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Speech Rate and Syntactic Complexity as Multiplicative Factors in Speech Comprehension by Young and Older Adults

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ABSTRACT

An experiment is reported in which young and older adults heard short English sentences that differed in syntactic complexity and speech rate. The syntactic contrast pitted center-embedded sentences with a subject-relative clause against sentences with center-embedded object-relative clauses. Speech rate was varied using computer time-compression of the speech signal. Both young and older adults showed poorer comprehension accuracy for the more complex object-relative clause sentences than subject-relative sentences, with an age difference appearing only when sentences were presented at a very rapid rate. By contrast to accuracy scores, older adults took longer than the young adults to give their comprehension responses at all speech rates tested, with this age difference amplified by both speech rate and syntactic complexity.

Comprehension of spoken language requires rapid processing of the speech input as it is being heard. Given that average speech rates can often exceed 200 words per minute (Miller, Grosjean, & Lomanto, 1984), the rate at which speech must be recognized, analyzed for meaning and encoded in memory implies a serious challenge for the listener's perceptual and cognitive systems. To the extent that age-related neural decline may affect comprehension of rapid speech, one might expect performance changes in normal aging, even beyond the costs of sensory and higher level perceptual declines that increase with adult aging (Morrell, Gordon-Salant, Pearson, Brant, & Fozard, 1996; Schneider & Pichora-Fuller, 2001).

Normal aging is known to be associated with greater or lesser changes in gross brain anatomy, metabolic activity, and cell function (Ivy, MacLeod, Petit, & Markus, 1992; Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998). The behavioral consequences of these changes can include declines in working memory resources as well as slowing in a variety of perceptual and cognitive tasks (Kausler, 1991; Salthouse, 1996). Although linguistic knowledge remains generally spared in healthy older adulthood (Kemper, 1992; Kemper et al., 1993; Kempler & Zelinski, 1994; Wingfield & Stine-Morrow, 2000), processing declines do occur. Two of the most notable difficulties are the comprehension of sentences with complex syntax (Kemper, 1986, 1992; Obler, Fein, Nicholas, & Albert, 1991) and the comprehension of speech that arrives at an especially rapid rate (Wingfield, 1996; Wingfield, Poon, Lombardi, & Lowe, 1985; Wingfield, Tun, Koh, & Rosen, 1999).

The fact that speech rate and syntactic complexity both affect older adults' language comprehension does not mean that these two factors necessarily operate on the same neural processing

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architectures. One can ask at the behavioral level, however, whether the two methods of increasing processing difficulty act in an additive or multiplicative fashion on individuals' accuracy and speed of performance.

The syntactic contrast chosen for this experiment was accomplished using two well-studied syntactic forms: sentences containing either a subject-relative or an object-relative center-embedded clause. In subject-relative clause sentences (e.g., *Boys that help girls are caring*), the main clause (*Boys are caring*) is interrupted by the relative clause (*that help girls*). In object-relative clause sentences (e.g., *Boys that girls help are caring*) 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 added syntactic complexity of object-relative clause sentences has been shown to produce longer reading times for written text and more errors in comprehension than less complex subject-relative clause sentences (Just & Carpenter, 1992; Vos, Gunter, Schriefers, & Friederici, 2001).

In contrast to reading, where one can use eye-movements to control the rate of input, the listener must process the speech at the rate it is being delivered by the speaker. It should thus follow, first, that comprehension errors should be greater for object-relative than subject-relative clause sentences, and second, that this difference should be larger when the processing system is challenged by especially rapid speech rates. To the extent that older adults require more processing time to reach a given level of performance relative to young adults, one would expect effects of syntactic difficulty to be amplified by both speech rate and age.

Experimental studies of rapid speech typically use computer time-compression rather than relying on speakers attempting to speak very rapidly. This is so because even trained speakers attempting to speak rapidly introduce subtle and uncontrollable changes in articulatory clarity and in the pattern of linguistically based pauses and intonation contour (Miller et al., 1984; Speer, Wayland, Kjelgaard, & Wingfield, 1994). In the sampling method of time compression, a computer algorithm is used to delete small (e.g., 20 ms) segments at regular intervals from both speech and silent periods in the speech stream, with the remaining segments then abutted in time. Speech rate is varied by the frequency with which these small segments are deleted. The result of this process is speech reproduced in faster-than-normal time, but without the change in pitch that would, for example, accompany tape-recorder playback at faster-than-normal speed (Chodorow, 1979; Foulke, 1971).

The use of time-compressed speech would be expected to place the older adult at a disadvantage at three levels. At the peripheral level, older adulthood is often accompanied by an increased incidence of hearing loss, especially in the high frequency range. This can have a significant impact on speech perception, especially for high acoustic frequency low energy consonants (Morrell et al., 1996; U.S. Congress, Office of Technology Assessment, 1986). Older adults can also show central auditory processing deficits. Most notable is a difficulty with temporal resolution of rapidly arriving sounds (Gordon-Salant & Fitzgibbons, 1993; Moore, Peters, & Glasberg, 1992). For this reason speech recognition, even when successful, might be more effortful for older adults than for young adults, even when participants are equated for peripheral hearing acuity. This difficulty might be especially highlighted when listening to time-compressed speech. Indeed, in the audiological literature time-compression of words has long been proposed as a test for central auditory deficits, especially in older listeners (Konkle, Beasley, & Bess, 1977; Versfeld & Dreschler, 2002).

Although one should not underrate the importance of these purely auditory factors, especially at high compression rates that result in a loss of signal richness (Heiman, Leo, Leighbody, & Bowler, 1986), a large part of the effect of rapid speech lies at the cognitive level. It is at this level that time compression has its effect by removing the processing time that would ordinarily be available to the listener at slower speech rates (Chodorow, 1979; Foulke, 1971). To the extent that adult aging is accompanied by limitations in mental processing speed, healthy older adults would be especially challenged by the time pressure imposed by time-compressed speech. The result would be a lag effect as the older adults' comprehension of the syntactic structure and propositional relationships among the speech elements fall behind the rapid rate of the input.

Evidence for this cognitive role can be seen in the ways in which the effects of difficult listening conditions can be ameliorated. For example, age differences in speech recognition can be significantly reduced when words are heard in the presence of a supporting linguistic context (Perry & Wingfield, 1994; Pichora-Fuller, Schneider, & Daneman, 1995; Wingfield, Aberdeen, & Stine, 1991). At the discourse level, older adults' difficulties with time-compressed speech can be ameliorated by adding extended silent periods after sentences and clauses to allow additional time to mentally process what has been heard (Wingfield et al., 1999). These findings illustrate a cognitive component to the challenge of time-compressed speech beyond the peripheral and central auditory processing challenges described above.

Our goal in this experiment was to examine effects of syntactic complexity and speech rate separately and in combination on the immediate comprehension of sentences. Because of the logistics of creating sentences with varying degrees of syntactic complexity, many studies in the past have used relatively long sentences that might tax memory resources (e.g., Davis & Ball, 1989; Kemper, 1986; Obler et al., 1991; Waters & Caplan, 1996; Zurif, Swinney, Prather, Wingfield, & Brownell, 1995). In an attempt to minimize memory effects we constructed subject-relative and object-relative clause sentences that were only six words in length.

A second procedural decision related to the choice of a comprehension measure. Plausibility judgments have been frequently used as a measure of sentence comprehension (e.g., Just & Carpenter, 1992; Waters & Caplan, 1996). Although indicating whether a sentence is plausible or not requires that the sentence has been understood, correct responses also require extralinguistic, pragmatic judgements that add to the processing task. The same may be said for testing comprehension by requiring the participant to verify the truth of a statement (Poldrack et al., 2001). To simplify the listener's task we chose sentences in which a male or a female character is the agent of an action (e.g., *Boys that help girls are caring*). The participant's task would be to listen to the sentences and indicate with a key-press the gender (male/female) of the agent. This alternative to the traditional plausibility measure has been successfully used in past studies as a measure of sentence comprehension (e.g., Cooke et al., 2001).

One could entertain two hypotheses as to the outcome of this experiment. The first is that syntactic complexity adds a cost to sentence comprehension independent of speech rate. This simple additivity would be manifest in parallel performance functions for subject-relative and object-relative clause sentences across speech rates. A finding of additivity would be consistent with the notion of independent processors constrained only by an overall concurrence or overhead cost (Allport, Antonis, & Reynolds, 1972; Wickens, 1984). The alternative hypothesis is that the added work imposed by syntactic complexity compounds the effects of speech rate, producing a differentially greater effect of syntactic complexity at faster speech rates than at slower ones. Such a multiplicative effect would be expected if the two sources of difficulty added processing costs to a resource-limited processing system that acts as a general processing bottleneck (Broadbent, 1971; Kahneman, 1973). An additional question is whether the performance declines associated with speech rate and syntactic complexity are parallel for young and older adults, or whether the performance functions diverge as the processing load is increased, regardless of whether this load is determined by increasing syntactic complexity or by increasing speech rate. This latter possibility would be instantiated by an interaction between age, speech rate, and syntactic complexity.

Because of our use of short sentences, one might expect to see ceiling effects on comprehension accuracy with slower speech rates and syntactically simpler sentence forms. For this reason we also measured response latencies, timing the participants' responses from the ends of the sentences to their key-press gender responses. In this way we would have a supplementary measure that would not be constrained by potential ceiling effects for the less challenging conditions of subject-relative clause sentences heard at slower speech rates.

METHOD

Participants

The older adults were 30 community-dwelling volunteers, 9 men and 21 women, who ranged in age from 61 to 80 ($M = 72.2$, $SD = 4.5$). The group had a mean of 16.4 years of formal education ($SD = 2.0$), and a mean Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 1997) vocabulary score of 55.7 ($SD = 5.6$). The young adult participants were 30 university undergraduate and graduate students, 7 men and 23 women, with ages ranging from 18 to 27 ($M = 19.3$, $SD = 2.1$). The group had a mean of 13.8 years of formal education at time of testing ($SD = 1.2$) and a mean WAIS-III vocabulary score of 51.7 ($SD = 5.3$). Both groups were thus well-educated and had good vocabularies, with the older group having an average of 2.6 more years of formal education, $t(58) = 5.92$, $p < .001$, and, as is common for older adults (e.g., Bowles & Poon, 1985), a somewhat higher vocabulary score than the younger group, $t(58) = 2.83$, $p < .01$. The two groups were statistically equivalent in both forward (Young $M = 7.8$; Older $M = 7.8$, $t(58) = 0.28$, *n.s.*) and backward (Young $M = 6.2$; Older $M = 5.7$, $t(58) = 1.40$, *n.s.*) digit spans for spoken digits presented at a rate of one per second. All participants were native speakers of English and all reported themselves to be in good health, with no known history of stroke, Parkinson's disease, or dementing illness. Participants were also free of medications that might compromise cognitive function.

Although the older adults in this study had good hearing for their ages (cf., Morrell et al., 1996), significant differences in acuity were present relative to the young adults. Pure-tone audiometry showed the young adults to have a lower pure tone average (PTA; taken as the mean thresholds for tones at 500, 1000 and 2000 Hz) than the older adults (Young $M = 8.5$ dB; Older $M = 16.3$ dB, $t(58) = 6.18$, $p < .001$, for the better ear). Speech reception thresholds (SRTs; the lowest decibel level at which 2-syllable words can be correctly identified 50% of the time) were also measured. The younger participants also had on average lower SRTs than the older group (Young $M = 4.0$ dB, Older $M = 11.4$ dB, $t(56) = 4.60$, $p < .001$). (SRTs were unavailable for two participants.) We will have more to say about this age difference later in the paper.

Stimuli

To prepare the stimuli we first constructed 60 meaningful, 6-word English sentences built around subject-relative clause structures. For each of these sentences we then constructed a counterpart sentence that had the same words and characters performing the action as the original, but in which the meaning was expressed using an object-relative clause structure. For each sentence version we also constructed an additional sentence with the same words and structures but with the opposite gender performing the action. This procedure resulted in a total of 240 sentences, 60 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."

Thus, within the 240 sentences we had an equal number of sentences with 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 an average speech rate of approximately 205 words per minute (wpm) and then time-compressed using a computer-based sampling algorithm to 80%, 65%, 50%, and 35% of original speaking time (corresponding to 258, 321, 410, and 595 wpm, respectively). The method used was 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 22,000 pieces of data, only very small pieces of the speech signal are removed in the sampling procedure, thus minimizing any distortion and maintaining the original pitch contour of the sentence (Foulke, 1971; Chodorow, 1979).

The effect of this method of compression is to remove these small segments to a proportionally equal degree from all parts of words and brief silent periods as occur in fluent discourse. An alternative to this method would be to use a so-called nonlinear method of time compression, in which only steady-state portions of words (e.g., extended vowels) are compressed. At the word level, dependent on the importance of word prosody, differential compression of steady-state portions can produce greater intelligibility than the uniform compression method used here (Gordon-Salant & Fitzgibbons, 1993; Janse, 2003; Moore et al., 1992). We chose to use uniform compression to preserve the relative temporal patterning of natural speech which is important for syntactic parsing and comprehension at the sentence level (Goldman-Eisler, 1968; Shattuck-Hufnagel & Turk, 1996).

Procedures

Each participant heard all 240 sentences, 120 subject-relative and 120 object-relative sentences. Forty-eight sentences, 24 subject-relative and 24 object-relative, were presented at each of the five speech rates. Half of each sentence type had a male agent and half had a female agent. For each participant half of the sentences (with equal numbers of subject-relative and object-relative clause sentences and male and female agents) were presented in an ascending order of speech rates: 24 sentences at the original speaking rate, 24 at 80% of original speaking time, 24 at 65% of original speaking time, 24 at 50% of original speaking time, and 24 at 35% of original speaking time. When this sequence was completed, the remaining sentences were presented in reverse order, going from the fastest speech rate to the slowest speech rate. This procedure was adopted in deference to the older participants, who often react poorly in a standard counterbalanced design when the first stimuli they hear are at a very rapid speech rate. Although speech rates were blocked, subject-relative and object-relative clause sentences and sentences with male and female agents were intermixed within a speech rate. The particular sentences heard at each speech rate were counterbalanced across participants such that, by the end of the experiment, each sentence had been heard an equal number of times at each rate.

For each sentence, participants were instructed to press one of two keys to indicate whether a male or female character was performing the action. They were told to give their responses as quickly as possible without making careless errors. Participants were asked to make a response for each sentence; if unsure, they were asked to give their best judgment. Response accuracy and response latencies were collected for later analysis using PsyScope presentation software (Cohen, MacWhinney, Flatt, & Provost, 1993). Stimuli were presented from computer sound files over binaural earphones at a comfortable listening level which, once selected by the individual, was maintained across all conditions of the experiment.

The main experiment was preceded by a familiarization session to ensure that the instructions were understood and to familiarize participants with the sound of time-compressed speech. This session consisted of 16 sentences that included both subject-relative and object-relative clause sentences presented at the various speech rates used in the main experiment. None of these sentences was used in the main experiment.

Although our experiment would use each participant as his or her own control (i.e., effects of complex syntax and rapid speech rates would be contrasted with the same participants' responses to sentences with simpler syntax heard at slower rates) we wished to insure that any main effects of age on response time would not be a consequence of simple sensorimotor slowing. For this purpose the main experiment was preceded and followed by a control condition in which participants heard speech samples that had been filtered using a low-pass cutoff frequency of 250 Hz. This cutoff level allowed the participants to hear the duration of the speech samples but without any segmental (phonology) information. A control test with an independent group of participants insured this was so. The samples had the same distribution of durations as the stimulus sentences heard at the various rates. The participants' task was to press one of two marked keys as rapidly as possible at the instant the filtered signal ended. They were instructed to alternate their responses between a left and right key. This task was intended as a measure of participants' speed of response in a listening, key-press task that did not involve comprehension.

RESULTS

Response Accuracy

The left panel of Figure 1 shows the proportion of correct responses given by the young and older participants for subject-relative and object-relative clause sentences at each of the five speech rates. It can be seen that while the young and older adults demonstrated similar accuracy at slower rates of speech, the older adults' performance began to decline more quickly when speech rate was increased. These data were submitted to a 2 (Syntactic type: subject-relative, object-relative) × 5 (Speech rate: 100%, 80%, 65%, 50%, 35%) × 2 (Age: young, older) Analysis of Variance (ANOVA), with syntactic type and speech rate as within-participants variables and age as a between-participants variable.

As implied by visual inspection of the left panel of Figure 1, there was a significant main effect of syntactic type on response accuracy that favored subject-relative clause sentences, $F(1, 58) = 127.16$, $MSE = 0.0186$, $p < .001$, as well as a significant main effect of speech rate, $F(4, 232) = 213.89$, $MSE = 0.0063$, $p < .001$. There was a significant main effect of age, $F(1, 58) = 7.50$, $MSE = 0.003425$, $p < .01$, as well as a significant Age × Speech rate interaction, $F(4, 232) = 19.44$, $MSE = 0.0068$, $p < .001$, reflecting the finding that the older adults' accuracy began to decline sooner with increasing

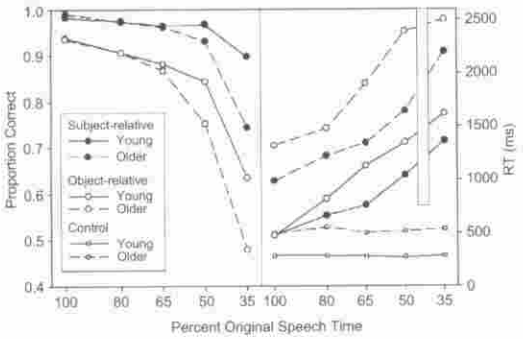

Fig. 1. Proportion of correct comprehension responses (left panel) and mean response times (RTs) to correct responses (right panel) for subject-relative and object-relative clause sentences as a function of speech rate for young and older adults. Mean response times to the right of the vertical bar in the right panel are based on relatively few data points especially for older adults' responses to object-relative sentences. The lower horizontal lines in the right panel show young and older participants' mean response times on a control task of sensorimotor speed that did not involve sentence comprehension.

speech rate than the young adults.' (Post hoc paired comparison t tests collapsing across syntactic type yielded significant age differences only for the two fastest speech rates.) Indeed, it can be seen that the older adults were showing only chance performance (50% correct) for the object-relative clause sentences when heard at the fastest speech rate.

The effects of syntactic complexity on comprehension were greater for the faster speech rates, supported by a significant Syntactic type × Speech rate interaction, $F(4, 232) = 25.73$, $MSE = 0.0084$, $p < .001$. However, syntactic complexity did not have a differentially greater effect on the older adults' accuracy performance than the young adults' (Syntactic type × Age, $F(1, 58) < 1$ ($MSE = 0.0186$)). The Syntactic type × Speech rate × Age interaction also failed to reach significance, $F(4, 232) < 1$ ($MSE = 0.0084$). The absence of these interactions, however, must to be viewed in the context of the anticipated ceiling and near ceiling effects for both age groups hearing subject-relative clause sentences at the slower speech rates. In addition, as we have seen, these data were also constrained by a floor effect for the older adults who were performing at a chance level for object-relative clause sentences heard at the fastest speech rate tested (35% of original speaking time). To gain a measure of processing difficulty that would not be subject to these constraints we turn to the potentially more sensitive measure of participants' latencies to their responses.

Response Times

The right panel of Figure 1 shows the mean response times in ms from the ends of the sentences to the young and older participants' correct key-press gender responses for subject-relative and object-relative clause sentences at each speech rate. Latencies were trimmed using a 2.5 standard deviation rule for each condition to insure that longer average response times were not simply a consequence of a small number of outliers (cf., Ratcliff, 1993).

The response time data shown in the right panel of Figure 1 were submitted to a 2 (Syntactic type: subject-relative, object-relative) × 4 (Speech rate: 100%, 80%, 65%, 50%) × 2 (Age: young, older) mixed design ANOVA, with syntactic type and speech rate as within-participants variables and age as a between-participants variable. We excluded from this analysis the fastest (35% of original time) speech rate condition because of a concern for the reliability of the older adults' mean response times for the object-relative clause sentences at this rate where, it will be recalled, the older adults were performing at no better than chance level. (The quickness of responses for the object-relative clause sentences at this point relative to the next most rapid rate is consistent with rapid guessing at this chance point.) The excluded data are to the right of the vertical bar in the right panel of Figure 1.

As suggested by inspection of the right panel of Figure 1, there were significant main effects of syntactic type, with correct responses to object-relative clause sentences taking longer than correct responses to subject-relative clause sentences, $F(1, 58) = 44.84$, $MSE = 309{,}573.39$, $p < .001$, of speech rate, with participants taking longer to respond as speech rates were increased, $F(3, 174) = 129.69$, $MSE = 104{,}981.32$, $p < .001$, and age, with older adults taking generally longer to respond than the young adults, $F(1, 58) = 15.72$, $MSE = 3{,}696{,}168.09$, $p < .001$. As observed for accuracy scores, there was also a significant Syntactic type × Speech rate interaction for participants' response times, $F(3, 174) = 18.55$, $MSE = 59{,}547.96$, $p < .001$. Post hoc t tests showed a significant effect of syntactic complexity for older adults at all speech rates tested. For the young adults, there was no significant effect of syntactic complexity at the normal speech rate. For these participants, a significant effect appeared only when speech was compressed to 80% of original speaking time or faster.

Although a significant Syntactic type × Age interaction did not appear in the accuracy data, response times were more sensitive to this effect, showing a significant Syntactic type × Age interaction, $F(1, 58) = 6.85$, $MSE = 309{,}573.39$, $p < .05$. That is, both young and older adults took longer to respond correctly to object-relative compared to subject-relative clause sentences, with this difference significantly amplified for the older adults. There was a marginal Age × Speech rate interaction, $F(3, 174) = 2.42$, $MSE = 104{,}981.32$, $p = .068$, but now a significant three-way Speech rate × Syntactic type × Age interaction, $F(3, 174) = 3.09$, $MSE = 56{,}078.22$, $p < .05$.

Although participants were instructed to listen carefully to each sentence, the nature of our sentences could allow a participant to know the agent of the action before the full sentence had been completed. For example, in the previously presented examples (*Men that assist women are helpful*, or *Women that men assist are helpful*) the decision that the male was the agent of the action could be made once the listener had heard the words *men*, *women* and *assist*. This would be true even though the full specifics of the action remained uncertain until the end of the sentence. It is open whether participants may have begun to initiate their responses at the earliest possible moment in a sentence or whether they waited until the end of the sentence before making their decision. There are certainly precedents in the literature for the latter case (Sternberg, 1966).

Because of this possibility we repeated the response time analysis but this time measuring response times from the critical word in each sentence (the word that allowed the correct gender judgment at the earliest point in the sentence). This analysis showed the same general pattern of main effects and interactions as observed for response times measured from the sentence endings.

Control Condition

The horizontal lines at the bottom of the right panel of Figure 1 show the response times for the control condition in which participants simply pressed a key as rapidly as possible the moment a non-informational filtered speech signal had ended. As might be expected from the aging literature (Kausler, 1991; Salthouse, 1996), the older adults responded more slowly than the young adults, $F(1, 58) = 40.82$, $p < .001$. However, there was no effect of stimulus duration, $F(4, 232) = 1.62$, *n.s.* ($MSE = 107{,}396.20$), nor was there a significant Age × Stimulus duration interaction, $F(4, 232) = 1.05$, *n.s.* ($MSE = 7{,}236.13$). As can be seen, if one were to subtract the control response times from the gender decision latencies it would reduce the magnitude of the age difference, but it would have no effect on the slopes. We thus conclude that the main effects and interactions shown for older adults' response times were not due simply to sensorimotor slowing or stimulus duration effects.

Hearing Acuity

It will be recalled that the pure tone averages (PTAs) and speech reception thresholds (SRTs) for the older participants were higher than for the young adults, a not unexpected finding when young and older adults are compared (Morrell et al., 1996). This difference is bound to raise the question of whether the factors involving age (a significant Age × Speech rate interaction on comprehension accuracy and significant Age × Syntactic complexity and Age × Speech rate × Syntactic complexity interactions in response times) were due to the group differences in hearing acuity for speech.

To answer this question we selected from our participants the 15 older adults with the lowest SRTs and 15 young adults with the highest SRTs for their age groups. For these two subgroups there was no significant difference between mean SRTs (Young $M = 8.7$ dB, $SD = 4.4$; Older $M = 7.3$, $SD = 2.6$, $t(28) = 1.01$, *n.s.*). The mean ages for these two subgroups were comparable to their two parent age groups as a whole (Young $M = 19.4$ years, $SD = 1.9$; Older $M = 72.3$ years, $SD = 4.4$). The average forward and backward digit spans and WAIS-III vocabulary scores for the two subgroups were also similar to their two parent groups. The two subgroups were thus representative of their two parent groups, except for not differing significantly in hearing acuity for speech.

A data plot and ANOVA for these two subgroups showed a similar pattern of data as was seen for all participants in Figure 1. It is important to note that all of the participants in this experiment, both young and older adults, had good hearing for their ages as determined by standard age norms (Morrell et al., 1996; U.S. Congress, Office of Technology Assessment, 1986). Nor should one underrate the importance of hearing acuity to the general communicative lives of older adults (e.g., Gordon-Salant & Fitzgibbons, 1997). Our point here is only that the differences observed for the older adults relative to the young adults in this study were not a simple consequence of acuity differences.

DISCUSSION

Our results are clear in showing that in listening, as in reading (e.g., Just & Carpenter, 1992; Vos et al., 2001), sentences with greater syntactic complexity (object-relative clause sentences) are more difficult to comprehend than those with less syntactic complexity (subject-relative clause sentences). This complexity effect is especially noteworthy because of its appearance even with the very short sentences used in this experiment in contrast with the longer, potentially more memory-demanding, sentences traditionally used to demonstrate syntactic complexity effects (e.g., Kemper, 1992; Obler et al., 1991). We also found that participants took longer to respond with correct agent-judgements to object-relative clause sentences than to subject-relative clause sentences. The syntax effect thus appears to be a robust one not dependent on sentence length, presentation modality, or on a particular response measure such as plausibility judgments or accuracy in sentence repetition (cf., Kemper, 1986, 1992; Obler et al., 1991; Waters & Caplan, 1996).

In addition to this overall effect of syntactic complexity, the present experiment showed that, for both young and older adults, the effect of syntactic complexity was amplified in response times to accurate responses when speech rates became more rapid. This multiplicative effect of two sources of processing difficulty does not, as we indicated earlier, necessarily imply that rate and syntactic complexity challenge the same neural processing areas. For example, lesion data and functional imaging studies implicate the left inferior frontal lobe (Broca's area) as having a unique role in syntactic processing as distinct from more posterior language regions (Goodglass, 1993; Ni et al., 2000). The processing of very rapid language input may especially engage other areas, such as portions of a fronto-striato-thalamic loop (Cooke et al., 2000). As we have seen in these behavioral data, however, at some level these two sources of processing difficulty combine to more than the sum of the two parts, such that the ordinary difficulty of syntactically complex speech is progressively amplified when the speech rates are increased.

Our choice of time compression of the speech as a method of increasing the processing challenge for the participants was a powerful one because of the many levels on which it may be thought to operate. These levels range from increasing lower-level perceptual difficulty (Heiman et al., 1986) to removing ordinarily available mental processing time at the cognitive level (Wingfield et al., 1999). It is important to note in this regard that we chose to increase the speech rate by uniform compression across all areas of the speech signal. As an alternative to this method one could selectively compress only those areas of words thought to be least important for a word's identification. For example, word recognition studies show that word onsets are especially important to the identification of words for young (Marslen-Wilson & Welsh, 1978; Marslen-Wilson & Zwitserlood, 1989) and older (Wingfield, Lindfield, & Goodglass, 2000) listeners. In a similar way, one could chose to compress just the steady-state acoustically redundant segments of words, such as extended vowel or fricative durations, while leaving the transient areas (e.g., areas of rapid consonant change) intact. Compressing individual words in this way would be expected to be less damaging to word identification than compressing all parts of a word equally, and even more so for older adults. This would be so because any age-related problems with temporal processing of the acoustic signal would be expected to have their greatest impact on the rapid-transient areas of the spoken words (Gordon-Salant & Fitzgibbons, 1993; Moore et al., 1992).

As indicated previously, our choice of uniform compression across all parts of the speech signal was predicated on our wish to maintain the relative temporal patterning of the speech. This was done because the relative durations of acoustically redundant steady-state portions of words can contain important syntactic information at the sentence level, especially when the speech becomes syntactically complex (Shattuck-Hufnagel & Turk, 1996; Wingfield, Wayland, & Stine, 1992). In so doing we weighted the potential loss of intelligibility due to compression of transient speech regions against previous work that has shown that older adults make excellent use of prosodic features at the sentence level for syntactic parsing and comprehension (Kjelgaard, Titone, & Wingfield, 1999; Wingfield, Lahar, & Stine, 1989).

This discussion of the potential impact of different methods of time compression illustrates the complexity of the issues underlying successful performance by the older listener. On the one hand, a reduction in sensory clarity would be expected to have a significant impact on cognitive performance, whether due to a loss of information or to the extra effort required for successful identification of a degraded signal. This extra effort could draw important resources that might otherwise be available for post-perceptual comprehension operations. This is a principle that will hold true in either visual (Scialfa, 2002) or auditory (Schneider, Daneman, & Pichora-Fuller, 2002) sensory domains. On the other hand, older adults may have developed considerable expertise in processing less-than-clear sensory input, as well as in using well maintained linguistic knowledge to supplement what might otherwise be a far more damaging perceptual difficulty (see Scialfa, 2002, for a discussion of top-down compensation for bottom-up decline).

Given the complexity of these issues, we do not wish to say how much of the detrimental effects of time compression on older adults' comprehension was due to challenges at the perceptual level due to central auditory processing deficits versus the loss of necessary processing time for higher-level cognitive-linguistic operations (cf., Chodorow, 1979; Gordon-Salant & Fitzgibbons, 1993; Heiman et al., 1986; Schneider et al., 2002; Wingfield et al., 1999). We can say that these effects were not a consequence of differences in simple hearing acuity because of the similarity in the pattern of results with respect to both syntactic complexity and speech rate for the subgroups of young and older participants who had similar thresholds for individual word recognition. This finding is consistent with others who have shown an age-related decrement for time-compressed speech for older and younger adults matched for hearing acuity (cf., Gordon-Salant, 1987; Gordon-Salant & Fitzgibbons, 1993, 1997).

Even when speech was compressed to 80% and 65% of original speaking time, as well as when the sentences were presented at their original fast-normal rate of 205 wpm, we saw that the older adults were able to identify the correct agent of subject- and object-relative clause sentences as accurately as the young. We also saw, however, that there was a significant age difference in the time required to give these responses. As can be seen from the control condition, older adults were also slower than young adults when simply required to press a key to signal the end of a non-informational speech-like sound. This general response slowing, however, would not account for the older adults' differentially longer response times to object-relative clause sentences than the young participants when each group is contrasted with their baseline levels for subject-relative clause sentences. Nor would this difference account for the three-way interaction of age, syntactic complexity and speech rate reflecting the finding that older adults took differentially longer to respond than the young adults when syntactically complex speech was presented very rapidly.

A difficult question to answer is whether the combined effects of speech rate and syntactic complexity are operating on what Caplan and Waters (1999) have referred to as the interpretive processing level (the processes whereby a listener or reader extracts the meaning of a sentence) or the post-interpretive processing level (processing in which something is done with this meaning – for example, answering a comprehension question, or evaluating its plausibility). The argument has been made, for example, that older adults are not at a disadvantage relative to young adults in sentence comprehension at the interpretive level. It has been hypothesized that when age differences in response to syntactic complexity are observed they are due to an age-related disadvantage in post-interpretive processes (Waters & Caplan, 2001; Kemper & Kemtes, 1999).

In the present study the question participants were asked – *What is the gender of the character performing the action*? – remained constant across all 240 experimental trials. In addition, unlike plausibility judgments as a measure of comprehension, the correct answer is unambiguous if the syntax of the sentence is correctly interpreted. Thus it could be argued that any post-interpretive processing remained constant across syntactic type and speech rate. If this reasoning is correct, the differentially greater impact of syntactic complexity and speech rate on the older adults' performance would have been happening at some stage before the post-interpretive level. That the age difference in accuracy occurred only under the challenge of rapid speech may suggest that the older adults were less effective than the young in perceptual processing of the rapid input, an effect that would hinder, and potentially delay, interpretive processing. The longer response times produced by the older adults in response to increasing speech rate and syntactic complexity, over and above our control condition estimate of age-related sensorimotor slowing, supports this interpretation.

Although the older adults in this study showed processing declines in the critical areas of syntactic complexity and rapid speech, it is important to note that the older adults' comprehension accuracy did not differ from the young adults until speech rates became very fast. Indeed, comprehension accuracy for the older adults, even for sentences with complex syntax, did not fall to a chance level until the sentences had been compressed to 35% of their original duration. This degree of compression corresponds to a speech rate of 595 wpm, a rate far faster than one would ever encounter in nature. This compression ratio also reflects the removal of more than half of the speech signal, where intelligibility of the speech, especially for the older adults, may have been severely challenged.

Our findings thus support the contention that, within broad limits imposed by listening conditions and memory demands, syntactic processing and sentence comprehension remain labile in healthy adult aging. At all speech rates, however, we also saw that the older adults required more time to produce their comprehension responses than the young adults, with this time differential increasing as the processing challenge was increased. This slowing may not be without consequence when one moves beyond very short sentences, such as those used here, to longer speech samples and connected discourse. In such cases even a small temporal lag between comprehension and rate of input could put the older adult at a progressively increasing disadvantage as extended speech continues to arrive. This is a performance limitation potentially alleviated by metering the rate of speech input either by general slowing (Wingfield & Ducharme, 1999) or by pausing at regular intervals to give the older listener additional time to process what is being heard (Wingfield et al., 1999). Such remediation, however, will be limited by the sufficiency of the sensory information and by other constraints that may operate on the cumulative processing of extended discourse.

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