milbrandt JC, Helfert RH. Central auditory aging: GABA changes in the inferior colliculus. *Exp Gerontol* 1995;30:349–60. [PubMed: 7556513]
- Dubno JR, Ahlstrom JB. Psychophysical suppression effects for tonal and speech signals. *J Acoust Soc Am* 2001;110:2108–19. [PubMed: 11681388]
- Dubno JR, Horwitz AR, Ahlstrom JB. Recovery from prior stimulation: masking of speech by interrupted noise for younger and older adults with normal hearing. *J Acoust Soc Am* 2003;113:2084–94. [PubMed: 12703719]
- Dubno JR, Lee FS, Matthews LJ, Mills JH. Age-related and gender-related changes in monaural speech recognition. *J Speech Lang Hear Res* 1997;40:444–52. [PubMed: 9130212]
- Duquesnoy AJ. Effect of a single interfering noise or speech source upon the binaural sentence intelligibility of aged persons. *J Acoust Soc Am* 1983;74:739–43. [PubMed: 6630729]
- Fitzgibbons PJ, Gordon-Salant S. Age effects on measures of auditory duration discrimination. *J Speech Hear Res* 1994;37:662–70. [PubMed: 8084196]
- Folstein MF, Robins LN, Helzer JE. The Mini-Mental State Examination. *Arch Gen Psychiatry* 1983;40:812. [PubMed: 6860082]
- Gazzaley A, Cooney JW, Rissman J, D'Esposito M. Top-down suppression deficit underlies working memory impairment in normal aging. *Nat Neurosci* 2005;8:1298–300. [PubMed: 16158065]
- Gazzaley A, Clapp W, Kelley J, McEvoy K, Knight RT, D'Esposito M. Age-related top-down suppression deficit in the early stages of cortical visual memory processing. *Proc Natl Acad Sci U S A* 2008;105:13122–6. [PubMed: 18765818]
- Gordon-Salant S, Fitzgibbons PJ. Temporal factors and speech recognition performance in young and elderly listeners. *J Speech Hear Res* 1993;36:1276–85. [PubMed: 8114494]
- Green DM. A maximum-likelihood method for estimating thresholds in a yes-no task. *J Acoust Soc Am* 1993;93:2096–105. [PubMed: 8473622]
- Green DM, Forrest TG. Temporal gaps in noise and sinusoids. *J Acoust Soc Am* 1989;86:961–70. [PubMed: 2794249]
- Groose JH, Hall JW 3rd, Buss E. Gap duration discrimination in listeners with cochlear hearing loss: effects of gap and marker duration, frequency separation, and mode of presentation. *J Assoc Res Otolaryngol* 2001;2:388–98. [PubMed: 11833611]
- Haga S, Shinoda H, Kokubun M. Effects of task difficulty and time-on-task on mental workload. *Japanese Psychological Research* 2002;44:134–143.
- Harris KC, Mills JH, Dubno JR. Electrophysiologic correlates of intensity discrimination in cortical evoked potentials of younger and older adults. *Hear Res* 2007;228:58–68. [PubMed: 17344001]
- Harris KC, Mills JH, He NJ, Dubno JR. Age-related differences in sensitivity to small changes in frequency assessed with cortical evoked potentials. *Hear Res* 2008;243:47–56. [PubMed: 18597958]
- Harris KC, Dubno JR, Keren NI, Ahlstrom JB, Eckert MA. Speech recognition in younger and older adults: a dependency on low-level auditory cortex. *J Neurosci* 2009;29:6078–87. [PubMed: 19439585]
- Hart, SG.; Staveland, LE. Development of NASA-TLX: results of empirical and theoretical research. In: Hancock; Meshkati, editors. *Human Mental Workload*. Elsevier and North-Holland; Amsterdam: 1988.
- He N, Dubno JR, Mills JH. Frequency and intensity discrimination measured in a maximum-likelihood procedure from young and aged normal-hearing subjects. *J Acoust Soc Am* 1998;103:553–65. [PubMed: 9440340]
- He NJ, Horwitz AR, Dubno JR, Mills JH. Psychometric functions for gap detection in noise measured from young and aged subjects. *J Acoust Soc Am* 1999;106:966–78. [PubMed: 10462802]

- Humes LE. Do 'auditory processing' tests measure auditory processing in the elderly? *Ear Hear* 2005;26:109–19. [PubMed: 15809539]
- Humes LE, Christopherson L. Speech identification difficulties of hearing-impaired elderly persons: the contributions of auditory processing deficits. *J Speech Hear Res* 1991;34:686–93. [PubMed: 2072694]
- Humes LE, Busey TA, Craig JC, Kewley-Port D. The effects of age on sensory thresholds and temporal gap detection in hearing, vision, and touch. *Atten Percept Psychophys* 2009;71:860–71. [PubMed: 19429964]
- Lister J, Tarver K. Effect of age on silent gap discrimination in synthetic speech stimuli. *J Speech Lang Hear Res* 2004;47:257–68. [PubMed: 15157128]
- Lister J, Besing J, Koehnke J. Effects of age and frequency disparity on gap discrimination. *J Acoust Soc Am* 2002;111:2793–800. [PubMed: 12083214]
- Lister JJ, Roberts RA. Effects of age and hearing loss on gap detection and the precedence effect: narrow-band stimuli. *J Speech Lang Hear Res* 2005;48:482–93. [PubMed: 15989406]
- Lister JJ, Koehnke JD, Besing JM. Binaural gap duration discrimination in listeners with impaired hearing and normal hearing. *Ear Hear* 2000;21:141–50. [PubMed: 10777021]
- McDowd JM. An overview of attention: behavior and brain. *J Neurol Phys Ther* 2007;31:98–103. [PubMed: 18025955]
- Mesulam M. Brain, mind, and the evolution of connectivity. *Brain Cogn* 2000;42:4–6. [PubMed: 10739582]
- Moore BC, Peters RW, Glasberg BR. Detection of temporal gaps in sinusoids by elderly subjects with and without hearing loss. *J Acoust Soc Am* 1992;92:1923–32. [PubMed: 1401537]
- Naatanen R, Paavilainen P, Tiitinen H, Jiang D, Alho K. Attention and mismatch negativity. *Psychophysiology* 1993;30:436–50. [PubMed: 8416070]
- Penner MJ. Detection of temporal gaps in noise as a measure of the decay of auditory sensation. *J Acoust Soc Am* 1977;61:552–7. [PubMed: 845317]
- Phillips SL, Gordon-Salant S, Fitzgibbons PJ, Yeni-Komshian GH. Auditory duration discrimination in young and elderly listeners with normal hearing. *J Am Acad Audiol* 1994;5:210–5. [PubMed: 8075417]
- Pichora-Fuller MK, Singh G. Effects of age on auditory and cognitive processing: implications for hearing aid fitting and audiology rehabilitation. *Trends Amplif* 2006a;10:29–59. [PubMed: 16528429]
- Pichora-Fuller MK, Schneider BA, Benson NJ, Hamstra SJ, Storzer E. Effect of age on detection of gaps in speech and nonspeech markers varying in duration and spectral symmetry. *J Acoust Soc Am* 2006b; 119:1143–55. [PubMed: 16521775]
- Reitan RM, Wolfson D. Conventional intelligence measurements and neuropsychological concepts of adaptive abilities. *J Clin Psychol* 1992;48:521–9. [PubMed: 1517447]
- Roberts RA, Lister JJ. Effects of age and hearing loss on gap detection and the precedence effect: broadband stimuli. *J Speech Lang Hear Res* 2004;47:965–78. [PubMed: 15603455]
- Roland PE. Cortical regulation of selective attention in man. A regional cerebral blood flow study. *J Neurophysiol* 1982;48:1059–78. [PubMed: 7175557]
- Salthouse TA, Ferrer-Caja E. What needs to be explained to account for age-related effects on multiple cognitive variables? *Psychol Aging* 2003;18:91–110. [PubMed: 12641315]
- Schneider B, Speranza F, Pichora-Fuller MK. Age-related changes in temporal resolution: envelope and intensity effects. *Can J Exp Psychol* 1998;52:184–91. [PubMed: 10095852]
- Schneider BA, Hamstra SJ. Gap detection thresholds as a function of tonal duration for younger and older listeners. *J Acoust Soc Am* 1999;106:371–80. [PubMed: 10420628]
- Schneider BA, Pichora-Fuller MK, Kowalchuk D, Lamb M. Gap detection and the precedence effect in young and old adults. *J Acoust Soc Am* 1994;95:980–91. [PubMed: 8132912]
- Singh G, Pichora-Fuller MK, Schneider BA. The effect of age on auditory spatial attention in conditions of real and simulated spatial separation. *J Acoust Soc Am* 2008;124:1294–305. [PubMed: 18681615]
- Snell KB. Age-related changes in temporal gap detection. *J Acoust Soc Am* 1997;101:2214–20. [PubMed: 9104023]

- Strouse A, Ashmead DH, Ohde RN, Grantham DW. Temporal processing in the aging auditory system. *J Acoust Soc Am* 1998;104:2385–99. [PubMed: 10491702]
- Tiffin J, Asher EJ. The Purdue pegboard; norms and studies of reliability and validity. *J Appl Psychol* 1948;32:234–47. [PubMed: 18867059]
- Tombaugh TN, McIntyre NJ. The mini-mental state examination: a comprehensive review. *J Am Geriatr Soc* 1992;40:922–35. [PubMed: 1512391]
- Trainor LJ, Trehub SE. Aging and auditory temporal sequencing: ordering the elements of repeating tone patterns. *Percept Psychophys* 1989;45:417–26. [PubMed: 2726404]
- Verhaeghen P, Salthouse TA. Meta-analyses of age-cognition relations in adulthood: estimates of linear and nonlinear age effects and structural models. *Psychol Bull* 1997;122:231–49. [PubMed: 9354147]
- Walton JP, Simon H, Frisina RD. Age-related alterations in the neural coding of envelope periodicities. *J Neurophysiol* 2002;88:565–78. [PubMed: 12163510]
- Walton JP, Frisina RD, Ison JR, O'Neill WE. Neural correlates of behavioral gap detection in the inferior colliculus of the young CBA mouse. *J Comp Physiol [A]* 1997;181:161–76.
- Young G, Zavelina L, Hooper V. Assessment of workload using NASA Task Load Index in perianesthesia nursing. *J Perianesth Nurs* 2008;23:102–10. [PubMed: 18362006]

Figure 1. Mean pure-tone thresholds (dB HL) (± 1 SEM) for the right ears (test ears) of younger participants (filled) and older participants (open) plotted as a function of audiometric frequency (Hz).

Figure 2.

Effects of gap location and gap location uncertainty on gap detection thresholds. **A.** Individual and mean gap detection thresholds when gap location was fixed for younger adults (filled) and older adults (open). Mean gap detection thresholds were significantly larger in older than younger adults when the gap was located in the beginning of the noise. **B.** Individual and mean gap detection thresholds when gap location was varied from trial to trial for younger adults (filled) and older adults (open). Gap detection thresholds were significantly larger in older than younger adults when the gap was located in the beginning or end of the noise. **C.** Mean gap detection thresholds for younger adults (filled) and older adults (open) for the fixed conditions

(circles) and random conditions (triangles). Significant differences in gap detection for fixed and random conditions were observed for older but not younger adults.

Figure 3.

Individual variation in processing speed (Purdue pegboard assembly) predicts gap detection thresholds for the random condition only ($r = -.68$, $p = .001$).

Table 1

Processing Speed and Workload

Test Type	Older Participants		Younger Participants	
	Mean	SD	Mean	SD
Connections	Simple *	22.05	7.08	34.97
	Complex ***	13.30	3.26	22.61
Pegboard	Right Hand *	12.74	2.22	15.90
	Left Hand *	11.90	2.74	14.43
	Both Hands **	10.15	2.58	12.67
	Assembly ***	29.38	6.55	42.10
NASA TLX	Mental Demand ***	16.40	1.58	10.30
	Physical Demand	7.00	4.50	5.00
	Temporal Demand	7.50	5.28	8.40
	Performance	43.20	8.60	45.60
	Effort	16.00	2.31	12.70
	Frustration	5.30	4.08	6.60

* p<0.05;
** p<0.01;
*** p<0.001

Mean and standard deviations for processing speed (number of items), Purdue Pegboard (number of assemblies or units) and NASA TLX (subjective ratings) for younger and older adults. Note that the Performance score consists of three questions.

Table 2
Individual variation in processing speed predicts gap detection when gap location was random but not when location was fixed

Variable	Pearson Correlation (<i>r</i>)					
	Connections			Pegboard		
	Simple	Complex		Right	Left	Both
Fixed Conditions						
Beginning	-0.42	-0.38		-0.36	-0.20	-0.24
Middle	-0.16	-0.30		-0.26	-0.15	-0.01
End	-0.33	-0.29		-0.38	-0.28	-0.22
Random Conditions						
Beginning	-0.65**	-0.53*		-0.67**	-0.67**	-0.64**
Middle	-0.32	-0.42		-0.50*	-0.44	-0.18
End	-0.42	-0.37		-0.50*	-0.55*	-0.37

* $p < 0.05$;
** $p < 0.01$

Table 3

Processing speed and gap detection thresholds for the fixed conditions predict age-related differences in gap detection for random conditions.

Model	F	Significance	Partial Eta Squared
Random-Beginning			
Corrected Model	12.03	0.000	0.69
Intercept	12.28	0.003	0.43
Fixed-Beginning	11.82	0.003	0.43
Pegboard-Assembly	8.69	0.009	0.35
Age	0.64	0.434	0.04
Random-End			
Corrected Model	9.63	0.001	0.64
Intercept	3.19	0.093	0.17
Fixed-End	12.55	0.003	0.44
Pegboard-Assembly	2.42	0.034	0.13
Age	0.01	0.940	0.00

Note: Effects of age are no longer significant after controlling for the variance from gap detection in the fixed condition and processing speed.