Effects of Adult Aging and Hearing Loss on Comprehension of Rapid Speech Varying in Syntactic Complexity

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Abstract

Comprehension of spoken language by older adults depends not only on effects of hearing acuity and age-related cognitive change but also on characteristics of the message, such as syntactic complexity and presentation rate. When younger and older adults with clinically normal hearing and with mild-to-moderate hearing loss were tested on comprehension of short spoken sentences that varied in syntactic complexity, minimal effects of age and hearing were seen in comprehension of syntactically simpler sentences, even at rapid speech rates. By contrast, both age and hearing loss were associated with poorer comprehension for more syntactically complex sentences, and these differences were further exacerbated by increases in speech rate. These findings illustrate a dynamic interaction between age, hearing acuity, and characteristics of the spoken message on speech comprehension.

Key Words: Aging, hearing loss, speech comprehension, speech rate, syntactic complexity

Abbreviations: DPOAE = distortion-product otoacoustic emission; fMRI = functional magnetic resonance imaging; MCL = most comfortable listening level; PET = positron emission tomography; PTA = pure-tone average; wpm = words per minute

Sumario

La comprensión del lenguaje hablado en adultos mayores depende no sólo de los efectos de la agudeza auditiva y de los cambios cognitivos relacionados con la edad, sino también de las características del mensaje, tales como la complejidad sintáctica y la velocidad de presentación. Cuando adultos jóvenes y viejos con audición normal o con hipoacusias leves a moderadas, fueron evaluados en cuanto a la comprensión de frases cortas habladas que variaban en su complejidad sintáctica, se vieron mínimos efectos relacionados con la audición o la edad, en el manejo de la oraciones de mayor simpleza sintáctica, aún a velocidades rápidas del habla. En contraste, tanto la edad como la hipoacusia se asociaron con una comprensión más pobre para frases sintácticamente más complejas, y dichas diferencias se exacerbaron aún más conforme aumentó la velocidad del habla. Estos hallazgos ilustran una interacción dinámica para la comprensión del lenguaje, entre la edad, la agudeza auditiva, y las características del mensaje hablado.

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Palabras Clave: Envejecimiento, hipoacusia, comprensión del lenguaje, velocidad del habla, complejidad sintáctica

Abreviaturas: DPOAE = emisión otoacústica por producto de distorsión; fMRI = imágenes por resonancia magnética funcional; MCL = umbral de escucha más confortable; PET = tomografía por emisión de positrones; PTA = promedio tonal puro; wpm = palabras por minuto

In spite of its seemingly automatic nature, the comprehension of everyday speech challenges our perceptual and cognitive systems on a number of levels. One of these is the rate at which speech arrives. While speech in thoughtful conversation may be as "slow" as 90 words per minute (wpm), average speech rates in ordinary conversation vary between 140 and 180 wpm, and a radio or television newsreader working from a prepared script can easily exceed 210 wpm (Stine et al, 1990). In addition to low-level processing of this rapidly changing acoustic signal, speech comprehension regularly requires the involvement of higher-level cognitive processes. Natural speech is often underarticulated to the degree that many words in fluent discourse would be completely unintelligible were it not for listeners' ability to rapidly factor in the surrounding linguistic context (Pollack and Pickett, 1963; Hunnicutt, 1985; Lindblom et al, 1992; Wingfield et al, 1994). The sentences in spoken discourse are also not necessarily delivered in a simple canonical form with uncomplicated syntax.

These challenges can create special difficulty for older adults. An important issue is the frequent occurrence of an age-associated decline in peripheral and central auditory processing capabilities that can significantly affect the perception of speech (Humes, 1996; Morrell et al, 1996). This is especially so when the speech is rapid, degraded, or heard in noise (Schneider and Pichora-Fuller, 2000). In addition to these sensory changes, however, a general slowing of perceptual and cognitive operations and reductions in working memory capacity are also hallmarks of the aging process (Wingfield et al, 1988; Kausler, 1994; Salthouse, 1994, 1996). ("Working memory" refers to the ability to hold and manipulate information in immediate memory [Just and Carpenter, 1992; Baddeley, 1996].)

The former factor (perceptual and cognitive slowing) contributes to older adults' well-known difficulty with especially rapid speech (Sticht and Gray, 1969; Konkle et al, 1977; Letowski and Poch, 1996; Wingfield, 1996; Gordon-Salant and Fitzgibbons, 1997), and the latter factor (a decline in working memory efficacy) contributes to older adults' greater difficulty with deconstructing syntactically complex speech (Davis and Ball, 1989, Kemper, 1992; Kemtes and Kemper, 1997). Indeed, when older adults are subjected to rapid speech with complex syntax, the combined effects on spoken sentence comprehension have been shown to be multiplicative (Wingfield et al, 2003).

Because linguistic knowledge and the procedural rules for its application are well preserved in older adulthood (see Wingfield and Stine-Morrow, 2000, for a review), older adults' difficulties with single word identification can be significantly reduced when these words are heard in a sentence context (e.g., Wingfield et al, 1991; Pichora-Fuller et al, 1995; Gordon-Salant and Fitzgibbons, 1997; Dubno et al, 2000). On the negative side, however, audiometric testing for speech can also underestimate the effects of age and hearing loss when listeners are confronted by speech with cognitively demanding syntactic structures, as often happens in everyday life. This may be one of the number of reasons why formal audiometric testing does not always correlate with older adults' everyday listening experience.

To understand the cognitive burden syntactic complexity can impose for successful comprehension of even short sentences, consider a syntactically simple sentence consisting of two clauses connected by the conditional "when." An example might be, "Boys are caring when they help girls." As the sentence unfolds in time, one processes the first clause, "boys are caring," then the modifying clause, "when they help girls," and then integrates the two to give the full sentence its meaning.

Occasionally, however, one can encounter a sentence with the meaning expressed in the form of an abbreviated but still relatively simple structure using a center-embedded clause. Such a sentence, referred to as a subject-relative center-embedded clause sentence (subject-relative clause sentence) might be, "Boys that help girls are caring." In this sentence form, the main clause frame ("Boys are caring") is interrupted by the relative clause ("that help girls"). In this case there is an added burden of retaining the embedded clause, processing the main clause, and then integrating the two. Because of the rapidity of ordinary speech, this syntactic operation must be conducted on a potentially fading memory trace of what has been heard (Zurif et al, 1995).

Although subject-relative clause sentences may add a burden to the comprehender's working memory resources, an object-relative center-embedded clause sentence (object-relative clause sentence), such as "Boys that girls help are caring," represents an even greater burden. This is so because in object-relative clause sentences the relative clause not only interrupts the main clause, but the head noun phrase functions as both the subject of the main clause and the object of the relative clause. This construction adds two levels of difficulty. Because the thematic roles in object-relative clause sentences are not canonical, they require extensive thematic integration in contrast to the more canonical subject-relative clause sentences (Warren and Gibson, 2002). In addition, to determine these thematic roles, one must keep the subject of the sentence in mind for a longer time than in subject-relative clause sentences (Cooke et al, 2002).

This added processing complexity associated with object-relative clause sentences is known to produce more comprehension errors than subject-relative clause sentences, even for young adults (Just et al, 1996; Cooke et al, 2002). This syntactic complexity effect has been shown to be differentially greater for older adults, both in terms of comprehension errors (Wingfield et al, 2003) and slower patterns of self-pacing of recorded speech when one is allowed to control the input rate (Waters and Caplan, 2001; Fallon et al, 2006). That this processing difference reflects a demand on central cognitive resources independent of input domain can be seen in parallel findings for visual presentations in which object-relative clause sentences produce slower reading times and more comprehension errors than less complex subject-relative clause sentences for young adults (e.g., Just et al, 1996), and especially so for older adults (Stine-Morrow et al, 2000).

Similar findings of extra processing effort being required for comprehension of linguistically complex materials (such as with object-relative clause sentences as compared to subject relative clause sentences), have also appeared in neuroimaging studies, suggesting that this effect is a fundamental one. For example, in PET (positron emission tomography) and fMRI (functional magnetic resonance imaging) studies, one sees increased patterns of cortical neural activation in the anterior left hemisphere language areas for object-relative clause sentences relative to subject-relative clause sentences for both written (Just et al, 1996; Caplan et al, 1998; Cooke et al, 2002) and spoken (Caplan et al, 1999; Peelle et al, 2004) presentations.

The target population in this study was older adults in good health and with good levels of education and verbal ability but who have mild-to-moderate hearing loss. None of the participants in this study regularly used hearing aids. This target population is a large one as it has been estimated that two out of three older adults with hearing loss do not regularly use hearing aids, with these numbers especially large in the mild hearing loss range (National Academy on an Aging Society, 1999).

In the present experiment, we used a four-group design to examine the effects of age and hearing loss on comprehension of spoken sentences that differed in syntactic complexity. For this purpose we identified younger and older adults with clinically normal hearing and a comparison group of young and older adults with mild-to-moderate hearing loss. A contrast between the participants with good and poor hearing matched for age would show the effects of hearing acuity on comprehension accuracy, while a comparison of the younger and older participants matched as nearly as possible on hearing acuity would show the effects of age.

The syntactic contrast we chose to use was the two well-studied syntactic forms described above: sentences containing either a subject-relative or an object-relative center-embedded clause (e.g., Just and Carpenter, 1992; Stine-Morrow et al, 2000; Vos et al, 2001; Cooke et al, 2002). In all cases, the sentences would have either a male (e.g., boy, uncle, king) or a female (e.g., girl, aunt, queen) character performing the action. The participant's task would be to listen to each sentence and, as soon as it had finished, to indicate with a key-press the gender (male/female) of the person performing the action. This method has been used successfully in past studies as a measure of sentence comprehension (e.g., Cooke et al, 2002; Wingfield et al, 2003; Peelle et al, 2004).

In order not to penalize doubly older adults by using very long sentences that might especially tax immediate memory, we constructed subject-relative and object-relative clause sentences that were only six words in length. In so doing we hoped to focus on the computational complexity of object-relative versus subject-relative clause sentences and the sentence-processing resources involved in immediate interpretive analysis (see Caplan and Waters, 1999).

In addition to syntactic complexity, we used time compression of the speech signal to vary the perceptual challenge of the heard sentences. The difficulty young and older adults experience with time-compressed speech can arise from two levels. One of these is the loss of signal richness and truncation of the rapid transient regions of the speech signal, especially with higher degrees of compression (Heiman et al, 1986; Janse, 2003). This would be expected to place a heavier processing burden on older adults with age-related peripheral hearing loss and/or central auditory processing deficits in the form of decreased efficiency in temporal and spectral resolution (Humes et al, 1992; Schneider and Pichora-Fuller, 2000). The second is the loss of ordinarily available processing time at the linguistic-cognitive level. This factor might especially challenge older adults who may need more time than younger adults for effective syntactic parsing, semantic integration, and the assignment of thematic roles. This latter point is supported by studies that show that older adults' recall of time-compressed speech can be made to match that of uncompressed speech if pauses are inserted at linguistically important points to allow the older adult time to "catch up" in their processing (Wingfield et al, 1999; see also Gordon-Salant and Fitzgibbons, 1997; Wingfield and Ducharme, 1999). It is likely that both of these factors contribute to the extra difficulty older adults have with rapid or time-compressed speech.

A major motivation for this experiment was the many reports in the literature that the differential effect of time compression on older relative to younger adults operates independently of hearing loss. In these studies the test subjects have been young and older adults with similar audiometric profiles in the speech frequency range (e.g., Gordon-Salant and Fitzgibbons, 1993; Letowski and Poch, 1996; Wingfield et al, 2003). It may follow from the above arguments, however, that significant effects of both age and hearing loss may appear when the processing demands are increased by both speech rate and by the syntactic complexity of the speech material.

Our experimental question was whether one would see exactly parallel declines in comprehension accuracy for younger and older adults with good and with poor hearing as processing load is increased by increasing speech rate and syntactic complexity. Alternatively one might see effects of both age and hearing, but with the performance functions of young and older adults with good and poor hearing diverging as the processing load is increased by both speech rate and syntactic complexity. The former finding would suggest independent contributions from aging and hearing loss on sentence processing. The latter finding would suggest that comprehension performance is mediated by a dynamic interplay of the effects of age, cognitive load, and hearing acuity operating in a multiplicative fashion on listener performance.

METHODS

Participants

A total of 40 participants took part in this study. All were tested audiometrically (air and bone conduction) to insure that the hearing losses in the hearing-impaired participants were sensorineural in nature. The audiometric evaluations were carried out using a GSI 61 audiometer (Grason-Stadler, Inc., Madison, WI) by way of standard audiometric techniques in a sound-attenuated testing room. Following otoscopic examination by an audiologist trained in otoscopy, tympanometry was conducted on all participants using the GSI 38 Auto Tymp (Grason-Stadler, Inc., Madison, WI) to document middle ear integrity and to help rule out conductive hearing loss. All participants met a criterion of middle ear pressure of no worse than -150 daPa and normal static compliance and gradient.

Distortion-product otoacoustic emissions (DPOAEs) were obtained for each participant using the AuDx (Bio-logic Systems Corp., Mundelein, IL) to help confirm cochlear hearing loss and to reject participants with possible auditory neuropathy (Starr et al, 1996). All participants were native speakers of American

English with good levels of education and verbal ability (see below) and all reported themselves to be in good health, with no known history of stroke or dementing illness.

The 40 participants were divided into four groups of ten participants each based on age (younger adults vs. older adults) and hearing status in the speech range (clinically normal hearing vs. mild-to-moderate hearing loss). Clinically normal hearing for speech was defined as a pure-tone average (PTA) for 1000, 2000, and 4000 Hz of less than 25 dB HL in the better ear (Hall and Mueller, 1997). As will be seen below, the four groups were well matched on years of formal education and verbal ability.

Young Adults with Clinically Normal Hearing

The ten younger adults with normal hearing ranged in age from 18 to 41 years (M = 27.2 years, SD = 7.1) and had a mean PTA (1000, 2000, 4000 Hz) in the better ear of 3.7 dB HL (SD = 2.1). As indicated, all participants in this and the other three groups were well educated and had good verbal ability. The group had a mean of 16.6 years of formal education (SD = 2.9) and good verbal ability as assessed by the Shipley Vocabulary Test (Zachary, 1986), with a mean score of 15.2 (SD = 1.5).

Older Adults with Clinically Normal Hearing

The ten older adults with clinically normal hearing ranged in age from 68 to 78 (M = 74.1 years, SD = 3.6) and had a mean PTA in the better ear = 13.8 dB HL (SD = 3.4). Although the older group had on average higher PTAs than the younger adults, $t(18) = 5.12$, $p < .001$, as indicated above, all fell within the range considered to be clinically normal for speech (Hall and Mueller, 1997). The older adults did not differ significantly from the younger adults in either years of formal education (M = 15.0, SD = 1.9), $t(18) = 1.45$, n.s., or in Shipley vocabulary scores (M = 15.9, SD = 2.0), $t(18)$ = 0.87, n.s.

Young Adults with Hearing Impairment

The ten younger adults with hearing impairment ranged in age from 19 to 39 years (M = 26.2 years, SD = 6.8), which did not differ significantly from the ages of the younger normal-hearing group, $t(18) = 0.32$, n.s. The young hearing-impaired group had a mean PTA in the better ear = 37.5 dB HL (SD = 7.5). They had a mean of 15.8 years of formal education (SD = 1.2), which did not differ significantly from either the younger normal-hearing group, $t(18) = 0.80$, n.s., or the older normal-hearing group, $t(18) = 1.10$, n.s. Their Shipley vocabulary scores (M = 14.3, SD = 1.2) also did not differ significantly from either the younger normal-hearing group, $t(18) = 1.34$, n.s., or the older normal-hearing group, $t(18)$ = 2.01, n.s.

Older Adults with Hearing Impairment

The ten older adults with hearing impairment ranged in age from 69 to 78 years (M = 74.7, SD = 2.9), which did not differ significantly from the older normal-hearing group, $t(18) = 0.41$, n.s. The older hearing-impaired group had a mean PTA = 32.2 dB HL (SD = 5.3), which did not differ significantly from the young hearing-impaired group, $t(18)$ = 1.83, n.s. They had a mean of 15.3 years of formal education (SD = 2.2), which did not differ significantly from the young normal-hearing group, $t(18) = 1.13$, n.s., the older normal-hearing group, $t(18) = 0.33$, n.s., or the younger hearing-impaired group, $t(18) = 0.64$, n.s. The older poor-hearing group had a mean Shipley vocabulary score of 14.8 (SD = 2.2), which did not differ significantly from either the young normal-hearing group, $t(18) = 0.47$, n.s., the older normal-hearing group, $t(18)$ = 1.16 , n.s., or the younger hearing-impaired group, $t(18) = 0.56$, n.s.

Stimulus Materials

The stimuli, which were taken from Wingfield et al (2003), were constructed from 56 meaningful, six-word English sentences with subject-relative clause structures. For each of these sentences, a counterpart sentence was constructed that had the same words and characters performing the action as the original, but with an object-relative clause syntactic structure. To control for any bias as to whether a male or a female might be performing a particular action, two versions were constructed for each of these sentences: in one a male performed the action, and in a second version a female performed the action. This procedure resulted in a total of 224 sentences, 56 of each of the following types:

1. Subject-relative clause, male agent: "Men that assist women are helpful."
2. Object-relative clause, male agent: "Women that men assist are helpful."
3. Subject-relative clause, female agent: "Women that assist men are helpful."
4. Object-relative clause, female agent: "Men that women assist are helpful."

In the first two sentences a male is performing the action: *assisting*. In the second two sentences a female is performing the action: *assisting*. Thus, within the 224 sentences, an equal number of sentences had either a subject-relative or an object-relative structure, and each of these had counterparts where either a male (e.g., uncle, brother) or a female (e.g., aunt, sister) character was the agent of the action.

All of the sentences were recorded by a female speaker of American English at a fast-normal average speech rate of 205 wpm and then time compressed to 80%, 65%, and 50% of original speaking time (corresponding to 258, 321, and 410 wpm respectively) using SoundEdit software (Macromedia, Inc., San Francisco, CA). The time compression was accomplished using the sampling method of time compression in which the sound-editing software removes a certain proportion of the signal at regular intervals, depending on the compression ratio specified. For example, to compress a passage to 75% of its original playing time, every fourth piece of data in the sound signal would be removed. Because each second of the digitized speech contains 44,100 pieces of data, only very small pieces of the speech signal are removed in the sampling procedure, thus minimizing distortion and maintaining the original pitch contour of the sentence.

This equal-sampling method of time compression deletes small segments to a proportionally equal degree from all parts of words and brief silent periods that occur in sentences. One could alternatively use a nonlinear method of time compression in which only steady-state portions of words (e.g., extended vowels) are compressed and/or selective removal of any silent periods that may occur between words. At the word-level differential compression of steady-state portions can produce greater intelligibility than the uniform compression method used here (Moore et al, 1992; Gordon-Salant and Fitzgibbons, 1993; but see Janse et al, 2003). Our choice of uniform compression was predicated on our wish to preserve the relative temporal patterning of natural speech, where features such as brief pauses at clause boundaries and the lengthening of clause-final words can serve as cues to syntactic parsing and comprehension at the sentence level (Shattuck-Hufnagel and Turk, 1996; Kjelgaard et al, 1999; Janse et al, 2003).

Procedures

Each participant heard all 224 sentences, 112 subject-relative clause sentences, and 112 objective-relative clause sentences, with half of the subject-relative and half of the object-relative sentences having a male as the agent of the action and half having a female as the agent of the action. Fifty-six sentences (28 subject-relative and 28 object-relative, half with a male agent and half with a female agent) were presented at each of the four speech rates: the original 205 wpm rate (100% of original speaking time), and reduced to 80%, 65%, and 50% of the original speaking time (i.e., 258, 321, and 410 wpm). Speech rate presentations were blocked, with the order of speech rate presentations varied across participants. The particular sentences heard at each speech rate were also varied between participants.

In listening research there is always a choice of intensity level to be used: whether to present speech at each participant's personally selected level (MCL [most comfortable listening level]), at an intensity level relative to the individual or group's PTA (SL [dB sensation level]), or at the same absolute intensity level for all participants (HL [dB hearing level]). Each has its advantage for research, with a dB *HL* equivalent to levels typically encountered in ordinary conversational speech having arguably the greatest degree of real-world validity. For this present study, two intensity levels were employed. These were 60 dB HL and 75 dB HL selected to span the range of normal to moderately loud conversational speech in a quiet environment (CHABA, 1988). Within each speech-rate condition, half of the sentences were heard at 60 dB HL and half at 75 dB HL, with the sentences in the two intensities presented in a blocked design. The order in which stimuli at the two intensity levels were heard and the particular sentences heard at each intensity level and each speech rate within levels were varied between participants.

Participants were tested individually in a sound-attenuated testing room, with the stimulus sentences presented monaurally to the participant's better ear using Eartone 3A (E-

A-R Auditory Systems, Aero Company, Indianapolis, IN) insert earphones. The stimuli, which were prepared and stored as computer sound files, were presented via a GSI 61 audiometer (Grason-Stadler, Inc., Madison, WI) using Psyscope presentation software (Cohen et al, 1993).

Participants were instructed to listen to each sentence carefully and as soon as it was finished to press one of two appropriately labeled keys to indicate the gender of the character (male/female) performing the action. Participants were asked to give a response for each sentence; if unsure, instructions were to attempt one's best judgment. The main experiment was preceded by a brief practice session with feedback to ensure that the instructions were understood and to familiarize participants with the sound of time-compressed speech and the two intensity levels that would be used. Both subject-relative and object-relative clause sentences were presented in this practice session. None of these practice sentences was used in the main experiment.

RESULTS

The results of the experiment are summarized in Figure 1, which shows the mean percentage correct gender judgments for the four participant groups for sentences heard at each of the four speech rates tested. Data for the subject-relative clause sentences are shown in the left panel, and data for the object-relative clause sentences are shown in the right panel. As consistent with prior studies of both written (e.g., Just and Carpenter, 1992; Vos et al, 2001) and spoken (e.g., Wingfield et al, 2003; Peelle et al, 2004) sentences, one can see that object-relative clause sentences have generally lower comprehension scores than the subject-relative clause sentences. (Figure 1 shows the data collapsed across the two intensity levels as the two levels had no significant main effect on comprehension accuracy, nor did intensity interact with age, syntactic complexity, or speech rate.)

Subject-Relative Sentences

As can be seen in the left panel, although comprehension began to decline with faster speech rates, and especially so for the hearing-impaired participants, comprehension accuracy for these syntactically simpler subject-relative clause sentences remained above 85% correct even for the fastest speech rate. These trends were confirmed using a 2 (Hearing: normal, impaired) x 2 (Age: younger, older) x 4 (Speech rate: 100, 80, 65, 50% of original speaking time) mixed-design analysis of variance (ANOVA), with speech rate as a within-participants variable.

As implied by visual inspection of the left

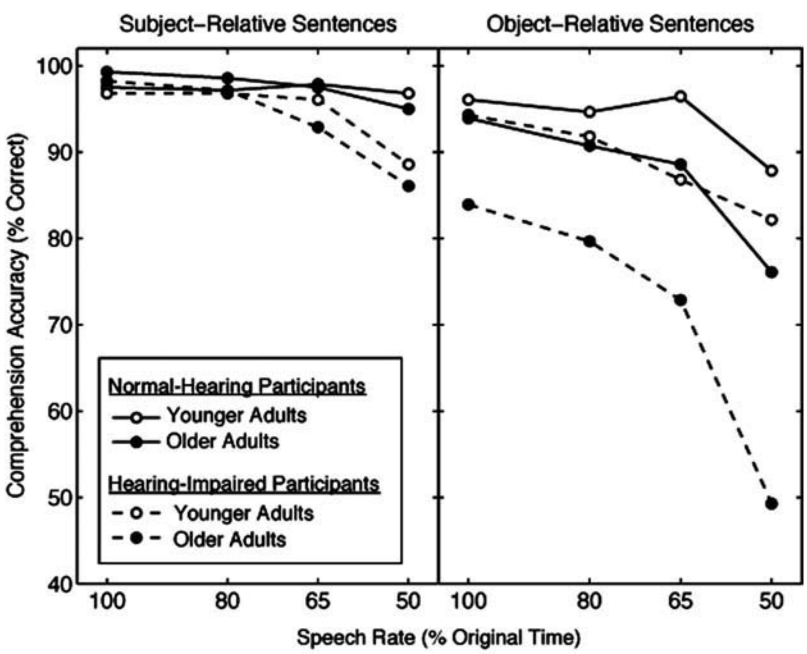

Figure 1. Comprehension accuracy for subject-relative clause sentences (left panel) and object-relative clause sentences (right panel) as a function of speech rate expressed as a percentage of original speaking time. Data are shown for young (open symbols) and older (closed symbols) adults with clinically normal hearing in the speech range (solid lines) and young and older adults with hearing impairment (broken lines).

panel of Figure 1, there was a significant main effect of hearing acuity, $F(1,36) = 9.99$, MSE = 46.11, $p < .005$, although this was most noticeable at the higher compression ratios. There was also a significant main effect of speech rate, $F(3,108) = 17.04$, MSE = 19.45, $p < .001$, reflecting a general decline in comprehension accuracy as speech rates increased. A significant Hearing × Speech rate interaction, $F(3,108) = 6.75$, MSE = 19.45, $p < .001$, however, confirmed that this effect of speech rate was differentially greater for the hearing impaired relative to the better-hearing participants. For these simpler subject-relative clause sentences, there was no main effect of age, $F(1,36) < 1$ (MSE = 46.11). Although there is a suggestion of the effect of hearing loss and speech rate being somewhat greater for the older than for the younger adults, neither the Hearing × Age, $F(1,36) < 1$ (MSE = 46.11) nor Age × Speech rate, $F(3,108) = 1.83$, n.s. (MSE = 19.45), interactions reached significance. Nor was there a significant Hearing × Age × Speech rate interaction, $F(3,108) < 1$ (MSE = 19.45).

Object-Relative Sentences

A marked contrast can be seen when the sentences were more syntactically complex, as shown in the right panel of Figure 1 for the object-relative clause sentences. In this case, most of the trends observed with the simpler subject-relative sentences now became significant. There were significant main effects on comprehension accuracy of hearing acuity, $F(1,36) = 10.36$, MSE = 421.45, $p < .005$, of age, $F(1,36) = 13.38$, MSE = 421.45, $p < .005$, and of speech rate, $F(3,108) = 47.79$, MSE = 53.82, $p < .001$. As with the subject-relative clause sentences, a significant Hearing × Speech rate interaction, $F(3,108) = 4.43$, MSE = 53.82, $p < .01$, reflected the finding that increasing the speech rate had a differentially greater impact on the hearing-impaired than on the better-hearing participants. With these more complex sentences, one now also observes a significant Age × Speech rate interaction, $F(3,108) = 9.69$, MSE = 53.82, $p < .001$, reflecting the frequently reported finding that rapid speech rates differentially affect older adults' performance for both recall and comprehension (see reviews in Wingfield, 1996; Gordon-Salant and Fitzgibbons, 1997). Indeed, at the fastest speech rate tested (50% compression), the older hearing-impaired participants attempting to process object-relative clause sentences were performing at approximately chance level.

In contrast with the subject-relative clause sentences, visual inspection of the right panel of Figure 1 suggests that with these more complex object-relative clause sentences, the effect of hearing loss tended to be greater for the older adults than for the younger adults. ANOVA showed marginal Hearing × Age, $F(1,36) = 2.82$, $p = .10$ (MSE = 421.45), and Hearing × Age × Rate interactions, $F(3, 108) = 2.19$, MSE = 53.82, $p = .09$. In view of these marginal interactions, we conducted a 2 (Hearing) × 2 (Age) simple effects ANOVA on just the comprehension data for the fastest (50% compression) speech rate. This analysis confirmed main effects of hearing, $F(1,36) = 12.10$, MSE = 218.29, $p < .005$, of age, $F(1,36) = 22.83$, MSE = 218.29, $p < .001$, and now a significant Hearing × Age interaction, $F(1,36) = 5.09$, MSE = 218.29, $p < .05$, showing that the effects of age were compounded by hearing loss when the task was sufficiently difficult.

DISCUSSION

As Gordon-Salant and Fitzgibbons (1997) have pointed out, some research on speech understanding in older adulthood has emphasized the importance of cognitive factors as well as auditory factors in adult aging (e.g., Jerger et al, 1989; van Rooij and Plomp, 1990) while other research has suggested that cognitive factors in aging are minimal in speech understanding relative to auditory factors (e.g., Humes et al, 1994; Humes, 1996; Schneider et al, 2005).

In part, these mixed opinions may be due to the types of cognitive tests used from one study to the next: some tests may be more sensitive to age differences than others, some may test different aspects of cognitive function, and many cognitive tests have been shown to have poor reliability (Salthouse, 1991). In the present experiment, we took a different approach to cognitive and auditory factors in speech understanding by using as participants healthy, active young and older adults with good levels of education and verbal ability but using speech materials that are known to differ significantly in their cognitive demands. It can be seen, for example, that when the linguistic processing task was increased in difficulty, hearing loss played a larger role in performance than when the syntactic form was less computationally complex. The same is true for effects of speech rate and age.

It is especially important to note that the syntactic difficulty effect in these results occurred with very short six-word sentences, and that the contrasting subject-relative and object-relative clause syntactic pairs shared the same words. They differed only in whether the meaning was conveyed using a more or less canonical word order. The syntax effect can thus be attributed to the greater computational burden of an object-relative clause sentence versus a subject-relative clause sentence as generally argued in psycholinguistic theory (Just and Carpenter, 1992; Just et al, 1996; Warren and Gibson, 2002).

Looking at just comprehension performance for the syntactically simpler subject-relative clause sentences heard at a fast-normal speech rate would lead one to conclude that neither age nor hearing loss in the mild-to-moderate range has a significant effect on speech comprehension. Participants were at or near a ceiling of performance in both cases. Looking at more linguistically complex object-relative clause sentences, especially with faster speech rates, however, would lead one to the opposite conclusion. The current results thus suggest that both age-limited cognitive factors and hearing acuity are important in speech comprehension but that their effects may not appear until some threshold of processing difficulty has been crossed.

It should be noted that our stimuli (six-word sentences) and task (judging the agent of an action) were especially chosen to minimize the role of memory ability that one might expect would put older adults at a special disadvantage (Kausler, 1994; Wingfield and Kahana, 2002). Had longer, more propositionally dense speech materials been employed, one might expect to see the effects of age, hearing, and speech rate to be amplified. Thus, to the question of whether age, cognitive limitations, and hearing status affect speech comprehension, one should include the question of the nature of the language materials and task, and the potential balance between older adults' well-established ability to use linguistic context to mitigate perceptual and memory declines on the one hand (e.g., Wingfield et al, 1991; Wingfield et al, 1994; Pichora-Fuller et al, 1995; Gordon-Salant and Fitzgibbons, 1997), and age-limited working memory resources with which to deal with especially complex syntax on the other (e.g., Carpenter et al, 1994; Kemtes and Kemper, 1997).

To find a significant effect of age beyond effects of peripheral hearing acuity does not in itself identify the source of the age effect and its interaction with rapid speech. In part these effects may arise from higher-level auditory processing deficits, such as age-related reductions in efficiency of temporal and spectral resolution (Schneider and Pichora-Fuller, 2000). Although the anatomic loci of such deficits may remain a matter of dispute (Humes et al, 1992), there is no question that efficient temporal and spectral processing are critically important for speech perception in general and for the processing of rapid speech in particular. Such effects, of course, would be equivalent whether a participant is hearing sentences with simpler or more complex syntax.

There have been arguments in the literature that the need for greater perceptual effort for successful perception by individuals with hearing loss may come at the cost of processing resources that would ordinarily be available for higher level comprehension operations, and when required, encoding of the materials in memory (Rabbitt, 1991; Murphy et al, 2000; McCoy et al, 2005). The minimal effects of hearing loss for the simpler subject-relative clause sentences at the less rapid speech rates for both the younger and older participants should thus not imply that, even under these conditions, hearing loss necessarily has no effect on downstream cognitive operations such as memory for what has been heard or higher-level comprehension operations at the discourse level. That is, the perceptual success as observed here for the easier conditions may still have come at a cost to processing resources that would otherwise be available for other, postperceptual, downstream cognitive operations (Rabbitt, 1968, 1991; Wingfield et al, 2005).

This limited-resource and effort argument may underlie the present finding that age differences will appear when the processing load is increased either by syntactic complexity of the speech materials, reduced hearing acuity, or both. Such difficulties would be expected for older adults, where working memory capacity and processing speed are rarely equivalent to that of younger adults (Kausler, 1994; Salthouse, 1994, 1996). It would also follow that young adults with hearing loss would show special difficulty with syntactically complex materials and increased speech rates, albeit to a lesser degree, as we observed here. Taken together, the present results suggest that neither age-related cognitive constraints, nor peripheral hearing acuity alone, will give the full picture for individuals' effectiveness in sentence comprehension.

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