Published in final edited form as:

Psychol Aging. 2010 September ; 25(3): 730–735. doi:10.1037/a0019300.

Response Latencies in Auditory Sentence Comprehension: Effects of Linguistic versus Perceptual Challenge

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Abstract

Older adults with good hearing and with mild-to-moderate hearing loss were tested for comprehension of spoken sentences that required perceptual effort (hearing speech at lower sound levels), and two degrees of cognitive load (sentences with simpler or more complex syntax). Although comprehension accuracy was equivalent for both participant groups, and for young adults with good hearing, hearing loss was associated with longer response latencies to the correct comprehension judgments, especially for complex sentences heard at relatively low amplitudes. These findings demonstrate the need to take into account both sensory and cognitive demands of speech materials in older adults' language comprehension.

Understanding spoken language is such a common everyday activity that we often fail to appreciate the complexity of a task that requires a rapid dynamic interplay of both perceptual and cognitive operations. These operations include decoding the speech signal into phonemes, determining lexical identity, and syntactically parsing the speech input to yield a semantically meaningful representation in working memory. These operations, furthermore, must be conducted rapidly as the speech is arriving in real time. Because of the limits in processing speed and attentional capacity associated with adult aging (Bopp & Verhaeghen, 2005; Fisk & Sharp, 2004; Salthouse, 1991, 1996), it should thus not be surprising that older adults lose efficiency in sentence comprehension (Burke & Shafto, 2008).

In addition to age-related limits in cognitive factors, it has been estimated that more than 80% of adults over the age of 70 have some degree of hearing loss (e.g. Cruickshanks, et al., 1998; Davis, 1990; Gordon-Salant, 2005). Hearing loss may not only cause a listener to miss words in speech or result in an impoverished representation in memory (Surprenant, 1999; Surprenant, Neath, & Brown, 2003). There are also suggestions that perceptual effort, whether caused by the presence of background noise (Murphy, Craik, Li & Schneider, 2000; Rabbitt, 1968) or hearing loss (Rabbitt, 1991; Wingfield, Tun & McCoy, 2005), can have a negative impact on memory even when the to-be-recalled words themselves could be correctly identified.

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This latter finding can be characterized in terms of an *effortfulness hypothesis*: the suggestion that losses in auditory acuity may require the listener to invest extra effort in early stage perceptual processes, thus draining resources that might otherwise be available for comprehension and encoding of what has been heard in memory (Pichora-Fuller, 2003; Rabbitt, 1991; Tun, McCoy & Wingfield, 2009; Wingfield et al., 2005). Consistent with this hypothesis, work in our laboratory has shown that, relative to older adults with good hearing, an age-matched group with mild-to-moderate hearing loss had poorer recall for words heard in a running memory task, even though a perceptual check insured that the words could be correctly identified at the intensities at which they were presented (McCoy et al., 2005). It has also been shown that even a relatively mild hearing loss can compound the effects of rapid speech rates and syntactic complexity in older adults' comprehension of spoken sentences (Wingfield, McCoy, Peelle, Tun & Cox, 2006).

In the above-cited studies, the effects of perceptual effort associated with age-related hearing loss were evidenced in poorer comprehension and/or memory performance relative to younger and older adults with good hearing. This raises the question of whether one may observe downstream effects of effortful perception even in a case where comprehension has nevertheless been successful. In order to investigate this question we selected a sentence comprehension task that would be made to vary in both perceptual and linguistic difficulty while still allowing for correct comprehension. Our question was whether conditions of increased early-stage perceptual difficulty might slow the production of these comprehension responses, relative to conditions representing a reduced perceptual challenge.

For this experiment we manipulated cognitive demands by presenting sentences of equivalent length, but with the sentence meaning expressed with either a relatively simple or a more complex syntactic structure. The stimuli, sentences with subject-relative or object-relative clause structures, have been shown in numerous studies to produce reliable differences in ease of comprehension and recall in both young and older adults (e.g., Fallon, Peelle, & Wingfield, 2006; Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Stewart & Wingfield, 2009; Waters & Caplan, 2001). Perceptual difficulty was manipulated by varying the sound level of the stimulus sentences within a range for each individual that still allowed words to be identified. Our key questions were first, whether older adults with hearing loss would show differentially longer latencies in their successful comprehension responses relative to age-matched controls with better hearing. Second, to the extent that this result is obtained, we wished to determine whether this effect of hearing acuity would be further impacted by added perceptual demands (represented by lower presentation levels) and increased cognitive load (represented by increasing syntactic complexity).

Although our focus is on the effects of hearing acuity in older adults, we included a group of good-hearing young adults to illustrate maximal performance that might be expected without the impediments of age-related cognitive change and hearing loss.

Method

Participants

The older participants were 36 healthy, community-dwelling adults, 8 men and 28 women with an age range of 68 to 85 years, who received a monetary honorarium for their participation. All participants were native speakers of American English and all reported themselves to be in good health, with no known history of neuropathology that might affect their ability to perform the required tasks.

In order to examine the effects of hearing on performance, we created groups based on audiometric profiles. Participants underwent standard audiometric evaluation (air conduction) using a GSI 61 Clinical Audiometer (Grason-Stadler, Inc., Madison, WI) in a sound-attenuated testing room in which the experiment would be conducted. We obtained puretone thresholds at 500, 1000, 2000, and 4000 Hz (see Table 1). In addition, we tested speech recognition thresholds (SRTs) using a recorded CID W-1 list of spondees (Auditec of St. Louis, MO). The older adults were divided into two groups based on their SRTs in the better ear. Thresholds for the older adults in the good-hearing group ranged from 10 to 20 dB HL, with a mean of 15.8; although these were higher than would be expected for young adults, they nevertheless met a criterion level typically considered to be clinically normal for speech (e.g., Katz, 2002). Thresholds for the poor-hearing group ranged from 25 to 40 dB HL, with a mean of 28.9, and were in the range of mild-to-moderate hearing loss.

The groups of good-hearing and poor-hearing older adults were similar in gender composition and were matched for age and years of formal education (both $p > .05$). The two hearing-acuity groups did not differ significantly in verbal ability (Shipley vocabulary; Zachary, 1986), or in any of the tests of cognitive performance shown in Table 1, including working memory span (Letter-number sequencing, Wechsler, 1997), speed of processing and executive function (Digit symbol substitution, Wechsler, 1997) or Trailmaking A; Reitan, 1958). An exception was Trailmaking B, in which the good-hearing group performed better than the poor-hearing, $t(34) = 2.93$, $p < .01$.

The younger group consisted of 24 university undergraduates, 6 men and 18 women with an age range of 18 to 26 years, who received either course credit or a monetary honorarium for their participation. As shown in Table 1 the younger adults had good hearing, and as would be expected, outperformed the older adults on tests of speed and working memory (e.g., Salthouse, 1991, 1996).

Sentence Stimuli

The test stimuli consisted of 96 sentences selected from those used by Fallon et al. (2006) to provide two types of syntactic complexity: sentences with subject-relative (SR) and object-relative (OR) center-embedded clause structures. As indicated earlier, these syntactic structures are known to differ in processing difficulty (Just et al., 1996). Comprehension of the SR sentences of the sort used for this study (e.g., “*The dog that chased the cat hopped the fence*”) requires the listener to understand that *the dog hopped the fence* is the main clause of the sentence interrupted by the relative clause, *that chased the cat*. The syntactically more complex OR counterpart sentences had the same words as the subject-relative sentences (e.g., “*The dog that the cat chased hopped the fence*”), but in which the head noun phrase (*The dog*) serves as both the subject of the main clause and the object of the relative clause. This produces added processing difficulty and a greater cognitive burden (Carpenter, Miyaki, & Just, 1994), such that OR sentences take longer to process (Wingfield, Peelle & Grossman, 2003) and produce more comprehension errors (Carpenter et al., 1994). This extra processing burden is also revealed in functional neuroimaging studies, where comprehension of OR sentences is accompanied by broader patterns of neural activity compared to patterns of activity for SR sentences (Just et al., 1996; Peelle, McMillan, Moore, Grossman & Wingfield, 2004), especially for older adults (Peelle, Troiani, Wingfield, & Grossman, in press; see the review in Wingfield & Grossman, 2006).

All sentences were digitally recorded onto sound files (16-bit) at a sampling rate of 44,000 Hz using SoundEdit 16 (Macromedia, San Francisco, CA) for the Macintosh computer (Apple, Cupertino, CA) by a female speaker of American English using a natural intonation pattern at an average speaking rate of 124 words per minute.

Procedure

The task involved listening carefully to a stimulus sentence, and when it was finished, responding to a comprehension question for a True/False response (e.g., “The dog chased the cat. T/F?”). The question appeared in a high contrast large font size on a computer monitor immediately after the offset of the sentence presentation. Responses were made by pressing one of two labeled computer keys. A PsyScope computer script (Cohen et al., 1993) controlled stimulus presentation and recorded response latencies from the presentation of the test question to the participant’s key-press response. As a methodological note it can be seen that measured response latencies would include processing the spoken sentence, reading the probe question, and making a comprehension judgment. In this experiment the True/False questions were all of the same length and form regardless of the syntactic complexity of the sentences they probed (e.g., “The car hit the truck”; “The actor insulted the critic”), and were varied across participants to occur with both subject relative and object relative sentence versions. As a result, these times would be included but would be approximately constant across conditions.

Sentences were presented monaurally to the better ear using Eartone 3A (E-A-R Auditory Systems, Aero Company, Indianapolis, IN) insert earphones. The stimuli were prepared and stored as computer sound files, then presented via a GSI 61 audiometer (Grason-Stadler, Inc., Madison, WI). Test sentences were blocked by sound level such that 12 sentences (6 SR, 6 OR) were presented at each of 3 experimental sound levels across 6 blocks of trials, beginning with the highest sound levels, decreasing to the lowest, and increasing again to the highest levels. Sound levels were adjusted for each individual to represent 25 dB (*high level*), 20 dB (*medium level*), and 15 dB (*low level*) over his or her own speech recognition threshold (SRT). Each sentence was heard only once by any participant, with the sentences counterbalanced across participants such that, by the end of the experiment, each sentence had been heard an equal number of times in each of its syntactic forms and at each intensity level.

To insure that listeners could hear the speech at each of their three sound levels, they were asked to listen to and repeat sentences of the same form as those to be used in the main experiment. All participants showed the ability to correctly repeat back sentences at all three sound levels. This test procedure was followed by a practice session in which participants heard 12 SR and OR sentences with sample test questions in order to familiarize them with the task. None of these sentences was used in the main experiment. Following this familiarization session, participants began testing with a warm-up block of 12 sentences presented at a comfortable sound level of 30 dB over SRT.

Results

Comprehension Accuracy

As intended, accuracy was excellent across conditions, although as expected, participants were more accurate in responding to the syntactically simpler sentences (.93 correct comprehension responses) than the more complex sentences (.84). These accuracy data were analyzed with a three-way mixed design analysis of variance (ANOVA), with syntactic complexity (2: simple, complex) and sound level (3: High, Medium, Low) as within-subject variables, and group (3: young good-hearing, older good-hearing, older poor-hearing) as a between-subjects variable. The effect of syntactic complexity was significant, $F(1,57) = 46.52$, $p < .001$, $MSE = .01$, partial $\eta^2 = .45$, and accuracy was significantly greater at the high (.90) and medium (.89) sound levels relative to the low sound level (.86); $F(2,114) = 4.62$, $p < .05$, $MSE = .01$, partial $\eta^2 = .08$. There were no significant differences among the groups on accuracy, (means of .89 for young, .89 for older good-hearing, .88 for older poor-

hearing), $F(2,57) < 1.0$, $MSE = .02$, partial $\eta^2 = .01$, nor were there any significant interactions among group membership, syntax and sound level. With good accuracy established, our focus thus moved to our primary interest; potential differences in the latencies to the comprehension responses.

Response latencies

Figure 1 shows mean response latencies for correct comprehension responses for the three participant groups on syntactically simple and complex sentences, plotted across high, medium, and low sound levels relative to each group's mean SRT (such that absolute sound levels were lower for the individuals in the good-hearing than in the poor-hearing groups). Inspection of the figure suggests that responses for the syntactically complex sentences were generally slower than those for the simpler subject-relative sentences. It also appears that the older good-hearing adults were similar to the younger adults in response latencies and patterns, but that the older poor-hearing adults were relatively slower and showed a different pattern across sound level. That is, the effect of sound level appears to be minimal for the younger adults and the good-hearing older adults, but most pronounced for the older poor-hearing adults while processing the syntactically complex sentences.

To confirm these patterns, an ANOVA was conducted on participants' response latencies that included syntactic complexity (2: simple, complex) and sound level (3: High, Medium, Low) as within-subject variables, and group (3: Young good-hearing, Older good-hearing, Older poor-hearing) as a between-subjects variable. A significant main effect of syntax reflected faster response times for the syntactically simpler sentences relative to the sentences with more complex syntax, $F(1,57) = 81.16$, $p < .001$, $MSE = 237438.12$, partial $\eta^2 = .59$. The main effect of group was significant, $F(2,57) = 10.03$, $p < .001$, $MSE = 3879814.46$, partial $\eta^2 = .26$, and Bonferroni tests confirmed that the younger adults and older good-hearing adults did not differ significantly in overall latencies, but both were faster than the older poor-hearing group (a significance level of $p < .05$ used throughout this discussion). The effect of sound level was significant, $F(2,114) = 9.06$, $p < .001$, $MSE = 157105.71$, partial $\eta^2 = .14$, and most importantly, these effects were moderated by a significant three-way interaction between group membership, syntax, and sound level, $F(4,114) = 2.85$, $p < .05$, $MSE = 128015.41$, partial $\eta^2 = .09$.

We explored this interaction further with follow-up tests. The impression given in Figure 1 of minimal effects of sound level for the young good-hearing and the older good-hearing adults was reflected in Bonferroni tests: neither group showed significant differences in latencies across sound level, for either the syntactically simpler or more complex sentences. The appearance of a contrasting pattern for the poor-hearing older adults was confirmed by a separate ANOVA conducted on these data. This analysis showed not only significant effects of syntax, $F(1,17) = 18.46$, $p < .001$, $MSE = 371843.65$, partial $\eta^2 = .52$, and sound level, $F(2,34) = 5.06$, $p < .05$, $MSE = 197232.24$, partial $\eta^2 = .23$, but also a significant Sound level X Syntax interaction, $F(2,34) = 5.72$, $p < .01$, $MSE = 146334.06$, partial $\eta^2 = .25$. Bonferroni comparisons did not show a significant effect of sound level on response latencies for the simpler subject-relative sentences, in contrast with significantly longer latencies for the low sound level relative to the medium and high sound levels for the syntactically more demanding object-relative sentences.

Discussion

The effortfulness hypothesis as initially articulated by Rabbitt (1968;1991) describes the apparent paradox that degraded speech, whether due to background masking or reduced hearing acuity, has negative effects on accuracy of comprehension or recall even when it can be demonstrated that the individual words themselves were sufficiently clear for their

correct identification (McCoy, et al., 2005; Murphy et al., 2000; Pichora-Fuller, 2003; Tun et al., 2009; Wingfield et al., 2005). The effortfulness hypothesis has much in common with resource notions in cognitive aging theory (e.g., Anderson, Craik & Naveh-Benjamin, 1998; Craik & Byrd, 1982), represented in this case by perceptual effort drawing upon an individual's limited attentional resources that might otherwise be available for downstream operations such as comprehension of sentences with complex syntax or encoding what has been heard in memory. In previous research the consequences of perceptual effort have been measured primarily in terms of failures in comprehension or recall (e.g., McCoy et al., 2005; Murphy et al., 2000; Wingfield et al., 2006; see the review in Pichora-Fuller, 2003). Here we show that the processing load imposed by complex syntax may slow comprehension responses, even when they are correct (see also Wingfield et al., 2003), and most important, that this slowing is compounded by hearing loss and low sound levels.

Because sentences were in all cases presented above the individual's auditory threshold for speech, it is not surprising that for the young and older adult good-hearing groups sound intensity levels beyond this threshold (i.e., 15 dB, 20 dB, and 25 dB above SRT) had little effect on accuracy or latency of comprehension responses. Although we found no age differences overall in accuracy of response on this task, which involved simple True/False comprehension judgments, such differences might be observed with a more demanding task. It is thus especially notable that significant differences still appeared when we examined participants' latencies to their comprehension responses. In this regard the contrast of interest appears for the older adult group with poorer hearing when listening to speech presented at the lowest intensity level versus the medium and high levels. Even though these levels were above threshold, these lower intensities resulted in slowed comprehension responses, but only for sentences with complex syntax. Thus, this response slowing was not simply a consequence of a degraded input, as it was evident only for more syntactically complex sentences, but not for their syntactically simpler counterpart sentences of the same length, spoken by the same speaker, and presented at the same sound intensity level. To put these sound levels in perspective in terms of everyday listening environments, for the young good-hearing group, the three presentation levels ranged from the equivalent of a whisper to that of a soft conversation (Katz, 2002). For the group of older adults with good hearing, who had a higher average threshold than the young adult group, the three presentation levels were equivalent to the range represented by soft conversations in everyday listening, while for the older adult poor-hearing group, with their still higher auditory thresholds, the sentences were heard at levels equivalent to those typically encountered in normal conversational speech (Katz, 2002).

In everyday conversation, listeners rarely have the luxury of adjusting a speaker's volume to their own optimal levels. The implication of our present finding is that comprehension by older adults with mild-to-moderate hearing loss may be slowed by perceptual effort, thus delaying comprehension, with such delays potentially accumulating in a snowballing fashion over the course of a conversation. As we have seen, this slowing would be especially apparent when speech is heard at lower sound levels, such as the amplitudes used in this study, and when the target speaker's utterances are syntactically complex. Both situations are often encountered in everyday conversation, representing a case of "double jeopardy" for many older listeners. Conversely, having excellent hearing may help minimize age differences in performance on tasks involving meaningful speech, as we saw with this sample. Our present findings underscore the need to consider both sensory and cognitive demands together, not in isolation, in order to understand speech communication in older adults.

Acknowledgments

This research was supported by NIH Grant AG019714 from the National Institute on Aging. We also gratefully acknowledge support from the W.M. Keck Foundation.

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Figure 1.

Response latencies (s) for comprehension responses to syntactically simpler subject-relative sentences and syntactically more complex object-relative sentences when heard at three intensity levels relative to listeners' auditory thresholds. Data are shown for good-hearing young adults (left panel), older adults with good hearing (middle panel) and older adults with mild-to-moderate hearing loss (poor-hearing older adults). Error bars represent one standard error.

Table 1

Characteristics of Participant Groups

	Older Adults					
	Younger Adults			Older Adults		
				Good Hearing	Poor Hearing	
N	24		18			
	Mean	SD	Mean	SD	Mean	SD
Age	19.5	2.0	74.4	3.8	76.9	3.6
Education (yrs.)	14.1	1.5	16.8	2.3	16.9	2.2
SRT (dB HL)	5.4	4.6	15.8	4.3	28.9	5.0
Pure Tone Thresholds (dB HL)						
500 Hz	9.5	5.6	16.9	6.2	26.1	10.4
1000 Hz	5.8	6.9	15.6	5.4	28.1	8.8
2000 Hz	3.5	5.6	16.4	9.5	30.3	9.5
4000 Hz	2.7	7.0	27.8	14.9	41.7	11.9
Shipley Vocabulary	14.7	2.0	17.3	2.1	16.5	2.6
LNS	15.1	2.4	13.5	2.9	12.2	2.7
DSS	71.4	12.3	60.5	12.9	53.0	9.6
Trails A	27.0	8.7	34.6	7.8	39.0	13.3
Trails B	56.4	17.1	68.0	21.2	93.0	29.3

Note: Older adult groups did not differ on *t*-tests in measures other than hearing acuity and Trails B. SRT = Speech Reception Threshold in better ear. LNS = Letter-Number Sequencing. DSS = Digit-Symbol Substitution.