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Cognitive Factors in Auditory Performance: Context, Speed of Processing, and Constraints of Memory

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Abstract

This paper describes several techniques used to explore the role of cognitive factors in auditory performance in elderly adults. Two factors, cognitive slowing and age-related memory constraints, receive special attention. Assessing listeners' ability to report the content of time-compressed speech shows elderly adults to be especially vulnerable to rapid speech input. Such effects, however, are ameliorated by effective use of linguistic knowledge, which, unlike processing speed, remains relatively stable in adult aging. A second technique is described in which intelligibility is tested for words excerpted from fluent speech, first presented in isolation and then with varying amounts of preceding or following context from the original utterances. Memory constraints are shown to have a significant effect on elderly listeners' ability to use linguistic context that follows an acoustically ambiguous region for a retrospective analysis of what had been heard. Thus, cognitive factors can both enhance and limit auditory performance in elderly listeners.

Key Words: Aging, linguistic context, memory, time-compressed speech

Generalized slowing across a variety of perceptual, cognitive, and motor domains is often considered a hallmark of the aging process (Cerella, 1985; Salthouse, 1991). The term "generalized" need not imply that a single slowing factor operates equally on all tasks or processing domains in an individual (Cerella, 1994; Fisk and Fisher, 1994; Myerson et al, 1994). Rather, it specifies that slowing does occur in elderly adulthood, and that it can be shown to accompany a range of performance decrements in a variety of cognitive activities (Salthouse, 1991).

Cognitive slowing, whether a cause or consequence of lowered efficiency in processing operations, implies that perceptual operations that require rapid input processing should be especially vulnerable in elderly adulthood. Spoken language is a prime example of rapid input that requires rapid on-line analysis. Although speech rates in normal conversation show wide variability (Miller et al, 1984), conversational rates typically vary between 140 to 180 words per minute (wpm). A TV or radio newsreader working from a prepared script can easily exceed 210 wpm (Stine et al, 1990). Because of the rapidity of speech, we might expect to see very large age effects in speech processing, especially when speech rates are increased. As it happens, this is true, but the size of the effect depends on the kinds of speech materials involved and the presence or absence of support from linguistic context.

SLOWING, SPEECH RATE, AND LINGUISTIC CONTEXT

We can illustrate the effects of slowing on speech processing by giving young adult and elderly listeners recorded speech that has been time compressed. This can be accomplished by digitizing a recording of natural speech and using a computer to periodically delete small segments from the speech stream. If the discarded segments are kept small, their absence will go unnoticed when the remaining segments are then abutted in time. When played back at

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normal speed, the result is speech reproduced in less than normal time, but without the distortion in pitch that would, for example, accompany tape-recorder playback at faster than normal speed. By reiteratively removing these small unnoticed segments equally from both speech and silent periods in the speech stream, one preserves the relative temporal patterning of the natural speech, an important factor in speech processing. The degree of compression is controlled by the frequency with which the tape segments are deleted (Foulke, 1971).

Studies have shown that young adults can follow time-compressed speech quite well. So long as the speech content is not too taxing, rates twice that of normal can be handled — although not without effort on the part of the listener (Foulke, 1971; Wingfield, 1975). Time compression will lose some richness of the speech signal, but its effects are presumed to be due primarily to the loss of normally available processing time (Aaronson et al, 1971; Overmann, 1971; Chodorow, 1979). A general slowing in perceptual processing speed associated with normal aging would thus predict that elderly listeners should find a loss of such processing time especially damaging.

Figure 1 shows data taken from a study by Wingfield et al (1985) who tested young and elderly adults' accuracy of report for three types of speech materials presented at four speech rates. The first type of speech consisted of meaningful English sentences, five to eight words in length. For the second type of materials, the words of these normal sentences were rearranged to form an additional set of "sentences" that retained the elements of formal syntactic structure but were semantically anomalous. Such sentences (e.g., "Colorless green ideas sleep furiously," or "Frisky water drank clear dogs") are referred to as syntactic strings, and have a long history in psycholinguistics research. Finally, the words of the original sentences were again rearranged, this time in random order, to produce completely meaningless and unstructured word strings. These are referred to as random strings. The speech materials were recorded by a female speaker of American English in normal intonation for the normal sentences and syntactic strings, and in list intonation for the random strings, in which each of the words was spoken with equal stress and timing.

The left panel of Figure 1 shows the average percentage of words reported correctly for these materials by young adults, and the right panel shows performance for a group of healthy

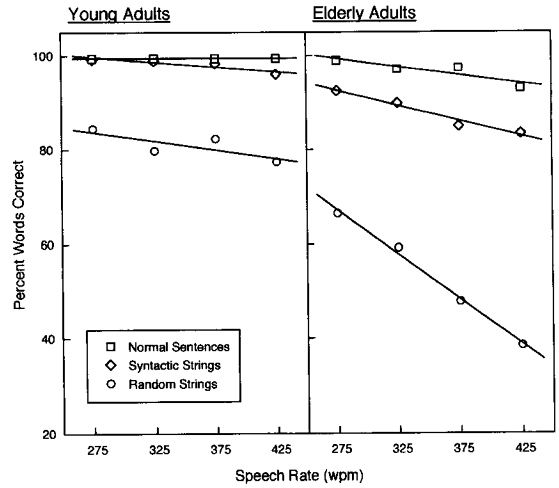

Figure 1 Percentage of words correctly reported as a function of speech rate for normal sentences, syntactic strings (word sequences deprived of meaning but following general syntactic form), and random strings (totally unstructured word sequences with neither meaning nor syntactic constraints). Data for young adults are shown in the left panel and data for elderly adults are shown in the right panel. (Data from Wingfield et al, 1985.)

elderly adults. Each subject heard examples of the three types of speech materials at four rates: 275, 325, 375, and 425 wpm. The materials and rates were counterbalanced across subjects, and a within-subjects design was used, such that each subject's performance in the various conditions was always tested against his or her own performance level in the other conditions. The young subjects (18–22 years of age) and the elderly subjects (65–73 years) were all well educated and had good verbal ability scores as measured on WAIS-R vocabulary. The elderly group, who were active, community-dwelling adults, had age-appropriate memory spans and hearing, and all reported themselves to be in good health. (See Wingfield et al, 1985, for added detail.)

The y-intercept differences for normal sentences, syntactic strings, and random strings can be presumed to reflect the greater processing and memory challenge represented by the progressively less structured verbal materials. Our primary interest, however, is on the slopes of these functions, the degree to which processing becomes progressively more difficult as speech rate is increased.

One might consider the subjects' responses to random strings as closest to "pure" processing ability, as there is no context to facilitate word recognition or to help the subjects infer what they might have missed. In this case, the elderly subjects show a dramatically steep decline in report accuracy with increasing speech rate. We can also see, however, that the steepness of the slope functions progressively decreases for the syntactic strings and the normal sentences. That is, were one to look at just the young and elderly subjects' performance for the normal sentences, one could erroneously conclude that increasing the speech rate caused only minimally more of a problem for the elderly subjects than for the young subjects. Indeed, at the slowest rate used in this study (a very rapid 275 wpm), both young and elderly subjects' performance was close to a "ceiling" of 100 percent accuracy. (Recall that normal conversational speech rates ordinarily average between 140 to 180 wpm.)

This experiment makes two points. The first is that the nearly ubiquitous slowing one sees across a range of processing domains in normal aging (Salthouse, 1991) also has an impact on elderly subjects' auditory processing for natural language. The second is that these age-related deficits in processing speed interact with the content and structure of the speech materials. This source of compensation for declining processing capability derives from effective use of linguistic knowledge. Indeed, results such as these add to the belief that, except in advanced stages of neuropathology, linguistic knowledge and its application remain resistant to loss in aging (Light, 1990; Wingfield and Stine, 1992; Kempler and Zelinski, 1994).

Our focus here has been on rapid speech as a source of challenge for a slowed processing system associated with aging. There are, of course, common differences in the sensitivity of the peripheral auditory system in young and elderly adults with age-normal hearing (Olsho et al, 1985). These changes include decreased sensitivity, especially in the high frequencies, which can be damaging to speech perception (Humes et al, 1994; Olsho et al, 1985). Speech recognition by the elderly is also known to be more vulnerable to the presence of background noise (Dubno et al, 1982; Duquesnoy, 1983; Gordon-Salant, 1987), reverberation patterns that might simulate listening in a hall with unfavorable acoustics (Gordon-Salant and Fitzgibbons, 1993), or when speech is filtered through bandwidths simulating telephone transmission (Bergman et al, 1976; Bergman, 1980).

The y-intercept differences between the young and elderly adults in Figure 1 may thus be influenced by peripheral sensitivity changes as well as by differences in the processing requirements imposed by the addition and removal of linguistic structure in the speech materials. The strength of this latter effect can be seen in the large difference between the y-intercepts for sentences versus random word strings, even for the young listeners. Similarly, it might seem that an auditory system with compromised peripheral sensitivity might be especially susceptible to a reduced richness in the acoustic signal associated with time compression. This factor might thus combine with the elderly's special vulnerability to a loss of processing time and affect the slope differences we observe in Figure 1.

The dynamic between stimulus degradation, presbycusis, and cognitive slowing remains an important area for research. What data we do have, however, suggests that the age effect in the perception of time-compressed speech is independent of effects of peripheral sensory impairment. That is, when young and elderly adults are matched for hearing acuity (i.e., comparing young adults with a hearing loss that matches that of an elderly group, or comparing normal-hearing young adults with elderly adults who have no audiometric signs of presbycusis), elderly listeners continue to show special vulnerability to time-compressed speech (Luterman et al, 1966; Sticht and Gray, 1969; Konkle et al, 1977; Gordon-Salant and Fitzgibbons, 1993). Regardless of the source of the processing deficit, however, the data shown in Figure 1 offer dramatic evidence for the compensatory power available from coherent linguistic structure for young and elderly adults.

The detection and resolution of linguistic structure is known to be facilitated by the prosodic marking that ordinarily accompanies natural speech (Wingfield, 1975). Such prosodic features include the intonation pattern (pitch contour) of the spoken sentences, word stress (a complex subjective variable based on pitch, timing, and loudness), pauses that sometimes occur between major syntactic elements of a sentence, and the lengthening of final vowels in words immediately prior to a clause boundary. These prosodic features are intrinsic to speech production, and are probably organized at the earliest stages of sentence planning (Ferreira, 1993). When experiments are conducted in which prosodic information and linguistic information are independently varied, elderly listeners can be shown to make good use of prosodic information in on-line speech processing, especially under difficult listening conditions (Cohen and Faulkner, 1986; Stine and Wingfield, 1987; Wingfield et al, 1989, 1992).

WORD-ONSET GATING AND AGE

The experiment described above using time-compressed speech gives a comprehensive picture of elderly adults' speech recognition because of its focus on the processing of complete sentences. We now narrow our focus to the perception of individual words, using a more analytic study that demonstrates one kind of detailed processing that underlies the preservation of whole sentence comprehension.

Speech could not be processed at the rate it is if the full duration of a word had to be heard before it could be identified. We can see how much word-onset information is minimally necessary for word identification by using word-onset gating (Grosjean, 1980). In this technique, subjects are allowed to hear, for example, the first 50 msec of a word, then the first 100 msec of the word, then the first 150 msec of the word, and so on, until the word can be correctly identified. Using this technique, it has been shown that words heard in a sentence context can be recognized, on average, within as little as 200 msec of their onset, or when less than half of their full acoustic duration has been heard. Words heard in isolation from a sentence context require, on average, only 130 msec more (Grosjean, 1980; Marslen-Wilson, 1984; Tyler, 1984).

This rapid identification is made possible because the number of words sharing the same initial sounds (the word-initial cohort) is limited, and as more and more of a word onset is heard, the number of potential word candidates decreases at a dramatic rate (Tyler, 1984; Wayland et al, 1989). In fact, a simple power function relating the number of possible word candidates at a particular point in word-onset duration, and the probability of correct word identification, can account for 94 percent to 99 percent of the variance in auditory word recognition (see Wayland et al, 1989, for these data as well as for psychophysical functions for words of different syllable lengths).

Elderly subjects with age-normal hearing can be expected to require somewhat longer word-onset gate sizes for correct word identification, although this difference may amount to less than a single 50-msec gate (Wingfield et al, 1991; Perry and Wingfield, 1994). Indeed, these figures are only slightly longer for left hemisphere lesion stroke patients with moderate to severe aphasia (Wingfield at al, 1990).

Starting from their own baselines for word recognition in isolation, however, elderly subjects make differentially greater use of context to facilitate recognition than do young adults matched for education and general verbal ability (Wingfield et al, 1991; Perry and Wingfield, 1994). Specifically, those age differences that appear for words in isolation disappear when the words are heard within a sentence context. Such results show that elderly listeners, like young adults, use top-down processing (semantic and syntactic constraints) in conjunction with phonologic bottom-up processing (based on sensory-acoustic information) in auditory processing for speech.

The most adaptive system would be one in which declining bottom-up processing capability is proportionally counterbalanced by a corresponding increase in the use of top-down information. As a general rule, this seems to be the case in healthy aging (Wingfield et al, 1991).

MEMORY CONSTRAINTS ON AUDITORY WORD RECOGNITION

There are cases, other than rapid speech, in which the elderly are less proficient at processing spoken language than young adults. This occurs, for example, when inferential processes and rapid gist extraction are required (Cohen, 1979), and when the speech has especially complex syntax (Norman et al, 1991). There is another case that is more subtle and less easily observed, except by controlled experiment. That is, although it can be shown that elderly subjects can make excellent use of preceding context to facilitate word recognition, this is not equally so for the use of context that follows a target word.

It is known that words spoken in connected discourse are often poorly articulated. This can be demonstrated by splicing individual words out of speech recordings and then testing their intelligibility when they are presented in isolation (Lieberman, 1963; Pickett and Pollack, 1963; Pollack and Pickett, 1963). This lack of clarity can be thought of as a "functional adaptation," in which speakers adapt the richness of their articulatory output to their tacit knowledge that the listener will use the linguistic context to compensate for poverty in articulation (Lindblom et al, 1992). Such a system would conserve articulatory effort, where, all things being equal, the higher the probability of a word in context, the less clearly it will need to be articulated (Lieberman, 1963; Hunnicutt, 1985). Indeed, those same studies that have shown poor intelligibility for words out of context show that, when the words are spliced back into their original sentence contexts, they sound crystal clear (Lieberman, 1963; Pickett and Pollack, 1963; Pollack and Pickett, 1963).

It may be for this reason that the lack of articulatory clarity of words in connected speech has received relatively little attention in the audition literature. In most studies of single word perception, words are spoken clearly, in citation form. In studies of connected speech, the lack of articulatory clarity may be present, but it will be masked by the perceptual support supplied by the linguistic context in which the words are embedded.

If we assume that speech is processed in an on-line interactive fashion (Moss and Marslen-Wilson, 1993; see the review by Wingfield, 1993), the continual recoding and consolidation of input this implies would keep the running memory load relatively light (Abney and Johnson, 1991). This would not be true, however, when words remain acoustically ambiguous until their identity has been clarified by the context that follows the word. Such cases are by no means rare (Grosjean, 1985; Connine et al, 1991). We know that significant memory constraints do accompany normal aging (Wingfield et al, 1988; Salthouse, 1991). Off-line retrospective analyses that require temporary memory storage for the unidentified signal and the words that follow it might thus especially burden a short-term working memory system already compromised by age. The gating experiment previously described showed that elderly adults can make good use of a preceding context for word recognition. In the following experiment, we replicate this effect, but also go beyond it, by comparing effects of forward and backward linguistic context on word recognition. It is also here that we demonstrate an age limitation in context utilization in the mechanism of speech perception.

Figure 2 shows data taken from a study in which young and elderly listeners were tested on their ability to use preceding or following context to recognize the identity of words that had been excerpted from recordings of connected speech (Wingfield et al, 1994). The stimuli consisted of English sentences, ranging in length from 12 to 16 words, which were read aloud by a female speaker of American English in a natural manner in normal intonation. A speech-editing system on a computer was used to splice out each word from the sentences for presentation in isolation. This method was used to select one word from each sentence that was difficult to recognize in isolation (and that was preceded and followed in the original sentence by at least four words).

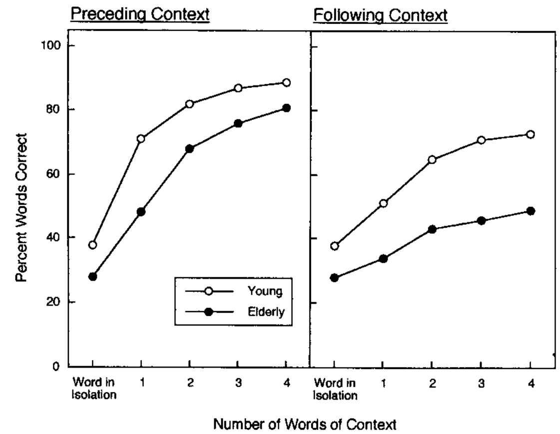

Figure 2 Percentage of target words correctly identified by young and elderly adults when words were heard in isolation and when they were heard either preceded (left panel) or followed (right panel) by from one to four words from the original utterance. (Data from Wingfield et al, 1994.)

The young subjects (ages 18–22 years) and elderly subjects (ages 63 to 76) were again healthy adults with good levels of education and verbal ability and with normal hearing for their ages. (See Wingfield et al, 1994, for additional detail.)

The left panel of Figure 2 shows intelligibility scores (percentage of words correctly identified) when the words were heard in isolation, and when they were presented to the subjects with the one word that had immediately preceded it in the original sentence, and then with the two, three, and four preceding words from the original sentence. It can be seen that, although the elderly subjects start from a marginally lower intelligibility baseline for the words heard in isolation than the young subjects (37.5% correct vs 27.7%, $p < .09$), the overall pattern of improvement with each additional word of preceding context is similar. Indeed, an analysis of variance (ANOVA) conducted on just the preceding context data showed a significant main effect of context ($p < .001$), but no main effect of age, nor a significant age by context interaction.

Part of the context effect when a target word is presented with the immediately preceding word can be attributed to short-range coarticulation cues that can influence phoneme recognition when neighboring sounds are supplied (Daniloff and Hammarberg, 1973; Yeni-Komshian and Soli, 1981). The improvement that continues to occur as two, three, and four words of context are added would be beyond the range of coarticulation. In these cases, the context effect would have to be due to the linguistic context at the level of syntax and sentence meaning. The important point, however, is the similarity in relative increments of improvement for the young and elderly subjects as increasing context was supplied prior to the target word.

A qualitatively different pattern is seen for the effects of a following context. These data are shown in the right panel of Figure 2 for the same two groups of subjects. (The particular target words and sentences heard in the preceding and following context conditions were counterbalanced across subjects.)

Utilization of context that follows an unidentifiable word requires a retrospective or "off-line" analysis, in which a memory representation of the target word (acoustic or phonologic) must be held for a brief period awaiting the arrival of the following context. The shallower context functions in the right panel of Figure 2, relative to those in the left panel, show that neither subject group made as effective use of a following context as a preceding one. This was true even though, for these stimuli, we had gathered normative data using a "cloze" procedure (see Wingfield et al, 1994) to ensure that the degree of contextual constraint was equated for both context directions. In this case, an ANOVA showed that context continued to have a significant effect on correct word identification ($p < .001$), but now there was a significant effect of age ($p < .01$) and a significant age by context interaction ($p < .05$). That is, while both groups gained some advantage from a following context, the relative improvement gained by the elderly subjects was differentially less than it was for the young subjects. (A third condition, not plotted here, used a bilateral context. Not surprisingly, this produced the strongest facilitation.)

The memory-conserving properties of on-line processing, as speech is processed "forward" in time, enables elderly listeners to make effective use of context to compensate for slowing or other losses that would ordinarily appear in isolated bottom-up processing. It should be noted in this regard that the use of top-down support from linguistic context was also seen in the young subjects' data in the experiments we have described. It has long been recognized that speech perception, whether by young or elderly adults, is inherently context dependent. This context dependence can be seen from the level of the influence of an acoustic surround on the identification of particular phonemes (Liberman et al, 1967) to the level of linguistic context that has been our primary focus here. The use of context may sometimes be conscious, as when one is confronted by a noisy telephone line and consciously attempts to infer the identity of a particular static-masked word. At other times, the use of context may be "precognitive," to use Liberman and Mattingly's (1989) term, in the sense that context utilization operates without conscious mediation. In either case, contextual information plays an important role in speech processing for both young and elderly adults.

By contrast to the effective use of forward context, we have seen in this experiment how a memory constraint in the elderly can interfere with their ability to hold information for effective use of downstream context in order to conduct retrospective analyses that are a natural part of everyday language processing. In this case, a limitation in immediate memory span can lead to a failure of comprehension.

CLOSING NOTE

It is important to stress that the subjects in these studies were healthy, well-educated, young and elderly adults. None were neurologically compromised by stroke, or had any sign of dementing illness, and all had been screened for hearing acuity appropriate to their age group. Conducting the sorts of experiments we have described here with hearing-impaired elderly populations would certainly be expected to produce a lowering of y-intercepts consequent to a general performance decrement. The relative shapes of the context-enhancement curves, however, would help us understand the dynamics of the interaction between top-down and bottom-up sources in auditory processing under these circumstances.

One of our challenges in extrapolating from clinical auditory assessment to everyday communicative ability is thus to take into account cognitive factors that may in some cases limit, and in other cases enhance, real-world performance in the elderly listener.

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