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Dissociations in Perceptual Learning Revealed by Adult Age Differences in Adaptation to Time-Compressed Speech

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When presented with several time-compressed sentences, young adults' performance improves with practice. Such adaptation has not been studied in older adults. To study age-related changes in perceptual learning, the authors tested young and older adults' ability to adapt to degraded speech. First, the authors showed that older adults, when equated for starting accuracy with young adults, adapted at a rate and magnitude comparable to young adults. However, unlike young adults, older adults failed to transfer this learning to a different speech rate and did not show additional benefit when practice exceeded 20 sentences. Listeners did not adapt to speech degraded by noise, indicating that adaptation to time-compressed speech was not attributable to task familiarity. Finally, both young and older adults adapted to spectrally shifted noise-vocoded speech. The authors conclude that initial perceptual learning is comparable in young and older adults but maintenance and transfer of this learning decline with age.

Keywords: speech comprehension, perceptual learning, aging, time-compressed speech, frequency-shifted speech

One of the hallmarks of human speech perception is our ability to recognize words produced by different speakers, even though the acoustic representation of any given word differs from person to person. For example, across different speakers, formant frequencies corresponding to a single vowel category vary extensively (Peterson & Barney, 1952), and even words produced by the same speaker can vary in duration depending on previous contextual information (Shields & Balota, 1991). When listening to everyday conversations, we are largely unaware of these variations. However, when processing speech that is more removed from that to which we are accustomed—be it a significantly different speech rate, intonation, or accent—we can become acutely conscious of the difficulties presented. Even so, under these conditions we may notice that, over time, we are able to understand a speaker who was unintelligible at the beginning of a conversation or lecture. This gradual adjustment highlights the flexibility of our perceptual processing and the remarkable ability of the auditory system to normalize across a wide range of speech parameters.

One characteristic of speech that fluctuates widely is the rate at which it is produced. This is true even within a single conversation, in which speakers frequently alter their speaking rate by significant amounts (Miller, Grosjean, & Lomanto, 1984). These variations can, in turn, affect the perceptual criteria applied by listeners. Miller and Liberman (1979), for example, investigated the stop-semivowel distinction of /ba/ and /wa/ and found that deleting the last 216 ms of a vowel caused the /b/–/w/ category boundary to shift toward a shorter duration. They concluded that listeners use the overall duration of syllables to interpret transition duration. Effects of speech rate are also readily apparent with more complex linguistic stimuli: Regardless of age, listeners find rapid speech more difficult to comprehend and remember, with this difficulty amplified for syntactically complex sentences (Gordon-Salant & Fitzgibbons, 1993; Wingfield, Peelle, & Grossman, 2003). The variability of speech rate in everyday conversation, as well as the potential perceptual difficulties caused by this variability, implies that the ability of listeners to adjust to changes in speech rate is critical for successful comprehension of spoken language.

In the experiments presented here, we used a computer program to artificially compress speech to very rapid rates to study perceptual adaptation. The time compression method we used is a variation of the sampling method, in which small portions are deleted at regular intervals from both voiced and silent portions of the speech signal. The remaining portions of the signal are then abutted in time, which results in a signal that is shorter in duration than the original but that retains the same pitch and relative temporal patterning (Foulke, 1971). This technique has several advantages over studying perceptual adaptation with unaltered stimuli. First, when speech rate changes are of the magnitude encountered in everyday conversation, temporal normalization occurs almost immediately, making any adjustment difficult to study. Second, when speakers attempt to increase their speaking rate naturally, they tend to distort the normal proportion of speech to silence (Lane & Grosjean, 1973), which may make the speech less intelligible when compared with artificial time compression, espe-

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cially at extremely rapid rates (Janse, 2003). The use of computer compression algorithms to produce speech rates much faster than what could be spoken naturally allows us to push the perceptual system to its limit and observe the characteristics and time course of perceptual adaptation.

Several studies have investigated perceptual adjustment to time-compressed speech in young adults. These studies have consistently shown that when young adults are presented with 10–20 sentences compressed to a very rapid rate, their recall accuracy increases with practice (Altmann & Young, 1993; Dupoux & Green, 1997; Mehler et al., 1993; Pallier, Sebastián-Gallés, Dupoux, Christophe, & Mehler, 1998; Sebastián-Gallés, Dupoux, Costa, & Mehler, 2000). In addition, adaptation has been observed in response to artificially synthesized speech (Schwab, Nusbaum, & Pisoni, 1985) and phonetically legal nonwords (Altmann & Young, 1993). Young adults also demonstrate a high degree of improvement in time-compressed speech comprehension in one language after exposure to time-compressed speech in a second language with similar phonemes, regardless of whether they understand the second language (Sebastián-Gallés et al., 2000). The presence of perceptual adaptation in response to nonwords and words in a language not understood by the listener strongly suggests that adaptation does not require knowledge of word structure or meaning and therefore occurs at some prelexical stage of processing.

Because of the importance of spoken language comprehension throughout the life span, the continuing ability of the perceptual system to understand different speakers is essential. The fact that older adults are able to understand a wide variety of speakers indicates that they are able to normalize across several speech parameters, including rate. This observation has been confirmed experimentally by studies showing that older adults' recall accuracy for speech compressed to between 80% and 65% of its original duration is essentially equivalent to that for normal speech (Wingfield et al., 2003; Wingfield, Wayland, & Stine, 1992). By way of contrast, age-related differences in perceptual learning have been reported in a number of modalities (e.g., Fernandez-Ruiz, Hall, Vergara, & Diaz, 2000; Gilbert & Rogers, 1996; Rogers, Fisk, & Hertzog, 1994), including some evidence indicating that older adults are less able than young adults to normalize across various speech parameters (Sommers, 1997). These studies raise the question of whether perceptual learning in the context of speech comprehension will be preserved. Studying older adults' perceptual learning in this context is appealing for two reasons. First, speech comprehension is an overpracticed task and therefore presumably is relatively resistant to age-related declines. Second, it is a behaviorally relevant task, so results of these studies may have practical consequences for communication practices with older adults. To date, adaptation to rapid speech has not been studied in older adults. Thus, the extent to which older adults can adapt to this rapid sensory input is unknown.

The fact that older adults' overall competence on linguistic tasks remains quite good (e.g., Wingfield & Stine-Morrow, 2000) supports the notion that their perceptual systems are still generally flexible. However, many peripheral and cognitive changes occur in normal aging that adversely affect speech comprehension. At a sensory level, older adults generally have poorer hearing acuity than do young adults (Morrell, Gordon-Salant, Pearson, Brant, & Fozard, 1996). Peripheral causes of this decline include loss of both inner and outer hair cells of the inner ear and decreased blood flow to important auditory structures, resulting in declines in frequency discrimination, intensity discrimination, and performance on simultaneous masking tasks (Schneider, 1997). In addition to this peripheral hearing loss, older adults exhibit declines in temporal auditory processing. For example, compared with young adults, older adults require a significantly larger gap between adjacent tones to perceive them as separate (Schneider & Hamstra, 1999; Schneider & Pichora-Fuller, 2001).

Older adults also demonstrate a general age-related decline in processing speed (Salthouse, 1994, 1996). This limitation would likely have an especially pronounced effect on spoken language comprehension: Unlike written language comprehension, in which the reader has the opportunity to reread material, speech comprehension is by its very nature a time-dependent process. From the acoustic signal, words must be recognized, syntactic structure determined, and meaning integrated with other constituent units, all while new information continues to arrive. When sensory input is rapid, listeners have less time to process the speech signal; this time constraint should make time-compressed speech especially difficult for older adults to process, independent of any changes in auditory acuity.

The effects of these age-related declines are evident even at the level of word processing. Older adults perform worse than their younger counterparts on time-compressed word identification tasks, with this difference accentuated at faster speech rates (Beasley & Maki, 1976; Konkle, Beasley, & Bess, 1977). At the sentence level, older adults' comprehension of time-compressed speech is also differentially impacted relative to young adults' (Wingfield, 1996; Wingfield et al., 2003). In addition to word identification, processing connected discourse requires the organization of language into meaningful units, an operation that is presumably adversely affected by reductions in the amount of available processing time. In support of this notion, Wingfield, Tun, Koh, and Rosen (1999) inserted silent periods at clause boundaries in passages of time-compressed speech. The silent periods had the same total length as the total amount of speech signal deleted, such that overall passage length was kept constant. Thus, the added silent periods increased the amount of processing time available to the listener at syntactic boundaries but had no effect on the degraded sensory input. At a moderate rate of compression (240 words per minute [wpm]), this additional time brought both young and older adults back to their baseline levels for recall accuracy. At a faster rate (300 wpm), however, young adults returned to baseline, but older adults did not. This illustrates the fact that although available processing time affects speech comprehension, perceptual factors still play a large role in speech intelligibility, particularly for older adults.

Our goal in the current set of studies is to determine whether auditory perceptual learning of compressed speech sounds is equivalent in young and older adults. To do so, we investigate whether older adults can adapt to highly compressed speech and how this adaptation compares with that seen in young adults. Older adults' ability to successfully comprehend spoken language under a variety of conditions indicates that they are capable of such adaptation. Conversely, the cognitive declines associated with normal aging suggest that any improvement might happen over a longer time scale in older adults or may be absent altogether at very rapid speech rates.

Experiment 1

As noted earlier, several previous studies have demonstrated perceptual adaptation to rapid speech by young adults. In one such study, Dupoux and Green (1997) presented young adults with a series of 20 sentences compressed to 38% of their original duration (approximately 620 wpm). Each sentence consisted of 10 words: 7 content words and 3 function words. After hearing each sentence, participants wrote down as much of the sentence as they could. Recall accuracy was measured as the percentage of content words correctly recalled and was found to increase over the first 10–15 sentences before reaching an asymptote. As previously indicated, given that older adults' language processing capabilities are largely preserved in the face of natural variations in speech rate (Wingfield & Stine-Morrow, 2000), it follows that older adults must also be capable of perceptually adjusting to different speech rates. What is unknown is how this adjustment differs from that seen in young adults. The first purpose of Experiment 1 is to determine whether older adults show the same rate and magnitude of perceptual adaptation to time-compressed speech as do young adults.

With respect to this question, an important procedural decision centered on whether to present the sentences at the same speech rate for young and older adults. If we used speech rates in the range used in previous studies of perceptual adaptation (620 wpm), older adults would be placed at a considerable disadvantage (e.g., Wingfield et al., 2003). However, presenting speech at a rate slow enough to accommodate older adults would likely result in near-perfect performance by young adults. Thus, using any single presentation rate, we would not be able to compare rate of adaptation between the two age groups. We therefore equated young and older adults for performance accuracy by using individually selected speech rates.

A second question addressed by Experiment 1 was whether participants are able to transfer learning from one speech rate to a different speech rate. Dupoux and Green (1997) reported that switching to a slower speech rate in the middle of sentence presentation resulted in a brief decrease in recall accuracy when the original rate was resumed, indicating that perceptual adaptation does not perfectly transfer across different speech rates. In the current study we examined a related question: namely, whether adaptation to speech delivered at a very rapid rate would produce better than expected recall performance for speech at a slower rate presented immediately following this adaptation.

Finally, age-related declines in certain types of sentence processing and memory tasks might suggest that older adults would be impaired on any task that relies on verbal recall of previously presented material, as do the studies presented here. However, the sentences used in these studies are of relatively simple grammatical construction, and pilot studies indicated that they were easily recalled at near-perfect levels when uncompressed. The approach of having listeners recall presented sentences aloud is in close agreement with the approaches used in previous studies, in which participants wrote down the words that they were able to perceive (Dupoux & Green, 1997; Pallier et al., 1998; Sebastián-Gallés et al., 2000). We felt that keeping the tasks relatively consistent with these previous studies was important so that comparisons among studies could be drawn.

Method

Participants

The young adult participants were 20 university students, 14 women and 6 men, with ages ranging from 18 to 22 years ($M = 19.0$, $SD = 1.1$). They had a mean of 13.6 ($SD = 0.1$) years of formal education at time of testing and a mean Wechsler Adult Intelligence Scale (3rd ed.; WAIS–III; Wechsler, 1997) vocabulary score of 51.1 ($SD = 4.8$). The older adults were 20 healthy, community-dwelling volunteers, 16 women and 4 men, with ages ranging from 65 to 78 years ($M = 72.0$, $SD = 3.9$). The older adults had a mean of 15.6 years of formal education ($SD = 2.0$) and a mean WAIS–III vocabulary score of 55.6 ($SD = 5.7$).

Both groups were thus well educated and had good verbal ability, with the older group having an average of 2.0 more years of formal education, $t(38) = 3.93$, $p < .005$, and, as is common with older adults, a somewhat higher vocabulary score than the young group, $t(38) = 2.72$, $p < .05$ (Verhaeghen, 2003). All participants were native speakers of English, and none had a history of stroke or illness that might affect cognitive performance.

Although the older adults in this study had good hearing for their age (Morrell et al., 1996), significant differences in acuity were present relative to the young adults. In general, the young participants had better hearing acuity than the older participants, measured by both pure tone average (PTA) for 500, 1000, and 2000 Hz ($M_{\text{young}} = 7.8$ dB, $M_{\text{older}} = 14.9$ dB), $t(38) = 3.80$, $p < .005$, and speech reception threshold (SRT; lowest decibel level at which two-syllable words can be correctly identified 50% of the time; $M_{\text{young}} = 5.0$ dB, $M_{\text{older}} = 11.3$ dB), $t(38) = 3.05$, $p < .005$, for participants' better ear. A level of 25 dB or better for PTA or SRT is typically taken as clinically normal for speech (Hall & Mueller, 1997).

Materials

The stimuli consisted of 60 sentences. Each sentence contained 10 words (7 content words and 3 function words) and 14–16 syllables. A female native speaker of American English recorded the sentences at a fast-normal speaking rate of approximately 220 wpm. The sentences were equated for difficulty in a preliminary study in which young and older adults were tested for recall accuracy. Time compression of the stimuli was performed with SoundEdit software (Macromedia, Inc., San Francisco, CA) via the sampling technique, in which small segments are periodically deleted equally from both speech and silent intervals, with the remaining segments then abutted in time. Speech rate is varied by the frequency with which these small segments are deleted. This procedure maintains the relative temporal pattern of the speech, including relative lengthening of words prior to clause boundaries and relative word duration as an indicator of stress, cues important to speech perception (Shattuck-Hufnagel & Turk, 1996).

The stimuli were divided into two sets. The first set consisted of 40 sentences, divided into 10 groups of 4 sentences each, that would be used in the calibration session and transfer phase (see the *Procedure* section). The second set consisted of 20 sentences, divided into 10 groups of 2 sentences each, that would be used in the adaptation phase. Sentence sets were counterbalanced across participants, such that, by the end of the experiment, each group of sentences appeared in each possible position for a given set.

For this and all subsequent experiments, stimuli were presented binaurally over earphones at a comfortable listening level for all participants. The presentation level, once set, was not changed during the experiment.

Procedure

Calibration session. Prior to the beginning of the main experiment, we conducted a calibration session with all participants to determine speech rates at which each individual, young or older, would produce the same level of recall accuracy. To allow room for improvement without risking ceiling or floor effects, we set the target accuracy levels at 30% and 70%. The speech rate yielding 30% correct recall was used as the adaptation rate. The speech rate yielding 70% correct recall prior to adaptation was used to test transfer of learning from a fast rate to a slower one.

During the calibration session, participants heard four sentences at each of nine different speech rates, with sentences blocked by rate and presented in an ascending fashion (i.e., getting faster). All participants received sentences at 210, 440, 550, 629, 677, and 733 wpm. In addition, young participants heard sentences at 772, 815, and 880 wpm, and older participants heard sentences at 367, 489, and 587 wpm. Following each sentence, participants were asked to repeat as much of the sentence as possible and press a key when they were finished recalling. An additional keypress initiated presentation of the next sentence; participants were instructed to proceed when they were ready, with no emphasis on proceeding quickly. Beginning after the third rate tested, participants were asked to define vocabulary words between rates in an attempt to minimize adaptation during this calibration session.

Sentence recall was scored online by the researcher, and the rates were determined at which each participant's recall accuracy was closest to 30% and 70% correct recall of the content words of the sentences. Following the calibration session, there was a break of approximately 10 min, during which participants underwent audiometric screening and performed digit span tasks. Again, this was done to reduce possible carryover of any adaptation that might have occurred during the calibration session.

Adaptation phase. Participants heard 20 sentences at the rate determined during the calibration session to yield approximately 30% accurate recall of content words. As in the calibration session, participants listened to and immediately recalled each sentence as it was heard and pressed a key to indicate they were finished recalling the sentence. The time from the end of stimulus presentation to this keypress, hereafter referred to as *recall time*, provided a measure of how long participants took to recall each sentence. When participants were ready to hear the next sentence, they pressed a second key, which initiated the next stimulus presentation. The time between the two keypresses, hereafter referred to as the *pacing time*, indicated the break taken by each participant between sentences. Latencies for keypress responses were recorded with PsyScope presentation software (Cohen, MacWhinney, Flatt, & Provost, 1993). Sentence recall was tape recorded for later analysis.

Transfer phase. After completing the adaptation phase, participants heard four sentences at the rate determined during the calibration session to yield approximately 70% accuracy. There was no pause between the adaptation and transfer phases, and participants were not informed that there would be a change in speech rate.

Results

When determining recall accuracy, we gave credit only for words recalled exactly as they appeared in the stimulus sentences (i.e., synonyms were considered errors). Recall of a correct word with a grammatical suffix (e.g., a plural ending) added was considered correct; thus, if the presented word was "chair," "chairs" was considered a correct response. Added words or syllables (e.g., "high chair" or "chairman") were not counted as errors. There was no penalty for guessing. We adopted these scoring criteria because we were primarily interested in what portion of the acoustic signal listeners were able to accurately perceive; in the examples above, it would be assumed that listeners were indeed able to accurately perceive "chair." Finally, we considered only content words in calculating recall accuracy, as function words could easily be guessed. These scoring guidelines are in good agreement with those used in previous studies (e.g., Dupoux & Green, 1997).

The left panel of Figure 1 shows recall accuracy for the young and older participants as a function of increasing speech rate in the calibration session prior to the main experiment. Note that the sentences were successfully recalled by all participants when uncompressed, which indicates that they were well within the older adults' memory span. The mean of the speech rates that yielded 30% accuracy for young participants was 669 wpm (*SD* = 47).

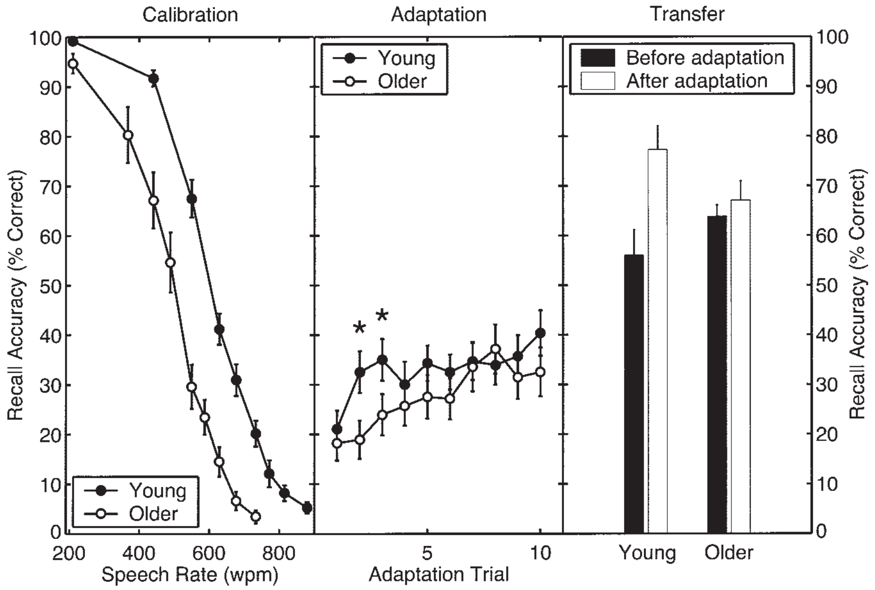

Figure 1. Recall accuracy for the calibration, adaptation, and transfer phases of Experiment 1. Each adaptation trial consisted of two unique sentences. Error bars represent 1 standard error. wpm = words per minute. $^{*}p <$ .05 (for adaptation phase only).

The mean of the speech rates required for the older participants to attain this 30% correct level was 569 wpm ($SD = 66$), a significantly slower rate, $t(38) = 5.6$, $p < .001$. This confirms the need to use different rates for the young and older participants to put them on the same baseline.

Recall accuracy for the adaptation phase is displayed in the middle panel of Figure 1. For convenience, we grouped the 20 presented sentences into 10 adaptation trials, with each trial comprising two unique sentences. As can be seen for the recall levels for the 1st trial of the adaptation phase, the use of the slower speech rates for the older participants as determined in the calibration session was successful in placing the two age groups at the same accuracy level at the beginning of the adaptation trials, $t(38) = 0.6$, *ns*. We submitted the data for the two age groups across adaptation trials to a 10 (adaptation trial: 10 trials of 2 sentences) × 2 (age: young, older) mixed design analysis of variance (ANOVA), with trials as a within-subject variable.

The main effect of adaptation trial was significant, $F(9, 342) = 3.99$, $MSE = 0.03$, $p < .001$, consistent with the appearance of a significant improvement for both age groups over the course of the adaptation trials as the participants received repeated exposure to time-compressed speech. There was no main effect of age, $F(1, 38) = 2.71$, $MSE = 0.11$, which indicates that young and older adults' improvement did not significantly differ from one another. The Age × Adaptation Trial interaction also was not significant, $F(9, 342) < 1$, $MSE = 0.03$. Although this overall interaction failed to reach significance, a visual inspection of the adaptation curves in Figure 1 suggests that the older adults took longer to achieve the same level of adaptation as the young adults. To test this possibility, we conducted post hoc uncorrected *t* tests at each adaptation trial and found that young and older adults' recall accuracy differed significantly only for Adaptation Trials 2 and 3.

The data for the transfer phase are shown in the right panel of Figure 1. The black bars are taken from the calibration session and show the mean percentage of recall accuracy for the speech rates chosen to put the two age groups at a similar baseline accuracy level of approximately 70% correct. The mean of the rates used for young participants was 545 wpm ($SD = 54$); the mean of the rates used for older participants, 465 wpm ($SD = 62$), was significantly slower, $t(38) = 4.4$, $p < .001$. The accuracy functions in the calibration session in the left-hand panel of Figure 1 show mean accuracy levels at each speech rate. Given the range of speech rates chosen for the calibration session, participants' recall accuracy was rarely exactly 70%. When no rate resulted in 70% performance, we always chose a rate resulting in slightly lower accuracy to avoid ceiling effects; thus, the accuracy for both groups of participants was not identical, and both were slightly lower than 70%. However, the rates selected were slower than those used for the adaptation phase, and the difference in accuracy between the groups on these rates was not significant, $t(38) = 0.9$, which was our primary goal in selecting these speech rates.

The white bars in the right panel of Figure 1 represent participants' performance on these same rates immediately after the adaptation phase had been completed. The data shown in this panel were submitted to a 2 (condition: calibration session, transfer phase) × 2 (age: young, older) ANOVA. The main effect of condition was significant, $F(1, 38) = 17.00$, $MSE = 0.02$, $p < .001$, confirming that participants' performance at their respective speech rates was significantly better after the adaptation phase than in the initial calibration session prior to the main experiment. The main effect of age was not significant, $F(1, 38) < 1$, $MSE = 0.05$, but there was a significant Condition × Age interaction, $F(1, 38) = 7.44$, $MSE = 0.02$, $p < .05$, indicating that the young adults showed a greater transfer of adaptation from one rate to another relative to the older adults. Post hoc *t* tests confirmed a significant improvement for young adults' recall, $t(19) = 6.8$, $p < .001$, but no improvement for older adults, $t(19) < 1$, *ns*.

Participants' recall and pacing time data for the adaptation and transfer phases are shown in Figure 2. For convenience, we grouped the 24 presented sentences into 12 adaptation trials, with each trial being composed of two unique sentences; the vertical line indicates the boundary of the two phases. Both sets of data were analyzed with a 12 (adaptation trial: 12 groups of 2 sentences each) × 2 (age: young, older) mixed design ANOVA, with adaptation trial as a within-subject variable. Regarding the time participants took to recall the sentence, there were no significant main effects of adaptation trial, $F(11, 418) < 1$, $MSE = 1{,}885{,}275.27$; or age, $F(1, 38) < 1$, $MSE = 41{,}224{,}330.06$. The Adaptation Trial × Age interaction was also not significant, $F(11, 418) = 1.47$, $MSE = 1{,}885{,}275.27$. The pacing time data demonstrate that participants did slightly decrease the amount of time they took between sentences, as indicated by a main effect of adaptation trial, $F(11, 418) = 7.85$, $MSE = 310{,}282.29$, $p < .001$. However, there were no age differences, as indicated by both the lack of a main effect of age, $F(1, 38) < 1$, $MSE = 12{,}886{,}019.52$, and the lack of an Age × Adaptation Trial interaction, $F(11, 418) = 1.56$, $MSE = 310{,}282.29$. Thus, overall, young and older adults did not differ significantly in their recall or pacing behaviors during the adaptation and transfer phases.

As previously noted, although the older participants had good hearing for their age, there were significant age differences in participants' PTAs and SRTs. For this reason, we used a within-subject design and individually matched participants for starting

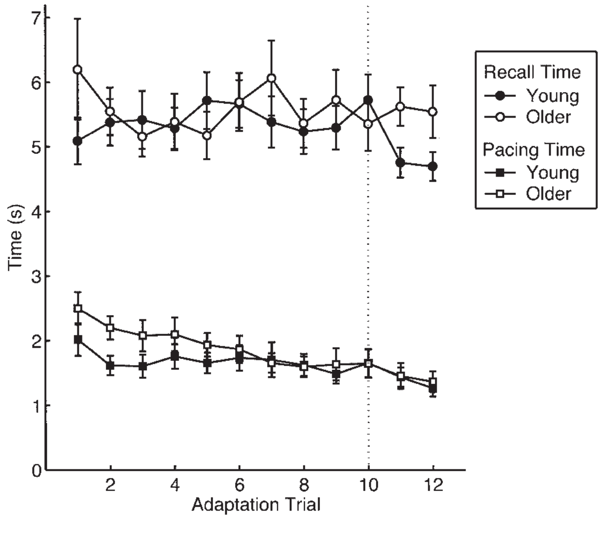

Figure 2. Recall and pacing times for young and older adults for the adaptation (Trials 1–10) and transfer (Trials 11–12) phases of Experiment 1. Each adaptation trial consisted of two unique sentences. The dotted vertical line indicates the boundary between adaptation and transfer phases. Error bars represent 1 standard error.

recall accuracy. To examine the extent to which hearing acuity might still have affected performance, we performed a median split for each age group on the basis of SRT for each participant's better ear, which resulted in participants with better and poorer hearing within each age group. We submitted the data from the adaptation phase to a 10 (adaptation trial: 10 trials of 2 sentences each) × 2 (age: young, older) × 2 (hearing: top of age group for SRT, bottom of age group for SRT) mixed design ANOVA, with adaptation trial as a within-subject factor and age and hearing group as between-subjects factors. There was no main effect of hearing, $F(1, 36) = 1.62$, $MSE = 0.10$, nor was there an Age × Hearing interaction, $F(1, 36) = 2.00$, $MSE = 0.10$. As with the initial analyses, there was no main effect of age, $F(1, 38) = 2.84$, $MSE = 0.10$. In addition, we conducted post hoc *t* tests for each data point for better versus poorer hearers within each age group. None of these tests showed significant differences due to hearing acuity for either age group.

Discussion

The results of Experiment 1 indicate that older adults, like young adults, demonstrate improved recall accuracy with repeated exposure to time-compressed sentences. Indeed, after the older adults listened to and recalled 20 time-compressed sentences, their recall accuracy increased 14%. For the young adults, the effect of this experience was even greater, resulting in a 19% increase in recall accuracy. Both of these figures are relative to the young and older adults' own baselines of performance, which take into account older adults' generally greater difficulty with time-compressed speech.

In the case of young adults, the source of this rapid adaptation has been discussed in terms of lower level adaptation in processing the acoustic properties of the compressed speech input and improving the ability to conduct the higher level operations of integrating this information at the word and sentence level (e.g., Dupoux & Green, 1997; Pallier et al., 1998). Although the present data show that by the end of the adaptation trials the older adults' improvement was similar to the young adults', the young adults showed a greater degree of improvement during the early adaptation trials. That is, the older adults appeared to have been adapting at a slower rate than the young adults.

A possible explanation for this discrepancy is that the young and older adults adopted different strategies at the beginning of the task. For example, the young adults might have taken more time when attempting recall and so were able to correctly produce more words. The similarity in the young and older adults' recall and pacing times makes this explanation unlikely. This leaves open two additional explanations for the discrepancy in initial learning between young and older adults. One possibility is that older adults' perceptual learning occurs at a slower rate, a finding that would be in agreement with other studies of adaptation in older age (e.g., Fernandez-Ruiz et al., 2000). However, the design of our experiment does not permit us to rule out a second possibility—namely, that participants' exposure to time-compressed speech during the calibration session affected their performance on the adaptation phase and that young adults were better able to retain the learning from the calibration session to the adaptation phase. If this were the case, one might expect to see the young adults showing greater accuracy than the older adults at the start of the adaptation phase as well as showing a more rapid rate of adaptation following this initial point. Although, as we have previously noted, there was not a significant difference between young and older adults' recall accuracy at the start of the adaptation phase, the young adults did demonstrate a significant advantage on Adaptation Trials 2 and 3.

The possibility that both groups of participants adapted during the calibration session is consistent with the fact that their performance at the beginning of the adaptation phase was lower than 30%, even though we specifically chose speech rates to result in this level of accuracy. That is, following the calibration session, we chose the rate at which each participant's recall accuracy was closest to 30%. However, at the beginning of the adaptation session, participants heard this same rate, and their performance was noticeably worse than 30%, indicating that the rate chosen at the end of the calibration session was based on participants' adapted—and thus enhanced—performance. It is feasible that young adults were able to maintain this learning across the 10-min break between the calibration session and the adaptation phase, which resulted in a faster rate of improvement. The greater ability of young adults to transfer perceptual learning is supported by the data from the transfer phase, which showed that adaptation helped the young adults significantly more than the older adults on a different, nonadapted rate of speech. The question of whether the calibration session indeed accounted for young adults' faster adaptation than older adults is addressed in Experiment 2.

We have suggested that participants' relatively low recall accuracy (i.e., below 30%) can be attributed to improvements during the calibration phase, when the rate was chosen. Further, we have argued that this improvement diminishes over time and that the rate of this decrease is slower for young adults, leading to their increased performance at the beginning of the adaptation phase relative to the older adults. An alternative explanation for participants' relatively low accuracy scores at the beginning of the adaptation phase—but one that does not account for the age differences—is that participants' recall was adversely affected by the switch between the very fast rate heard at the end of the calibration phase and the rate used for the adaptation phase. We believe this possibility can be ruled out on the basis of the available data from the transfer phase. If moving from a faster speech rate to a slower one were detrimental to performance, one would expect to see decreased performance in the transfer phase, as these sentences were slower than those heard in the immediately preceding adaptation phase. However, on the contrary, young adults demonstrated a significant increase in performance, whereas older adults' performance remained unchanged. Although further studies are needed to determine the effect of rate switching on adaptation, in the current study the switching does not appear to have been detrimental.

Finally, as noted previously, we purposefully used short sentences to minimize memory demands, particularly as these may differentially impact older adults' performance. As can be seen from the calibration session, both young and older adults demonstrated near-perfect performance with unaltered stimuli (i.e., at 220 wpm), indicating that older adults were capable of recalling the test sentences when the sentences were unaltered. The age differences in participants' recall at faster speech rates can thus be safely attributed to older adults' greater difficulty perceiving time-compressed speech and not to age-related memory differences.

Experiment 2

As indicated above, the data suggesting faster adaptation in young relative to older adults in Experiment 1 are complicated by the necessary inclusion of a calibration session prior to the assessment of adaptation. The first question addressed by Experiment 2 was whether this calibration session differentially impacted young adults' performance on the subsequent adaptation phase relative to the older adults. If the age differences seen in the initial adaptation trials in Experiment 1 were due to faster learning by the young adults, they should also appear when no calibration session is present. However, if the advantage of young adults was due to better retention over the 10-min break, these differences should not be present in the absence of a calibration session.

A second question addressed by Experiment 2 related to the absolute level of improvement that can be expected after exposure to time-compressed speech. Consistent with previous studies with young adults (e.g., Dupoux & Green, 1997), improvement for both young and older adults appeared to level off by the end of the 10 adaptation trials (20 sentences). This could mark the upper limit of perceptual learning, or it could be a temporary plateau. This question has remained unexplored even for young adults, however, as previous studies, as in Experiment 1, have involved presentation of no more than 20 consecutive sentences (Altmann & Young, 1993; Dupoux & Green, 1997; Mehler et al., 1993; Pallier et al., 1998; Sebastián-Gallés et al., 2000).

Our final question related to the procedure in Experiment 1 in which we placed young and older adults on the same accuracy baseline at the start of the adaptation trials. It remains to be seen how young and older adults' performance compares when they are equated for speech rate rather than response accuracy.

Experiment 2 addressed these questions by replicating Experiment 1 with three important modifications. First, there was no initial calibration stage; we used group data from Experiment 1 to determine presentation rates to equate young and older adults for starting accuracy. Second, to assess perceptual adaptation over a longer time scale than previously studied, we presented each participant with 40 sentences instead of 20. Finally, we used two groups of young adults: We presented one group of young adults with speech at a faster rate than the older adults to put them on the same starting baseline, as in Experiment 1, whereas a second group of young adults received speech at the same rate as the older adults.

Method

Participants

Participants were divided into three groups. Group 1 consisted of 30 older adults who heard sentences compressed to 550 wpm; Group 2 consisted of 30 young adults who heard sentences compressed to 677 wpm; Group 3 consisted of 30 young adults who heard sentences compressed to 550 wpm. Groups 1 and 2 were thus approximately equated for starting accuracy on the basis of data from Experiment 1 and hereafter are referred to as the *accuracy-matched* groups. Groups 1 and 3 were presented with sentences at the same speech rate and hereafter are referred to as the *rate-matched* groups.

Participant characteristics for all three groups are shown in Table 1. All participants were native speakers of English. The older adults were 30 healthy volunteers, 22 women and 8 men. The young adult participants were 60 university students, 32 women and 28 men. The older adults had an average of 1.5 years more education than the young adults, $t(88) = 3.7$, $p < .001$. There was no significant age difference in vocabulary score, $t(88) = 0.0$. As would be expected, the young adults demonstrated a significant advantage in hearing acuity relative to older adults (Morrell et al., 1996), measured by both PTA, $t(86) = 8.8$, $p < .001$, and SRT, $t(84) = 5.2$, $p < .001$, for participants' better ears. As in Experiment 1, however, the older adults still fell within the range considered to be clinically normal for speech (Hall & Mueller, 1997). The *t* tests performed on the two groups of young participants confirmed they did not differ significantly on any of the measures shown in Table 1. (PTAs were unavailable for 2 young participants, and SRTs were unavailable for 4 young participants.)

Table 1
Mean Participant Characteristics for Experiment 2

Characteristic	Older group (550 wpm) *M*	Older group (550 wpm) *SD*	Young group 1 (677 wpm) *M*	Young group 1 (677 wpm) *SD*	Young group 2 (550 wpm) *M*	Young group 2 (550 wpm) *SD*
Age (years)	73.0	4.9	19.4	1.6	19.7	1.3
Education (years)	15.7	2.8	14.0	1.4	14.3	1.3
Forward digit span	7.1	1.3	7.6	1.0	7.5	1.2
Backward digit span	5.7	1.4	6.0	1.4	5.4	1.6
Vocabulary (WAIS–III)	49.8	9.2	49.1	6.1	50.6	5.5
Best ear PTA (dB)	15.9	6.0	6.4	4.6	6.7	3.1
Best ear SRT (dB)	14.0	6.6	8.0	4.6	8.2	3.1

Note. wpm = words per minute; WAIS–III = Wechsler Adult Intelligence Scale, third edition; PTA = pure tone average, taken as the mean thresholds for tones at 500, 1000, and 2000 Hz; SRT = speech reception threshold, the lowest decibel level at which two-syllable words can be correctly identified 50% of the time.

Materials and Procedure

The stimuli consisted of 40 sentences taken from Experiment 1. As before, each sentence contained seven content words and three function words and ranged in length from 14 to 16 syllables. They were recorded by a female speaker of American English.

Participants first heard a single practice sentence at 550 wpm with instructions to recall as much as possible. They were then presented with 40 sentences compressed to 550 wpm (rate-matched young and older adults) or 650 wpm (accuracy-matched young adults), as described above. Following each sentence, they recalled as much as possible of that sentence, pressing a key to indicate they were finished with their recall. Presentation of the next trial was initiated with a second keypress. There were no breaks during the 40 sentences, although participants were allowed to take as much time as they wanted between sentences. The sentences were counterbalanced in groups of 4 sentences, and across all participants each sentence group was presented in each possible position.

Results

Figure 3 displays recall accuracy for the 40 presented sentences plotted as a function of 20 adaptation trials, with each trial containing 2 unique sentences. The bottom two curves show recall accuracy for the older adults and for the young adult group that was matched with them for starting accuracy (i.e., older adults who heard speech at 550 wpm and the young adults who heard speech at 677 wpm). The top curve shows the adaptation curve for the young adult group that heard speech at the same 550 wpm rate as the older adults.

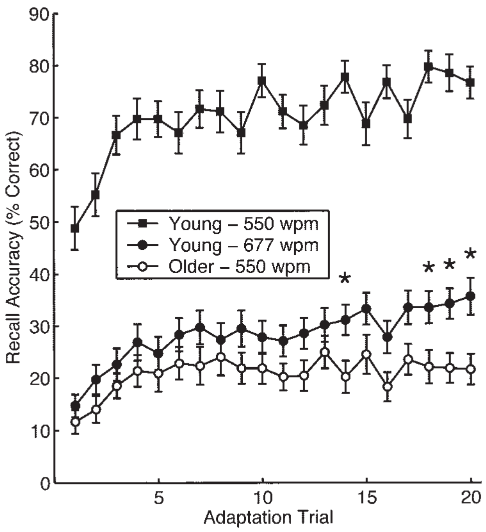

Figure 3. Recall accuracy for Experiment 2. Each adaptation trial consisted of two unique sentences. Error bars represent 1 standard error. wpm = words per minute. *$p < .05$.

The data for the older adults and the starting accuracy-matched young adults were submitted to a 20 (adaptation trial: 20 trials of two sentences each) × 2 (age: young, older) mixed design ANOVA, with adaptation trials as a within-subject variable. Recall accuracy improved over time, as indicated by a main effect of adaptation trial, $F(19, 1102) = 4.94$, $MSE = 0.02$, $p < .001$. Across the adaptation trials, the young adults showed better recall performance than the older adults, as evidenced by a main effect of age, $F(1, 58) = 4.79$, $MSE = 0.35$, $p < .05$. However, there was no Adaptation Trial × Age interaction, $F(19, 58) < 1$, $MSE = 0.02$, indicating that this age difference was consistent across all trials.

Although the Adaptation Trial × Age interaction was not significant, visual inspection of Figure 3 suggests that the difference between accuracy-matched young and older adults increased after 10 adaptation trials (20 sentences). To assess whether the accuracy-matched groups differed at later trials, we reran the ANOVA on the last 10 trials (Sentences 21–40), where we found a marginal Age × Trial interaction, $F(9, 522) = 1.85$, $MSE = 0.02$, $p = .06$, which suggests that the difference between young and older adults might have increased at later adaptation trials. To further examine this effect, we conducted post hoc *t* tests at each adaptation trial. Significant differences (with a $p < .05$ criterion, uncorrected) were found for Trial 14 and Trials 18–20, providing additional support for the idea that young adults improved more than older adults at later adaptation trials. Indeed, whereas the older adults' performance appeared to asymptote by 10 trials, the young group matched with the older group for initial starting accuracy continued to show improvement.

Our second comparison of interest was between the older adults and the rate-matched young adults. These data were submitted to a 20 (adaptation trial: 20 trials of two sentences each) × 2 (age: young, older) mixed design ANOVA, which showed a main effect of adaptation trial, $F(19, 1102) = 6.92$, $MSE = 0.02$, $p < .001$, again indicating that both young and older adults' recall accuracy improved with increasing exposure to time-compressed speech. A main effect of age confirmed that young adults' overall recall performance was higher, $F(1, 58) = 588.44$, $MSE = 0.42$, $p < .001$. Unlike the accuracy-matched groups, however, the rate-matched groups showed a significant Adaptation Trial × Age interaction, $F(19, 1102) = 2.35$, $MSE = 0.02$, $p < .01$. This confirms the impression in Figure 3 that the rate-matched young adults' recall accuracy improved over adaptation trials at a more rapid rate than did the older adults'.

The three upper curves in Figure 4 show the time to the completion of the participants' recall responses (recall time) over the course of the 20 adaptation trials for the three participant groups. The lower three curves show the data for the three participant groups' times between completion of recall and the keypress to initiate the next sentence (pacing time). The recall time data were submitted to a 20 (adaptation trial: 20 trials of two sentences each) × 3 (group: older adults, young adults matched with the older adults for initial accuracy, young adults matched with the older adults for speech rate) mixed design ANOVA. Although there was considerable variability in recall times over the 20 adaptation trials, all three groups tended to respond more rapidly as the adaptation trials progressed, as evidenced by a main effect of adaptation trial, $F(19, 1653) = 3.24$, $MSE = 1{,}505{,}841.28$, $p < .001$. This general reduction in recall time did not differ among the three groups: There was neither a significant main effect of group, $F(1, 87) < 1$, $MSE = 51{,}301{,}432.28$, nor a significant Adaptation Trial × Group interaction, $F(19, 1653) = 1.00$, $MSE = 1{,}505{,}841.28$.

These analyses were repeated on the pacing time data (the lower three curves in Figure 4). Pacing times, like the recall times, became more rapid with increasing trials, showing a significant main effect of adaptation trial, $F(19, 1653) = 6.82$, $MSE = 1{,}702{,}475.55$, $p < .001$. In this case, there was a marginally significant effect of group, $F(1, 87) = 2.95$, $MSE = 15{,}616{,}474.80$, $p = .06$, driven by the older adults' slightly slower

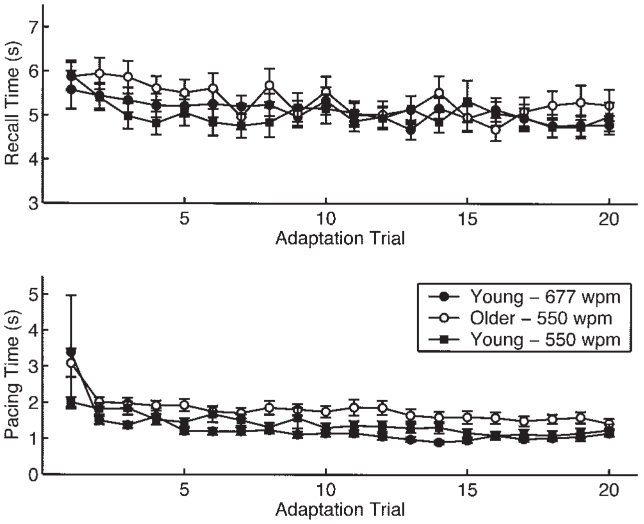

Figure 4. Recall and pacing times for young and older adults for Experiment 2. Each adaptation trial consisted of two unique sentences. Error bars represent 1 standard error. wpm = words per minute.

overall rate of pacing. However, there was no Adaptation Trial × Group interaction, $F(19, 1653) < 1$, $MSE = 1{,}702{,}475.55$.

Discussion

As expected from Experiment 1, when young adults received sentences at the same speech rate as older adults, the young adults' performance was markedly better. This finding is consistent with numerous studies showing that older adults have greater difficulty than young adults with comprehension and recall of time-compressed sentences (e.g., Gordon-Salant & Fitzgibbons, 1993; Wingfield et al., 1999; 2003). In the present experiment this was evidenced not only by the overall level of recall performance for the young adults hearing the speech at the same rate as the older adults (550 wpm) but also by the more rapid rate of improvement young adults demonstrated relative to older adults with equivalent amounts of experience at hearing and recalling time-compressed speech.

Experiment 2 also shows that although both the young and the older adults' recall performance improved over trials, the older adults' performance was beginning to asymptote before the 10th trial, whereas both groups of young adults continued to show gains across all 20 trials. This suggests an advantage in longer term learning for the young adults relative to the older adults. However, it is also possible that the young adults' slight advantage in starting recall accuracy, although not statistically different, was amplified at later trials.

The most important question answered by Experiment 2, however, was whether the young adults' more rapid adaptation to time-compressed speech seen in Experiment 1 might have been influenced by the young adults showing a greater carryover effect from the calibration session. In Experiment 2 we did not include a calibration session but used speech rates that had been found to produce, on average, similar recall levels for the young and older adults on the basis of Experiment 1. The results are clear in showing that, without prior exposure to time-compressed speech, the initial rates of improvement for young and older adults did not differ. We thus conclude that the young adults' performance in the adaptation phase of Experiment 1 was bolstered by a greater carryover from the calibration session.

Experiment 3

A typical finding on many types of recall tasks is that performance on later items is worse than performance on earlier items because of proactive interference (Underwood, 1957). Our results from Experiment 2 suggest that young adults continue to improve at later adaptation trials, whereas older adults do not. One important consideration is whether older adults' lack of improvement might be due to their increased susceptibility to proactive interference effects on their recall accuracy (e.g., Bowles & Salthouse, 2003; Schonfield, Davidson, & Jones, 1983; Winocur & Moscovitch, 1983). That is, it could be that although the older adults' perceptual adjustment indeed continued to keep pace with that of the young adults, their performance was simultaneously decreased because of interference build up, resulting in a lack of net improvement. In addition, although the experiments are relatively short, it is also possible that older adults might tire more quickly than young adults, which would similarly affect performance.

To determine whether older participants were differentially affected by proactive interference, we conducted a control experiment in which participants performed a simple paragraph recall task before and after their adaptation trials. If older participants were differentially affected by proactive interference during the adaptation trials, we would expect their performance on the sentences following the adaptation trials to be decreased to a greater extent than that of the young adults. Conversely, failure to find such an interaction would suggest that older adults were not differentially affected by proactive interference.

Method

Participants

The young adult participants were 30 university students, 20 women and 10 men, with ages ranging from 17 to 20 years ($M = 18.4$, $SD = 0.8$). The young adults had a mean of 12.4 years of formal education at the time of testing ($SD = 0.7$) and a mean WAIS–III vocabulary score of 51.4 ($SD = 4.7$). The older adults were 30 healthy volunteers, 19 women and 11 men, with ages ranging from 65 to 80 years ($M = 73.9$, $SD = 3.4$). The older adults had a mean of 15.9 years of formal education ($SD = 2.9$) and a mean WAIS–III vocabulary score of 52.5 ($SD = 7.8$). Both groups thus were well educated and had good verbal ability, with the older group having an average of 3.5 more years of formal education, $t(58) = 6.4$, $p < .001$, and vocabulary scores equivalent to those of the young group, $t(58) = 0.7$, *ns*. All participants were native speakers of English.

Materials

The adaptation sentences consisted of 40 sentences constructed in a manner similar to those in Experiments 1 and 2. Each sentence contained 10 words, 7 content words and 3 function words, and was recorded by a female speaker of American English at an average speaking rate of 200 wpm.

The short paragraphs that participants heard before and after the adaptation trials so that we could test for potential age differences in proactive interference each contained two sentences. These paragraphs ranged in length from 25 to 29 words (17–18 content words): for example, "Cobras and vipers lurk near the rice paddies in Burma making snakebites a frequent cause of death there. Still, many Burmese risk this and work in the paddies." They were recorded by a male speaker of American English at an average speaking rate of 161 wpm.

Procedure

The procedure was analogous to that used in Experiment 2, with the addition of short paragraphs before and after the adaptation trials. We gave participants instructions and presented them a single time-compressed sentence to familiarize them with the sound of time-compressed speech. They then heard the two preadaptation short paragraphs; after each paragraph, they repeated as much as possible. We instructed participants to recall paragraphs without summarizing or using synonyms.

Following these two initial paragraphs, participants heard 40 time-compressed sentences. As in the accuracy-matched groups from Experiment 2, we presented young and older adults with sentences compressed to different rates to equate them for starting accuracy: Young adults heard sentences at 680 wpm, and older adults heard sentences at 510 wpm. Following each sentence, they recalled as much as possible of that sentence, pressing a key to indicate they were finished with their recall. Presentation of the next trial was initiated with a second keypress. There were no breaks during the 40 sentences, although participants were allowed to take as much time as they wanted between sentences. The sentences were counterbalanced in groups of 4 sentences, and across all participants each sentence group was presented in each possible position. Following presentation of the 40 adaptation sentences, listeners heard and recalled two additional short postadaptation paragraphs. Across all participants, each paragraph occurred an equal number of times before and after the adaptation sentences.

Results

Listeners' performance in Experiment 3 is summarized in Table 2, which shows recall accuracy levels for the first 2 and last 2 of the 40 adaptation sentences as well as for the paragraphs preceding and following the adaptation trials. It can be seen that, as in the previous experiments, both young and older listeners' recall accuracy improved with exposure. We confirmed this observation by submitting these data to a 2 (adaptation trial: first 2 sentences, last 2 sentences) × 2 (age: young, older) ANOVA. As suggested by inspection of Table 2, there was a significant main effect of adaptation trial, $F(1, 58) = 20.99$, $p < .001$, $MSE = 0.04$. There was not a significant effect of age, $F(1, 58) < 1$, $MSE = 0.06$, nor a significant Age × Adaptation Trial interaction, $F(1, 58) < 1$, $MSE = 0.04$. In addition, unlike Experiment 2, post hoc t tests failed to reveal any significant age differences at any adaptation trial.

To address our primary question of whether older adults were more susceptible to proactive interference, we compared listeners' recall accuracy for paragraphs presented before the adaptation trials with their performance on the paragraphs following the adaptation trials by submitting the data to a 2 (training: before adaptation, after adaptation) × 2 (age: young, older) ANOVA. As can be seen from Table 2, participants' performance was slightly better following the adaptation trials, confirmed by a significant main effect of training, $F(1, 58) = 5.20$, $p < .05$, $MSE = 66.82$. As expected, older adults' overall recall accuracy was significantly lower than the young adults', resulting in a significant main effect of age, $F(1, 58) = 6.80$, $p < .05$, $MSE = 280.70$. However, there was not a significant Age × Training interaction, $F(1, 58) < 1$, $MSE = 66.82$.

Discussion

The goal of this control experiment was to assess the degree to which listeners' performance might be influenced by proactive interference and in particular whether this effect might be more pronounced in older adults. We found that participants' performance was slightly better following the adaptation trials—most likely because of increased attention to task demands as a result of experience—and that this small change was comparable for young and older adults. It therefore seems unlikely that listeners' performance was affected by proactive interference or fatigue. Most important, any such task-related effects were equivalent for young and older adults.

It should be noted that we did not observe any significant advantage for young adults in later adaptation trials, as was seen in Experiment 2. On the basis of the current data, we cannot completely rule out the possibility that, because of individual differences, proactive interference influenced the results of Experiment 2 but not Experiment 3.

Table 2
Mean Recall Accuracy (Percentages of Words Correct) for Experiment 3

	Adaptation trial				Paragraph recall			
	Beginning		End		Before		After	
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Young	20.2	2.7	34.5	3.2	52.1	14.8	55.7	14.8
Older	17.6	3.8	35.5	5.8	44.2	10.7	47.5	11.9

Experiment 4

Evidence from cross-linguistic studies strongly suggests that listeners adapt to time-compressed speech at a prelexical phonemic level rather than becoming more facile at higher levels of linguistic integration and analysis (e.g., Pallier et al., 1998; Sebastián-Gallés et al., 2000). Although the specific aspect of phonemes to which listeners adapt (e.g., voice onset time) is not known, it seems clear that as listeners learn to identify phonemes that have been temporally distorted, their recall accuracy increases.

However, an open question is whether some portion of the improved recall shown by both age groups after hearing samples of time-compressed speech can be attributed to increasing experience with the task. This might include learning the importance of active attention to the stimuli and/or improving inferring strategies when words or sounds are not heard clearly. In particular, we are interested in assessing whether there might be any age-related differences in learning as a simple consequence of task familiarity.

To address this question, we conducted a control experiment that replicated Experiment 1 but used white noise instead of time compression to reduce sentence intelligibility. The use of white noise to degrade sentences as a control condition is appealing because of the high degree of correlation between comprehension of time-compressed speech and speech in noise (e.g., Versfeld & Dreschler, 2002). Dupoux and Green (1997) attempted to address the issue of adaptation to speech in noise by young adults by asking whether practice on a group of 15 sentences in noise would aid comprehension for a set of five time-compressed sentences immediately following the noise-masked stimuli. The group that received practice with sentences in noise performed no better than control groups on the time-compressed sentences, which indicated that the perceptual adaptation for time-compressed speech was stimulus specific. However, it was not possible to tell whether participants had improved over the course of the 15 sentences presented in noise, only that this exposure was not beneficial in understanding time-compressed speech.

For these reasons, we felt that an experiment examining adaptation to speech in noise was warranted. In particular, we were interested in whether there would be any improvement over time in recalling speech heard in noise and, if so, how this improvement might compare in rate and magnitude with improvement for time-compressed speech seen in Experiments 1–3. Because the noise obscures the speech stimulus, we did not anticipate listeners perceptually adjusting to the stimuli; rather, any improvements in performance accuracy would presumably be due to nonperceptual factors, such as changes in attentional or recall strategies.

Method

Participants

The young adult participants were 20 university students, 10 women and 10 men, with ages ranging from 17 to 21 years ($M = 18.3$, $SD = 0.8$). The young adults had a mean of 13.2 years of formal education at the time of testing ($SD = 0.7$) and a mean WAIS–III vocabulary score of 48.0 ($SD = 5.8$). The older adults were 20 healthy volunteers, 12 women and 8 men, with ages ranging from 66 to 87 years ($M = 75.8$, $SD = 5.9$). The older adults had a mean of 15.1 years of formal education ($SD = 2.6$) and a mean WAIS–III vocabulary score of 48.7 ($SD = 9.4$). Both groups thus were well educated and had good verbal ability, with the older group having an average of 1.9 more years of formal education, $t(38) = 3.2$, $p < .01$, and vocabulary scores equivalent to those of the young group, $t(38) = 0.3$, *ns*. All participants were native speakers of English.

As in Experiment 1, the young adults demonstrated a significant advantage in hearing acuity relative to older adults, measured by both PTA ($M_{\text{young}} = 5.7$ dB, $M_{\text{older}} = 21.7$ dB), $t(37) = 7.0$, $p < .001$, and SRT ($M_{\text{young}} = 7.4$ dB, $M_{\text{older}} = 23.5$ dB), $t(37) = 5.7$, $p < .001$, for participants' better ear. Despite the presence of these age-related acuity differences, both age groups again fell within the range considered to be clinically normal for speech (Hall & Mueller, 1997).

Materials and Procedure

Stimuli. The stimuli were the same 60 sentences used in Experiment 1. Each sentence contained 10 words, 7 content words and 3 function words, and between 14 and 16 syllables. They were recorded by a female speaker of American English.

Calibration session. We mixed 36 stimulus sentences with different degrees of white noise to determine a signal-to-noise ratio at which both young and older participants would perform at similar levels of recall accuracy. Although signal-to-noise ratios varied, sentences were always presented at a normal (i.e., noncompressed) speech rate. Older participants heard 4 sentences in quiet and 4 sentences each at signal-to-noise ratios of −10.5, −9.0, −7.5, −6.0, −4.5, −3.0, 0, 3.0, and 9.0 dB (negative values indicate that the noise was louder than the speech signal, positive values indicate that speech was louder than noise, and a zero value indicates that the two were presented at the same intensity level). The young participants heard 4 sentences in quiet and 4 sentences each at signal-to-noise ratios of −15.0, −13.5, −12.0, −10.5, −9.0, −7.5, −6.0, −3.0, and 0 dB.

Sentences were blocked by signal-to-noise ratio and presented in a decreasing fashion (i.e., getting more difficult). The stimuli were prepared such that the average presentation level remained constant in spite of the changing signal-to-noise ratios (to decrease signal-to-noise ratio, we decreased the signal and increased the noise). Sentences used in the calibration session were counterbalanced in groups of four such that, by the end of the experiment, each group had appeared equally in all possible positions.

As in the previous experiments, following each sentence, participants were asked to recall as much of the sentence as possible and press a key when they were finished recalling. When participants were ready to hear the next sentence, they pressed a second key. Starting with the third ratio tested, participants were asked to define vocabulary words between ratios in an attempt to minimize potential adaptation that might occur during this initial calibration session. Recall was scored online by the researcher, and the ratio at which each participant's recall accuracy was closest to 30% was determined.

Following the calibration session, there was a break of approximately 10 min, during which participants underwent audiometric screening and performed digit span tasks. As in Experiment 1, this was done to reduce any adaptation that might have occurred during the calibration session before the beginning of the adaptation phase.

Adaptation phase. Participants received 10 trials, with two unique sentences per trial, at the signal-to-noise ratio determined during the calibration session to yield approximately 30% recall accuracy. As before, participants pressed a key to indicate they were finished recalling a sentence and a second key to initiate presentation of the next trial. Sentence recall was tape recorded for later analysis.

Results

The left panel of Figure 5 shows the recall accuracy for the young and older participants in the calibration session as a function

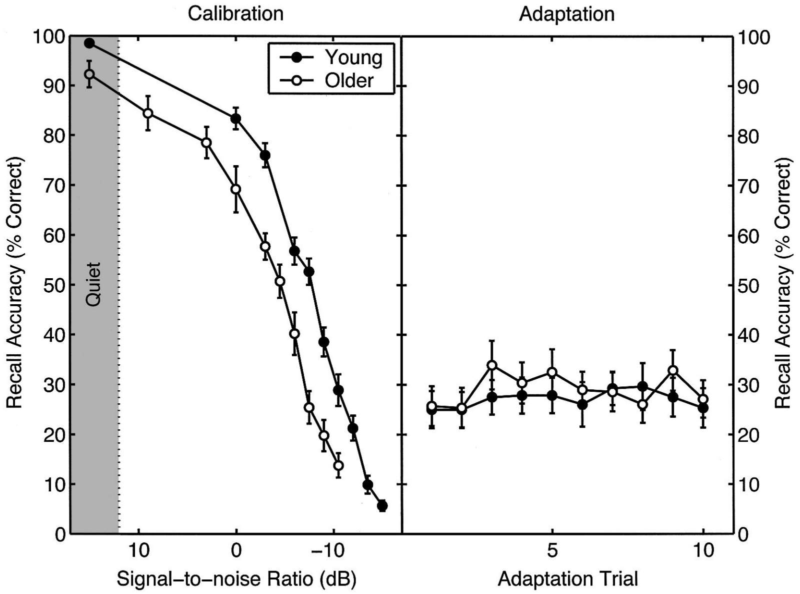

Figure 5. Recall accuracy for the calibration and adaptation phases of Experiment 4. Each adaptation trial consisted of two unique sentences. Error bars represent 1 standard error.

of decreasing signal-to-noise ratio. Analogous to the calibration session in Experiment 1 with time-compressed speech, both young and older participants' recall accuracy for the sentences decreased as signal-to-noise ratio was decreased. The mean of the signal-to-noise ratios required for the young participants to achieve 30% accuracy was −10.1 (*SD* = 1.1). For the older participants, the mean of the signal-to-noise ratios required for 30% accuracy was −6.8 (*SD* = 1.9), which was significantly higher than for the young adults, *t*(38) = 6.7, $p < .001$.

Adaptation curves for Experiment 4 are shown in the right panel of Figure 5. Although there was considerable variability in the data, it is apparent that there was no improvement in recall accuracy over the 10 trials for either group of participants. These data were submitted to a 10 (adaptation trial: 10 trials of two sentences each) × 2 (age: young, older) mixed design ANOVA. There was no main effect of adaptation trial, *F*(9, 342) < 1, *MSE* = 0.02, and no main effect of age, *F*(1, 38) < 1, *MSE* = 0.07, or Adaptation Trial × Age interaction, *F*(9, 342) < 1, *MSE* = 0.02. That is, when groups were equated for initial accuracy levels, there was no evidence of improved performance when speech was degraded to produce recall levels equivalent to those seen in Experiments 1–3.

Figure 6 shows the young and older participants' recall times (top two curves) and pacing times (lower two curves) for the adaptation phase. As before, the 20 presented sentences were grouped into 10 adaptation trials, with each trial containing 2 unique sentences. These data were analyzed via a 10 (adaptation trial: 10 groups of 2 sentences each) × 2 (age: young, older) mixed design ANOVA.

The recall times in response to noise-masked speech were marked by variability, with the ANOVA showing a main effect of adaptation trial on recall time, *F*(9, 342) = 2.59, *MSE* = 1,453,427.52, $p < .01$. Recall times appeared to be slightly longer for the older participants, but the main effect of age was not significant, *F*(1, 38) < 1, *MSE* = 55,403,487.57, nor was there an Adaptation Trial × Age interaction, *F*(9, 342) = 1.04, *MSE* = 1,453,427.52. Conducting the same ANOVA design on the pacing times showed a significant main effect of adaptation trial, *F*(9, 342) = 2.14, *MSE* = 509,510.75, $p < .05$, but no significant main effect of age, *F*(1, 38) < 1, *MSE* = 9,501,850.44, and no significant Adaptation Trial × Age interaction, *F*(9, 342) = 1.27, *MSE* = 509,510.75.

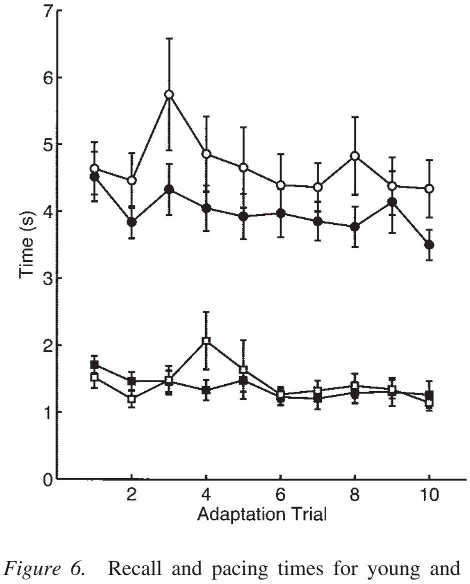

Figure 6. Recall and pacing times for young and older adults for the adaptation phase of Experiment 4. Each adaptation trial consisted of two unique sentences. Error bars represent 1 standard error.

Discussion

Experiment 4 shows that neither young nor older participants demonstrated any improvement in recall accuracy for noise-masked speech after exposure to 20 such sentences. Comparisons across different types of stimulus degradation must be made with care, even when these manipulations are matched for difficulty along a particular dimension, as in the current case. Our goal in the current experiment was to see whether familiarity with basic task demands, apart from stimulus-specific processing, resulted in improved performance over time. These general task requirements (hearing degraded sentences and recalling them) are consistent across experiments; thus, improvement based on familiarity should be evident regardless of the particular stimuli used. The lack of such improvement thus provides support for the argument that the adaptation observed in Experiments 1–3 was not simply due to task familiarity. Recall and pacing times, however, showed patterns that are similar to the experiments with time-compressed speech. This suggests that, unlike recall accuracy, the changes in those measures were due to practice with the general task and not related to perceptual learning.

Experiment 5

Our finding that listeners do not adapt to speech presented with broadband noise does not address the question of whether older adults are able to adapt to other forms of altered speech; their relative success adjusting to time-compressed speech suggests this might be possible. To more broadly assess older adults' capabilities of perceptual adjustment, we used another class of stimuli that have been used in auditory perceptual learning: spectrally shifted noise-vocoded speech.

Vocoding speech involves using a bank of analysis filters to extract the envelope of the speech signal at a given number of frequency bands. Each envelope is used to modulate white noise or sine waves, which results in a filtered signal with a nonspecific frequency. This signal, in turn, is passed through an output filter, which can be of any frequency. The resulting signals from each frequency band are then added together to synthesize a complete signal. Because frequencies for analysis and output filters are independent, speech information can be spectrally shifted. Although somewhat unnatural sounding, vocoded speech has been shown to be quite intelligible; using more frequency bands results in a more detailed (and thus more intelligible) signal (Davis & Johnsrude, 2003; Faulkner, Rosen, & Wilkinson, 2001).

Young adult listeners are known to be able to adapt to speech vocoded with a relatively small number of bands (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995) and vocoded speech that has been upwardly spectrally shifted (Rosen, Faulkner, & Wilkinson, 1999). In the current experiment, we used a large number of bands (16) to vocode the speech to minimize the distortion that resulted from the vocoding process. Speech vocoded with a large number of bands is completely intelligible when not spectrally shifted; thus, the primary loss of intelligibility is due to a change in the frequency at which information occurs rather than to a loss of spectral information. Finally, to minimize any impact of age-related hearing loss in higher frequencies (Morrell et al., 1996), we chose to shift the speech information downward.[1] In this way we were able to create stimuli whose difficulty was primarily due to a shift in the distribution of spectral information, in contrast to the temporal manipulations used in Experiments 1–3.

To avoid potential confounds due to an initial calibration session, we conducted pilot testing at various levels of spectral compression. The upper frequency of the output filters was systematically lowered along a logarithmic scale, and upper frequencies were determined that would approximately equate young and older adults for starting accuracy level, as in the previous experiments. None of the participants who ran in the pilot studies participated in the actual experiment.

Method

Participants

The young adult participants were 30 university students, 19 women and 11 men, with ages ranging from 18 to 21 years ($M = 18.5$, $SD = 0.8$). The young adults had a mean of 12.3 years of formal education at the time of testing ($SD = 0.6$) and a mean WAIS–III vocabulary score of 51.3 ($SD = 6.2$). The older adults were 30 healthy volunteers, 21 women and 9 men, with ages ranging from 65 to 79 years ($M = 73.9$, $SD = 3.1$). The older adults had a mean of 16.3 years of formal education ($SD = 2.3$) and a mean WAIS–III vocabulary score of 52.1 ($SD = 11.8$). Both groups thus were well educated and had good verbal ability, with the older group having an average of 4.0 more years of formal education, $t(58) = 9.2$, $p < .001$, and vocabulary scores equivalent to those of the young group, $t(58) = 0.4$, *ns*. All participants were native speakers of English.

Materials

Forty sentences similar to those used in Experiments 1–4 were constructed. Each sentence contained 10 words, 7 content words and 3 function words, and between 14 and 16 syllables. They were recorded by a female speaker of American English at an average rate of 200 wpm. As in Experiment 3, we presented short paragraphs (25–29 words, 18–20 content words, recorded at 158 wpm) before and after the adaptation trials to assess any potential effects of proactive interference.

All signal processing was carried out in MATLAB (Mathworks, Inc., Natick, MA) at a sampling rate of 44.1 kHz. The vocoding technique used was analogous to that of previous studies (e.g., Rosen et al., 1999; Shannon et al., 1995). The signal was first passed through a bank of 16 sixth-order Butterworth IIR analysis filters, having responses that crossed 3 dB down from the pass-band peak. These edge frequencies are shown in Table 3. For each band, the signal was half-wave rectified and low-pass filtered via a 2nd-order low-pass Butterworth filter with a cutoff of 320 Hz to extract the envelope. The envelope was then used to modulate broadband white noise; the resulting signal was then passed through an output filter (6th-order Butterworth IIR), with responses crossing 3 dB down from the pass-band peak as in the analysis filters. Edge frequencies of these output filters are shown in Table 3. One can spectrally shift information, as in the current experiment, by specifying frequencies for output filters that are lower than those of the input filters. Finally, information from each band was summed together to reform the speech signal. This final waveform was processed with a final low-pass filter at the frequency of the highest input filter (8000 Hz). This used a 6th-order elliptical filter forward and backward, resulting in the equivalent of a 12th-order elliptical filter with zero phase distortion.

Table 3

Edge Frequencies for Analysis and Output Filters Used in Experiment 5 Stimuli Creation

Band	Analysis frequency (Hz)	Output frequency (Hz)	
		Young	Older
1	150–192	150–179	150–180
2	192–247	179–214	180–217
3	247–316	214–256	217–260
4	316–405	256–306	260–313
5	405–520	306–366	313–376
6	520–666	366–437	376–451
7	666–854	437–522	451–542
8	854–1095	522–624	542–651
9	1095–1405	624–745	651–783
10	1405–1801	745–891	783–940
11	1801–2309	891–1065	940–1130
12	2309–2960	1065–1272	1130–1357
13	2960–3796	1272–1520	1357–1631
14	3796–4867	1520–1817	1631–1959
15	4867–6240	1817–2171	1959–2354
16	6240–8000	2171–2594	2354–2828

Procedure

The procedure was analogous to that used in Experiment 3. We gave participants instructions and presented them a single spectrally shifted sentence to familiarize them with the sound of spectrally shifted vocoded speech. They then heard the two short preadaptation paragraphs; after each paragraph, they repeated as much as possible. Participants were instructed to recall paragraphs without summarizing or using synonyms.

Following these two initial paragraphs, participants heard 40 spectrally shifted noise-vocoded sentences. As in the accuracy-matched groups in previous experiments, we presented young and older adults with sentences spectrally compressed to different levels to equate them for starting accuracy: Young adults heard spectrally shifted sentences with a top frequency of 2594 Hz, and older adults heard sentences with a top frequency of 2828 Hz (a lower top frequency indicates that the information has been spectrally shifted to a greater degree and thus is less intelligible). As before, following each sentence, participants recalled as much as possible of that sentence, pressing a key to indicate they were finished with their recall. Presentation of the next trial was initiated with a second keypress. There were no breaks during the 40 sentences, although participants were allowed to take as much time as they wanted between sentences. The sentences were counterbalanced in groups of 4 sentences, and across all participants each sentence group was presented in each possible position. Following presentation of the 40 adaptation sentences, listeners heard and recalled the two short postadaptation paragraphs. Across all participants, each paragraph occurred an equal number of times before and after the adaptation sentences.

Results

Figure 7 shows recall accuracy for the 40 presented sentences plotted as a function of 20 adaptation trials, with each trial con-

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[1] Because the number of bands remained constant across different spectral shifts, downwardly shifting the spectral information also resulted in a spectral compression of speech information. For our current purposes, it is not important whether the loss of intelligibility was due to the shifting of information or to spectral compression of information, as both involve manipulation of spectral characteristics of the speech rather than the temporal manipulations used in Experiments 1–3.

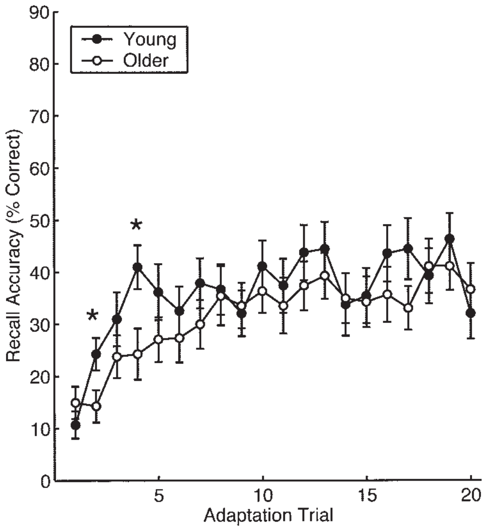

Figure 7. Recall accuracy for young and older adults in Experiment 5. Each adaptation trial consisted of two unique sentences. Error bars represent 1 standard error. $^{*}p < .05$.

taining 2 unique sentences. A visual inspection of these data indicates that both young and older listeners were able to adapt to spectrally shifted vocoded sentences. We submitted these adaptation data to a 20 (adaptation trial: 20 trials of 2 sentences each) × 2 (age: young, older) ANOVA. There was indeed a significant main effect of adaptation trial, $F(19, 1102) = 6.30$, $p < .001$, $MSE = 533.51$. However, young and older adults' performance did not differ, as indicated by the lack of a significant effect of age, $F(1, 58) = 1.60$, $MSE = 3640.40$, and the absence of an Age × Adaptation Trial interaction, $F(19, 1102) < 1$, $MSE = 533.51$. Post hoc *t* tests (uncorrected) revealed significant age differences at Adaptation Trials 2 and 4.

Participants' performance on the paragraph recall task was comparable before ($M_{\text{young}} = 43.4\%$ correct, $SD_{\text{young}} = 10.7\%$; $M_{\text{older}} = 41.6\%$ correct, $SD_{\text{older}} = 11.5\%$) and after ($M_{\text{young}} = 45.6\%$ correct, $SD_{\text{young}} = 11.5\%$; $M_{\text{older}} = 43.0\%$ correct, $SD_{\text{older}} = 10.8\%$) the adaptation trials. To determine whether participants' performance was influenced by proactive interference or fatigue, we conducted a 2 (training: before adaptation, after adaptation) × 2 (age: young, older) ANOVA on participants' recall scores. Although there was a slight trend toward increased accuracy following the adaptation trials, it was not significant, $F(1, 58) < 1$, $MSE = 73.48$. Young and older listeners' performance did not differ, $F(1, 58) < 1$, $MSE = 194.71$, and there was no Age × Training interaction, $F(1, 58) < 1$, $MSE = 73.48$.

Discussion

In Experiment 5, we have demonstrated that the characteristics of perceptual learning in older age observed in Experiments 1–3 are not specific to time-compressed speech. Rather than this sort of temporal manipulation, we manipulated the spectral content of the speech signal through vocoding and frequency shifting while leaving temporal information unaltered. Under these conditions, older adults again showed learning that was comparable in both rate and magnitude to that seen in young adults.

It should be noted that the similarities in improvement as listeners adapted to time-compressed speech or spectrally shifted vocoded speech do not necessarily imply similarity in the underlying mechanisms. Of primary relevance to the current question is the fact that the general characteristics of older adults' perceptual learning—namely, that it is comparable to that of young adults when equated for overall performance level—exists in multiple domains.

General Discussion

The current research demonstrates that older adults, like young adults, adapt to time-compressed speech. During initial exposure to time-compressed speech, the rate and magnitude of the older adults' improvement is comparable to that seen in young adults. However, older adults are impaired in their ability to transfer this learning to a second speech rate or retain it over time. This age dissociation suggests multiple components of perceptual learning that are differentially affected in normal aging.

Support for age-invariant initial adaptation to time-compressed speech is found in Experiments 2 and 3. In both experiments, which did not contain initial calibration sessions, there were no differences between young and older adults' recall over the first 10 adaptation trials when participants were matched for starting accuracy. This demonstrates the continuing ability of the perceptual system to normalize across changes in speech characteristics, despite the myriad perceptual and cognitive declines associated with older age.

The first evidence for an age dissociation in perceptual learning is found in Experiment 1, in which young adults were able to transfer learning on one speech rate to a second speech rate, whereas older adults were not. Subjectively, people listening to time-compressed speech report that uncompressed speech sounds very slow. On the basis of this observation, one might wonder whether these subjective reports are indicative of increased efficiency in speech comprehension. Although this appears to be true for young adults, the current results suggest that older adults' perceptual learning may exhibit a greater dependence on specific compression ratios. This is in general agreement with previous research with older adults that suggests that older adults exhibit greater specificity for some speech characteristics (e.g., Sommers, 1997).

The current studies also provide evidence consistent with a retention component of perceptual learning. As noted previously, removing the calibration session in Experiments 2 and 3 showed that accuracy-matched young and older adults adapted to time-compressed speech at the same rate. The difference in initial improvement during the adaptation phase of Experiment 1 can therefore be attributed wholly to participants' exposure during the calibration session—in particular, that young adults benefited from their exposure on the adaptation phase more than did older adults. The fact that in Experiment 1 perceptual learning was maintained to some degree despite a 10-min pause suggests a component of perceptual learning that lasts at least this long.

A final piece of evidence in favor of age-dissociable components to perceptual learning comes from the suggestion in Experiment 2 that young adults' recall accuracy continued to improve after 20 sentences, whereas older adults' improvement appeared to asymptote before this point. This was true for both accuracy-matched and rate-matched young adults and so appeared to be independent of speech rate. This finding challenges the previously held assumption that perceptual learning asymptotes by 20 presented sentences. However, we did not replicate this finding in Experiment 3, which used slightly different stimuli recorded by a different speaker. This suggestive finding warrants further investigation.

One important question is whether adaptation to time-compressed speech might be a simple consequence of task practice or strategy change rather than a result of perceptual learning. For example, over time, participants' criteria for guessing a degraded word might relax, such that they report more words at later adaptation trials than at earlier trials. Dupoux and Green (1997) investigated this issue by exposing participants to practice blocks of noncompressed speech, time-compressed speech, and speech in noise and then assessing all participants' recall accuracy on a test block of time-compressed speech. They found that only participants who received practice on time-compressed speech showed improved recall performance for the test block of time-compressed speech. However, the authors did not report whether practice with other versions of the task resulted in elevated accuracy scores, which would be an important part of the control condition. We addressed this issue in Experiment 4 by assessing participants' recall accuracy continuously throughout their exposure to sentences in noise. If participants' internal criteria for saying a word changed over time, we would expect the same response in the white noise condition as in the time-compressed speech condition. The absence of any improvement in the white noise condition indicates that this was not the case. The current results thus support the conclusions of Dupoux and Green (1997) that improvement in performance with exposure to time-compressed speech was not a consequence of improved task strategies.

In addition to demonstrating that older adults can adapt to speech manipulated in the time domain, we have also shown that, like young adults, older adults can adapt to speech manipulated in the frequency domain. In Experiment 5 we used spectrally shifted noise-vocoded speech and found that, as with time-compressed speech, older adults' learning was comparable to that of young adults. There was a suggestion that the young adults were able to adapt to spectrally shifted vocoded speech at a slightly faster rate than were the older adults. Because there was no calibration session, this cannot be attributed to previous exposure, as in Experiment 1. Most relevant to the current investigation is the finding that the overall magnitude of improvement for the two age groups was nearly identical, suggesting that different domains of auditory perceptual learning may be similarly preserved in normal aging.

Finally, it is important to note that we have focused on the similarity of young and older adults' short-term perceptual learning when they have been equated for starting accuracy level. When young adults hear sentences at the same speech rate as older adults, young adults perform significantly better. This is true not only for the overall level of recall accuracy, which is higher, but also for the initial rate of adaptation, which is faster than that seen in older adults. Thus, perceptual learning may help to mediate the challenge imposed on older adults by rapid speech, but not to a greater degree than for young adults.

In conclusion, the current data suggest that dissociable components of perceptual learning are differentially affected in normal aging. Although young and older adults did not differ in the rate or magnitude of initial perceptual learning, age-related declines were evident in the ability to retain the learning over a time course of minutes and in the ability to transfer this learning from one speech rate to a different rate.

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