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Elucidating the effects of ageing on remembering perceptually distorted word pairs

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We investigated the effects of age, background babble, and acoustic distortion of the word itself on serial position memory in a series of experiments involving six different auditory environments (quiet, and 12-talker background babble presented between, overlapping, or concurrent with word presentation or with two kinds of distortion applied to the words). To control for hearing, the level of babble or distortion was adjusted so that younger and older adults could hear the words equally well. Although the presence of continuous and word-flanking background babble adversely affected memory in the early serial positions in both age groups, only older adults' memory was adversely affected in the later serial positions. Moreover, younger adults' memory was not affected by acoustic word distortion, whereas one of the two types of temporal distortion adversely affected memory for later serial positions in older adults. The exact pattern of impairment and its interaction with age suggests that memory in older adults is more affected than that in younger adults in complex listening situations because they either need more time or have to employ more attentional resources to segregate different auditory streams, thereby depleting the pool of resources available for memory encoding.

Keywords: Speech perception in noise; Paired-associate memory; Young and old listeners; Stream segregation.

In order to successfully follow connected speech and extract the meaning of an utterance, a listener has not only to correctly perceive the individual words but also to integrate them into the broader linguistic context. The processes of committing heard information to memory and successfully retrieving it at a later point in time both play a crucial role in this process. Listeners' ability to remember information is affected by a number of

factors: (a) the linguistic complexity of the material; (b) the speed of its presentation; (c) the number of concurrent tasks in which the listener is engaged (e.g., listening to a conversation while answering email); and (d) the complexity of the auditory environment in which the to-be-remembered material is presented. Whereas a number of studies have explored the effect of these factors on young adults' listening performance, there are

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considerably fewer studies on how age affects memory in these situations. Moreover, investigations are typically restricted to the first three factors, and very little is known about how age affects a person's ability to remember heard material in complex auditory environments. In this study we explore how noise and auditory distortion affect the ability of older adults to remember heard material.

Remembering in noisy and complex auditory scenes

The presence of random noise, other talkers, and babble (many different people talking simultaneously) can interfere with perception and memory for unrelated words or word pairs (Heinrich, Schneider, & Craik, 2008; Murphy, Craik, Li, & Schneider, 2000; Rabbitt, 1968, 1991), sentences (Peelle & Wingfield, 2005; Pichora-Fuller, Schneider, & Daneman, 1995; Schneider, Daneman, & Murphy, 2005), monologues (Gordon, Daneman, & Schneider, 2009; Schneider, Daneman, Murphy, & Kwong-See, 2000), and dialogues (Murphy, Daneman, & Schneider, 2006) in both younger and older adults. The most straightforward interpretation of the results of these studies would be to assume that all of those competing signals cause peripheral (energetic) masking of the auditory signal, which then compromises the intelligibility of the words and their encoding into memory. Energetic masking occurs when the energy in the masking stimulus activates the same regions along the basilar membrane as those that are excited by the speech target thereby compromising the perceptual representation of the speech signal. One consequence may be a broader pattern of activation in the mental lexicon (Luce & Pisoni, 1998; Sommers, 1996), which then requires the engagement of more cognitive resources to facilitate lexical access (Luce & Pisoni, 1998; Sommers, 1996). Following this logic, similar results should occur when the target signal itself is distorted (Luce, Feustel, & Pisoni, 1983) rather than masked by a second signal.

However, there are also studies that indicate that not all masking signals adversely affect

speech in the same way (Brungart, Simpson, Ericson, & Scott, 2001) and that a complex auditory signal can adversely affect memory even when there is little or no decrement in intelligibility (e.g., Heinrich et al., 2008; Luce et al., 1983; Rabbitt, 1968, 1991). Such findings call into question an interpretation based solely on peripheral masking and rather suggest that higher order processes are likely to play an important role. One concept invoked in this context is that of informational masking (Carhart, Tillman, & Greetis, 1969; Durlach et al., 2003; Freyman, Balakrishnan, & Helfer, 2001; Li, Daneman, Qi, & Schneider, 2004; Pollack, 1975; see Schneider, Li, & Daneman, 2007, for a review). For example, a competing speech signal could interfere with the perception and subsequent memory of the target speech because it initiates its own activity in the phonemic, semantic, or syntactic systems, which cannot be inhibited (Hasher & Zacks, 1979). Moreover, those processes may deplete the already limited resources available for memory encoding of the primary target.

Another possibility is that before listeners can perceive and memorize words heard in a noisy background, they need to segregate the target signal from any competing sounds in the auditory landscape (stream segregation, see Bregman, 1990). Although streaming and sound segregation studies involving tone sequences or tone complexes have often found that sound segregation can occur independent of listeners' attention (e.g., Alain & Izenberg, 2003; Carlyon, Cusack, Foxton, & Robertson, 2001; Carlyon, Plack, Fantini, & Cusack, 2003; Snyder & Alain, 2007), other studies using concurrent presentation of more complex stimuli (e.g., synthesized vowels, Alain, 2007; Snyder & Alain, 2005) indicate that attentional mechanisms are engaged to achieve sound segregation.

Perceptual and cognitive interactions in memory

Heinrich et al. (2008) argued that a competing auditory stream might adversely affect memory because, in its presence, the listener has to deploy

attentional resources to extract the target information from it. If the attentional resources needed for stream segregation and word extraction were drawn from the same pool of mental resources as that supporting subsequent memory encoding and retrieval, attention-demanding memory processes, such as encoding, rehearsal, elaboration, and formation of associations, could be adversely affected. Compromised memory encoding, in turn, is likely to lead to a drop in memory performance. In this sense, attempting to memorize words presented in noise is similar to attempting to memorize words while engaging in another attention-demanding task.

Heinrich et al. (2008) drew support for their interpretation from five experiments in which they investigated the effects of a background babble (12 people talking simultaneously) on the memory of word pairs presented in a serial-position paradigm (Madigan & McCabe, 1971). In this paradigm listeners were serially presented with five pairs of semantically unassociated words. After they had heard all five pairs, listeners were prompted with the first word of one of the pairs and were asked to recall the second word in that pair. Typically, memory tended to improve as a function of the word pair's serial position. In the first experiment using this paradigm, Murphy et al. (2000) found that continuous background babble adversely affected memory performance in young adults for early but not late serial positions relative to a quiet baseline condition without babble. Using the same materials, Heinrich et al. found that when the babble was presented only between word pairs it had no effect on memory performance relative to the baseline. Hence, inadvertent processing of the babble content during the consolidation process (informational masking) could not be responsible for the adverse effects of continuous babble on memory performance. In a third experiment, Heinrich et al. found that the presence of babble only during word presentation also had no effect on memory. Thus, the disruptive effect of babble could not simply be due to babble energetically masking the target words, thereby corrupting their mental representation and adversely affecting consolidation. In addition,

when the babble flanked the word pairs (starting 500 ms before the word pair and finishing 500 ms after the end of the pair), its presence produced an effect similar to continuous babble. This last result could have occurred because participants directed their attention towards the auditory stream when the babble began in order to facilitate stream segregation and target word extraction. This caused the consumption of attentional resources, which were subsequently unavailable for memory encoding. This interpretation is supported by Sarampalis and colleagues (Sarampalis, Kalluri, Edwards, & Hafter, 2009) who showed that speech perception in background babble is effortful and resource demanding. Lastly, Heinrich et al. showed that resource limitations due to a dual task (perceiving and encoding the word pairs in a quiet background while performing a digit-monitoring task) led to a similar pattern of memory loss as did word presentation in continuous babble, thereby suggesting that the particular pattern of memory loss caused by continuous background babble might be due to attentional limitations.

How age affects remembering in noisy and complex auditory scenes

Although there is an extensive literature on how age affects memory for seen material (Nilsson, 2003; see Verhaeghen, Marcoen, & Goossens, 1993, for a review), there is little information on how ageing might modify the effects that the auditory background has on memory for heard material. The literature on speech recognition indicates that older listeners are more susceptible to perceptual distortion than are younger listeners (e.g., Gordon-Salant & Fitzgibbons, 1995) but not to the effects of informational masking (Agus, Akeroyd, Gatehouse, & Warden, 2009; Helfer & Freyman, 2008; Li et al., 2004). With respect to sound segregation, while the streaming of ABA tone sequences appears to be unaffected by age (Snyder & Alain, 2007), the segregation of synthetic vowel stimuli is (Snyder & Alain, 2005; Vongpaisal, & Pichora-Fuller, 2007). These results suggest that age differences in

streaming are more likely to occur when stimuli are more complex and speech-like.

A first indication of how age-related differences in stream segregation affect memory performance was given by Murphy et al. (2000), who found that older listeners' memory performance for words presented in quiet was remarkably similar to young listeners' memory performance for words presented in continuous background babble. In both conditions, older listeners recalled fewer words than younger adults in quiet for Serial Positions 1–3, but not for Positions 4 and 5. Murphy et al. suggested that the last two pairs of a list depended on working memory for recall, whereas the more temporally remote first three word pairs depended on a longer term episodic memory system for successful encoding and retrieval. Hence, the pattern of results suggested that both age and noise negatively affected episodic memory, but not working memory. If attentional resources need to be engaged to transfer words from working memory to episodic memory (Craik, 1983), then these results showed that the transfer to episodic memory suffered before encoding into working memory when resources were scarce. In younger listeners, this pattern of results occurred when listeners were required to segregate target words from the continuous background babble. In older adults, resource limitations may reflect general age-related reductions in the pool of attentional resources (Craik, 1983; Craik & Byrd, 1982; Craik & Simon, 1980; Hasher & Zacks, 1979). Hence, in the Murphy et al. (2000) study, resource limitations could have produced equivalent effects in the early serial positions even though the underlying reason for the limitation differed (age and background noise, respectively).

Murphy et al. (2000) also compared older and younger listeners' memory for word pairs in background babble when the level of background babble was adjusted in both age groups to make it equally difficult for younger and older listeners to identify the individual words. In this case, older listeners performed more poorly than younger listeners in all serial positions. This result was thought to occur because older adults'

pool of resources is generally smaller, and any additional strain (such as having to extract the target words from the babble) increased the processing load to the point where it affected even processes with relatively low demands, such as holding the fourth and fifth items in primary or working memory.

In the current study, we wanted to explore these claims in further detail and determine exactly how background babble increases the processing load for older listeners and what role masking and stream segregation play when older listeners are attempting to remember target words in continuous background babble.

EXPERIMENTAL DESIGN AND HYPOTHESES

Experiments 1–3 replicate for older adults the conditions tested in Heinrich et al. (2008) for young listeners. In Experiment 1 we investigated whether the presentation of babble between word pairs would disrupt memory in older adults. We might expect this to happen if the babble interfered with the rehearsal and subsequent consolidation of items in memory. We know that this is not the case for young adults (Heinrich et al.), yet there are reasons to believe that it could play a significant role for older adults. Various studies have demonstrated age-related inhibitory deficits in cognitive processes (e.g. Hasher, Zacks, & May, 1999). If these deficits extended to the inhibition of irrelevant babble during rehearsal, we might see an adverse effect on memory performance.

In Experiment 2 we investigated whether presenting the babble background only during word presentation would negatively affect memory in older adults relative to their performance in quiet or in continuous babble. Recall that Murphy et al. (2000) found that a continuous background babble reduced recall of words in older adults at all serial positions, a result that they attributed to severely restricted attentional resources for older adults. An alternative interpretation for the same result could be that older adults are more susceptible to the effects of masking than are younger

adults (Cobb, Jacobson, Newman, & Kretschmer, 1993; Gehr & Sommers, 1999; Li et al., 2004), although this effect may be more closely related to hearing loss than age per se (Klein, Mills, & Adkins, 1990). If that were the case, then masking only the words should affect memory in a manner similar to that of continuous babble.

In Experiment 3 we investigated the effects of flanking babble on memory performance in older adults. In our previous study, this was the only condition that adversely affected memory in young listeners and led to a decline similar to that seen for continuous babble. For older adults, it is even more likely than for young adults that their performance will be adversely affected by flanked babble because studies point towards age effects in more peripheral, sensory processes as well as in more central, higher order cognitive processes. On a peripheral level, starting babble shortly before the presentation of the words and finishing it shortly after may lead to more forward and backward masking for older than for younger listeners (Cobb et al., 1993; Durlach et al., 2003; Gehr & Sommers, 1999; Walton, Orlando, & Burkard, 1999). Whereas for younger listeners there is evidence that detection and recognition of words in noise is improved when the noise precedes the babble (Wagener & Brand, 2005), it is possible that flanking the words with babble would be a disadvantage to intelligibility for older adults. On a central level, if flanking noise initiates the same streaming mechanisms in older listeners as does continuous babble, then we might expect the same strain on resources and therefore a similar drop in memory performance. Alternatively, in older adults it is even possible that the improvement in speech intelligibility due to streaming is completely offset by the demands that streaming places on the smaller pool of attentional resources available to them (Craik, 1983; Craik & Byrd, 1982; Craik & Simon, 1980; Hasher & Zacks, 1979).

Finally, in Experiments 4 and 5 we wished to explore possible effects of perceptual distortion on young and older adults in more detail. Rather than using a babble masker as an additional signal to compromise the perceptual

representation of the target words, we sought to distort the target words themselves. Similar to the word-only babble condition, the distortion occurred only during word presentation. In the previous study, gating babble on and off with the target words had no effect on young adults. Hence we might expect that distortion would also not have an effect on younger adults. However, if the effects of energetic masking are more severe in older than in younger listeners, we might find that distorting the words themselves also affects memory in older adults even though it does not in younger adults.

All stimulus conditions, together with a time line of the presentation of word and babble segments in each experiment, are depicted in Figure 1.

Method

The stimuli, apparatus, testing protocols, participant pools, and research technicians were identical to those in both the Murphy et al. (2000) and Heinrich et al. (2008) studies. Hence, we have incorporated some of their data in the analyses presented below. Instances in which this has been done are identified as they occur.

Participants

A total of 50 young and 97 older adults participated in the study. Young adults were undergraduate students at the University of Toronto. Older participants were adults from the local community and provided their own transportation to the testing facility. All participants learned to speak North American English before the age of 5. The data on age, years of education, Mill Hill vocabulary score, babble threshold, and SPIN (Speech Perception in Noise test) were compared separately for young and older adults across experiments in one-way analyses of variance (ANOVAs). Except for one instance, where older adults in Experiment 1 had significantly more years of education than older adults in Experiments 4 and 5, there were no significant differences in any of these measures between experiments (see Table 1). In exchange for their participation they received \$10 per hour.

Figure 1. Stimulus conditions for Experiments 1–5.

Reading comprehension and working memory measures were also available for a subset of the older participants. These cognitive measures were collected in the context of other studies that were run in the same lab using the same participant pool. Reading comprehension was measured on 70 older adults using the Nelson–Denny reading comprehension test (Form E: Brown, Bennett, & Hanna, 1981). The test consisted of eight prose passages and 36 questions. Participants were allowed 20 min to complete the test. The mean of the Nelson–Denny scores for the 70 older adults was 21.7 (SD : 6.34). These results were compared to a group of 115 younger adults (Hannon & Daneman, 2004) who had a mean score of 23.02 (SD : 6.33). There was no significant difference between the groups, $t(183) = 1.37, p > .05$. Working memory measured by means of reading span (Daneman & Carpenter, 1980) was also available for 53 of the older adults and 77 of the younger participants who had taken part in

the experiments reported by Heinrich et al. (2008). The mean performance of the 53 older adults was 43.4 (SD = 8.5) out of 70. The working memory score of the young comparison group was 48.9 (SD = 8.0)—somewhat higher than that of older adults on this measure, a result that has been found previously, $t(128) = 3.82, p > .01$. This age difference between younger and older adults is typical in healthy ageing.

Material

The word pairs used were the same as those in Murphy et al. (2000) and Heinrich et al. (2008). The material consisted of a total of 400 two-syllable common nouns with a frequency of more than 1 per million (Kucera & Francis, 1967). Mean phonological neighbourhood density, computed by summing densities for one letter added or deleted, substituted, or transposed, was 4.58 (SD : 3.79). The counts were based on the norms given in CELEX (Baayen, Piepenbrock, & Gulikers, 1995). Mean word

Table 1. Participant details for all groups of listeners in Experiments 1–5

Experiment	N	Age range	Age M(SD)	Gender (M/F)	Education M(SD)	Vocab score M(SD)	Left-ear threshold	
							Babble M (SD)	R-SPIN
1	15	18–24	20.13 (1.55)	2/13	15.67 (1.72)	14.47 (1.51)	15.34 (3.20)	1.93 (1.86)
	15	64–81	69.33 (4.92)	4/11	16.43 (3.69)	15.33 (1.34)	23.16 (6.62)	8.50 (2.71)
2	16	18–23	19.69 (1.35)	4/12	15.06 (1.88)	13.38 (1.63)	15.30 (2.92)	0.44 (2.25)
	17	65–84	72.41 (6.47)	4/13	13.59 (2.69)	14.29 (2.02)	25.56 (8.41)	4.24 (3.47)
3	15	18–24	20.60 (1.81)	6/9	15.13 (1.55)	13.80 (2.68)	16.90 (1.08)	1.79 (1.73)
	15	65–83	69.47 (4.84)	4/11	14.60 (3.38)	15.07 (1.87)	21.75 (6.67)	4.00 (2.32)
4 (P)	10	20–24	21.20 (1.62)	2/8	16.60 (1.90)	13.50 (1.90)	13.57 (3.75)	
	10	65–78	67.50 (4.48)	5/5	13.20 (3.65)	14.70 (1.57)	23.03 (4.32)	
4 (M)	15	19–24	21.40 (1.72)	6/9	16.40 (1.92)	13.67 (1.99)	15.86 (4.54)	
	15	64–79	69.53 (4.75)	8/7	13.07 (2.50)	15.33 (2.32)	22.97 (4.70)	
5 (P)	10	18–21	19.80 (0.92)	4/6	14.70 (0.82)	13.70 (2.00)	15.92 (2.90)	
	10	67–83	74.80 (5.07)	4/6	13.80 (3.43)	14.90 (1.79)	23.26 (4.80)	
5 (M)	15	19–25	20.93 (2.28)	6/9	15.93 (2.58)	13.40 (2.69)	15.29 (3.68)	
	15	64–77	70.53 (3.56)	5/10	12.73 (2.71)	15.20 (2.93)	22.40 (5.53)	

Note: M = mean, SD = standard deviation. Education was measured in years of formal education, the vocab score was the result of the Mill Hill vocabulary test (score out of 20). P = perception experiment; M = memory experiment. R-SPIN = revised Speech Perception in Noise.

frequency (48.43, *SD*: 81.57), familiarity (515.62, *SD*: 61.21), concreteness (500.88, *SD*: 110.25), and number of phonemes per word (5.03, *SD*: 1.00) were taken from the Medical Research Council (MRC) Psycholinguistic Database (MRC Psycholinguistic Database: Machine Usable Dictionary. Version 2.00. Retrieved from <http://www.psy.uwa.edu.au/mrcdatabase/mrc2.html>; Coltheart, 1981). One-way ANOVAs with word position (first or second in a pair) as factor and two-way ANOVAs with word-pair position (1–5 in a list) and list number (1–40) as factors found no main effects or interactions for any of the variables.

Words were paired such that no obvious association existed between them. The individual words, spoken by a female speaker of North American English, were digitally recorded at a sampling rate of 20 kHz within a single-walled sound-attenuating chamber. All recordings had similar root mean square (RMS) values. For stimulus presentation, the words were delivered through a 16-bit digital-to-analog converter (TDT DD1) followed by a

10-kHz low-pass filter (TDT FT6–2, 60-dB attenuation at 11.5 kHz), a programmable attenuator (TDT PA4), and a weighted signal mixer (TDT SM3). All testing took place in a double-walled sound-attenuating chamber.

Procedure

Audiometric testing. Pure-tone air-conduction thresholds were determined for all participants for nine frequencies between 250 and 8,000 Hz and were used as inclusion criteria for the study. This was done in order to minimize the possibility that audiometric differences could act as an explanation for the potential differences in the memory task between the two age groups.

Pure-tone audiometry was tested using an Interacoustics Model AC5 audiometer; the left ear was always tested first. To participate in the study, participants were required to have pure-tone air-conduction thresholds of less than or equal to 30-dB HL (American National Standards Institute; ANSI, 1996) at all frequencies

between 250 and 2,000 Hz, less than or equal to 35-dB HL at 3,000 Hz in the test ear, and less than or equal to 45 dB at 4,000 Hz. There were no requirements for frequencies higher than 4,000 Hz. Moreover, listeners were permitted to exceed these criteria at one test frequency by 5 dB.

Babble threshold. The procedure was the same as that in Murphy et al. (2000) and Heinrich et al. (2008). Briefly, the threshold for detecting a speech babble was determined for individual listeners by means of an adaptive two-interval forced-choice procedure, which estimated the signal level corresponding to 79% correct detection (Levitt, 1971). The babble was taken from the modified Speech Perception in Noise (R-SPIN) test (Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984). The speech threshold was obtained for the right ear first and the left ear second. Because stimuli were presented to the left ear only during these experiments, Table 1 presents babble thresholds for the left ear only. Within each age group, there were no statistically reliable differences in mean babble threshold between experiments or between perception and memory groups when two separate groups existed within the same experiment (Experiments 4 and 5). When babble was present, word pairs were presented 50 dB above each listener's babble threshold.

Individually adjusting the signal-to-noise ratio (SNR). As in the earlier two studies, the low-context sentences from the R-SPIN test (Bilger et al., 1984) were used to determine for each individual the SNR that resulted in 50% correct identification of the sentence final word. Participants listened to at least two R-SPIN lists at SNRs chosen to bracket the 50% intelligibility point for the final word in low-context sentences. The SNR corresponding to the 50% point was then determined by interpolating between the SNR values used in the two lists. The resulting value, lowered by another 7 dB, was then used in the memory task. We used this procedure because we anticipated that it would result in a 91% accuracy with which listeners perceive the individual words (Murphy et al., 2000) when

they were presented in a babble background. Table 1 presents the average SNR values for 50% intelligibility of low-context R-SPIN sentences in Experiments 1–3.

Word recall. In all five experiments, participants listened to 40 lists containing five word pairs each. The words were randomly paired, with any obvious association between two words being avoided. Four seconds after a short warning tone (1-kHz tone presented at 90 dB for 500 ms) had indicated the beginning of a list, the first word was presented. Within each pair, there was a silent period of 100 ms between the words; the word pairs were played with a presentation rate of one pair every four seconds. Four seconds after the start of the final word pair a short warning tone indicated the beginning of the recall phase. After another four seconds participants were cued with the first word from one of the five previously presented word pairs and were asked to recall the second word of the pair. Only one pair from each list was cued. There was no time limit placed on the recall. Participants were encouraged to guess.

We use the term “serial position” to refer to the presented word pairs; for example, the first serial position refers to the first word pair and so forth. List order was identical for all participants, and the serial position of each word pair within the list was tested an equal number of times (8 times) within a session. The order in which the serial positions were tested was independently and randomly determined for each participant. There were no practice trials, and no feedback was provided. There was a break after the presentation of the first 20 lists. Memory performance for each serial position was measured.

EXPERIMENT 1: BABBLE PRESENT ONLY BETWEEN WORD PAIRS

In this experiment, the babble started 500 ms after the end of the word pair and finished 500 ms before the beginning of the next word pair. The 500-ms silence between word pair and babble

Figure 2. Audiometric thresholds as a function of frequency for all older participants in Experiments 1–5. A hearing level of 0 dB HL represents the performance of a normal-hearing young adult according to the American National Standards Institute (ANSI, 1996). Reprinted also are the thresholds of listeners in the young-adults companion study (Heinrich et al., 2008).

was inserted to prevent backward and forward masking.

One group of 15 older adults participated in Experiment 1. Their performance was compared to that of a group of younger listeners ($n = 15$) who had completed the same listening task and whose data are reported in Experiment 2 of Heinrich et al. (2008). The information regarding the young group is reprinted to facilitate the comparison between the two groups. Average audiometric thresholds for the left ear of young and older participants in this and all other experiments of the study are displayed in Figure 2. One older participant exceeded the required threshold for 2 kHz by 5 dB.

Results and discussion

Figure 3 plots the percentage of words correctly recalled as a function of serial position for younger (circles) and older (squares) adults in quiet (filled symbols) and when babble was presented only between word pairs (unfilled symbols). Visual inspection of these data suggests that the presence of babble between word pairs had no effect on performance in either younger

Figure 3. Average percentage of correctly recalled word pairs and standard errors of the means for word pairs presented in discontinuous babble presented only between word presentation (between-words noise) for young (empty circles, Experiment 2 of Heinrich et al., 2008) and older (empty squares) listeners. Also shown are recall results for word pairs presented in the quiet baseline condition for young (filled circle) and older (filled squares) from Murphy et al. (2000).

or older adults. This was confirmed by submitting the data to an age (young, old) by noise condition (quiet, babble between word pairs only) by serial position ANOVA with serial position as a within-subject variable and age and noise conditions as between-subject variables. The ANOVA confirmed significant main effects of serial position, $F(4, 224) = 103.30$, $MSE = 270.87$, $\eta^2_p = .65$, $p < .0001$, and age, $F(1, 56) = 6.75$, $MSE = 1,130.43$, $\eta^2_p = .11$, $p = .012$, but no significant effect due to noise condition ($F < 1$). There was, however, a significant two-way interaction between age and serial position, $F(4, 224) = 3.41$, $MSE = 270.87$, $\eta^2_p = .06$, $p = .01$. None of the other interactions were significant (all $F_s < 1$). Hence the presence versus absence of babble between word pairs had no

effect on either younger or older adults' performance, thereby replicating the age effects found in Murphy et al.'s (2000) baseline condition. Because there was no effect of noise condition, we collapsed over this variable to establish baseline conditions for younger and older adults.

EXPERIMENT 2: BABBLE GATED ON AND OFF WITH WORD PAIRS

In Experiment 2, the babble noise was gated on and off with each word pair in such a way that it started simultaneously with the onset of the first word of the pair and terminated with the end of the second word of the pair. The time period between the offset of the second word of the previous pair and the onset of the first word of the next pair was filled with silence.

The data of 17 older adults were collected and were compared to the results obtained for 16 young adults in Heinrich et al.'s (2008) Experiment 1. Moreover, the results of both of these groups were compared to the newly established quiet baseline of 30 young and 30 older adults from Experiment 1 in the current report. This combined baseline consisted of listeners who performed the memory task either in the absence of background babble (Murphy et al., 2000) or when the babble was only present between word pairs (see Experiment 1 for older listeners and Heinrich et al., 2008, for young listeners).

Results and discussion

Figure 4 plots percentage correct as a function of serial position for younger and older adults in the combined baseline condition and when babble is presented only during word presentation. This figure suggests that compared to the baseline, babble during word presentation adversely affects performance in older adults primarily during the later serial positions, yet does not have any adverse effect on younger adults. This was confirmed by submitting the data to an age (young, old) by noise condition (baseline, babble during

Figure 4. Average percentage of correctly recalled word pairs and standard errors of the means for word pairs presented in discontinuous babble presented only during word presentation (word-only noise) for young (empty circles, Experiment 1 of Heinrich et al., 2008) and older (empty squares) listeners. Also shown are recall results for word pairs in the baseline condition (filled symbols). The baseline consists of the combined results for the quiet and between-word babble conditions.

word presentation only) by serial position ANOVA with serial position as a within-subject variable and age and noise conditions as between-subject variables. This ANOVA confirmed significant main effects of serial position, $F(4, 356) = 87.79$, $MSE = 284.63$, $\eta^2_p = .50$, $p < .0001$, age, $F(1, 89) = 32.67$, $MSE = 1,079.07$, $\eta^2_p = .27$, $p < .0001$, and noise condition, $F(1, 89) = 9.61$, $MSE = 1,079.07$, $\eta^2_p = .10$, $p = .003$. In addition, there were significant two-way interactions between age and noise condition, $F(1, 89) = 6.50$, $MSE = 1,079.07$, $\eta^2_p = .07$, $p = .012$, and noise by serial position, $F(4, 356) = 6.48$, $MSE = 284.63$, $\eta^2_p = .07$, $p < .0005$, as well as a significant three-way interaction, $F(4, 356) = 2.83$, $MSE = 284.63$,

$\eta^2_p = .031$, $p = .025$. None of the other interactions were significant (all F s < 1). A separate ANOVA on the young participants found a main effect for serial position, $F(4, 176) = 46.04$, $MSE = 273.31$, $\eta^2_p = .51$, $p < .0001$, but no significant effect of noise condition nor a significant two-way interaction between noise condition and serial position. We therefore conclude that babble only during word presentation has no effect on the performance of young adults. In contrast, an ANOVA conducted on older adults' memory data confirmed significant main effects of serial position, $F(4, 180) = 43.022$, $MSE = 295.70$, $\eta^2_p = .49$, $p < .0001$, and for noise condition, $F(1, 45) = 20.78$, $MSE = 845.07$, $\eta^2_p = .32$, $p < .0001$, and a significant two-way interaction between serial position and noise condition, $F(4, 180) = 8.02$, $MSE = 295.70$, $\eta^2_p = .15$, $p < .0005$. Post hoc testing using the least significant difference (LSD) test indicated that the effect of word babble led to a significant drop in memory for the last two serial positions compared to baseline performance.

EXPERIMENT 3: FLANKING BABBLE

In Experiment 3, the babble was gated on 500 ms before the onset of the first word of the pair and gated off 500 ms after the offset of the second word of the word pair. The time period between the offset of babble after the second word of the previous pair and the onset of the babble before the first word of the next pair was filled with silence.

A total of 15 older adults were tested in addition to the 15 young adults tested for Experiment 3 in Heinrich et al. (2008). Their results were compared to the combined baseline of 30 young and 30 older adults that was already used in Experiment 2.

Results and discussion

Figure 5 displays percentage correct as a function of serial position for younger and older adults when babble is switched on 500 ms before word

Figure 5. Average percentage of correctly recalled word pairs and standard errors of the means for word pairs for which the babble is switched on 500 ms before the onset of the first word of the pair and switched off 500 ms after the offset of the second word of the pair (flanking noise) for young (empty circles, Experiment 3 of Heinrich et al., 2008) and older (empty squares) listeners. Also presented are recall results for word pairs presented in continuous babble (filled symbols) for young (circles) and older (squares) listeners taken from Murphy et al. (2000).

onset and off 500 ms after word offset (flanking noise, current experiment) and when the babble is present continuously (continuous noise, Experiment 2: Murphy et al., 2000). Visual inspection of Figure 5 suggests that flanked babble replicates closely the memory results for continuous babble in both age groups. This was confirmed by an age (young, old), noise condition (continuous babble, babble gated on and off 500 ms before and after the word pairs) and serial position ANOVA with serial position as a within-subject variable and age and noise conditions as between-subject variables. The analysis showed main effects of serial position, $F(4, 224) = 100.38$, $MSE = 327.20$, $\eta^2_p = .64$, $p < .0001$, Greenhouse–Geisser corrected, and age, $F(1,$

56) = 19.27, $MSE = 624.63$, $\eta^2_p = .26$, $p < .0001$, no effect of noise, $F(1, 56) < 1$, and no two- or three-way interactions (all $F_s < 1$). Hence, the two noise conditions (flanked and continuous) had similar effects on memory, resulting in poorer performance for older adults.

EXPERIMENT 4: DISTORTING THE WORDS—PART 1

Experiments 4 and 5 were designed to further explore the finding that older but not young adults showed effects of masking when the babble was played during word presentation only. We sought a manipulation that would decrease the intelligibility of the word pairs by the same amount as the babble (91% accuracy) but would distort the acoustic form of the words themselves, rather than mask them with a second signal. To do so, we chose to use a jittering procedure (Miranda & Pichora-Fuller, 2002; Pichora-Fuller, Schneider, MacDonald, Pass, & Brown, 2007). To understand how jittering distorts a sound, consider an undistorted signal, $y(t)$. The jittering process distorts the signal by introducing a variable time delay such that the distorted signal $x(t)$ is given by $y(t - \delta)$, where δ is a variable that changes randomly over time. Thus $x(t)$ either leads or lags $y(t)$ depending on whether δ is positive or negative. The value of δ is determined by the amplitude of a low-pass filtered white noise. The range of variation of δ (which has a mean value of 0) is determined by the root mean square (RMS) value of the low-pass noise. The rate of change in δ is controlled by the bandwidth (expressed in Hz) of the low-pass noise. For further details concerning this method see Pichora-Fuller et al. (2007).

To find a parameter combination that degraded perceptual accuracy of the words to 91%, we decided to keep the rate of change in time delay constant (at 100-Hz bandwidth, BW) and only to vary the range of time delays introduced into the signal. We then picked the range value that yielded an intelligibility score closest to 91%. In the subsequent memory experiment, all words were distorted using this parameter combination

and were presented at a sensation level of 50 dB. This was the same presentation level of the word pairs as that previously used for all experiments involving babble.

Finding the appropriate jitter levels

The 400 words used in the memory part of the experiment were presented in 10 lists of 40 words each to 10 participants in each age group. The words in each list were jittered at one of five RMS values (0.3, 0.35, 0.40, 0.45, and 0.50 ms) that were selected on the basis of pilot experiments to bracket a word identification rate of 91%. The rate of change, given by the bandwidth of the noise signal, was kept constant at 100 Hz. The pairing of lists with RMS values, as well as the order of list presentation, was counterbalanced across participants. The words in a list were presented over earphones (TDH-49) to the left ear at a rate of one every 5 seconds at an intensity level of 50 dB SL (i.e., 50 dB above each individual's babble threshold). Participants were asked to listen to and repeat each word. They were encouraged to guess whenever they did not hear a word properly. There were no practice trials, and no feedback was given. Participants were given a short break after the presentation of the fifth list. The experimenter, positioned outside the sound-attenuating booth, monitored the participant's performance by means of headphones. The listener's answers were compared to a checklist containing all the words, and any misidentified words were noted down. Moreover, all answers were tape-recorded and were subsequently double-checked for accuracy. For that purpose, a researcher different from the experimenter listened to the tape and compared the participant's answer with the answer written down by the experimenter. Discrepancies, which were very rare (less than 1 word in 200), were settled by consensus. Five jitter levels were tested for each age group. The level that resulted in word recognition accuracy closest to 91% was 0.5 ms for the young and 0.4 ms for the old. These values were used to distort the words for the memory task. In the memory part of the experiment, 15 young and 15 older participants listened to and

remembered the word pairs distorted with the respective jitter levels noted above.

Results and discussion

Figure 6 plots percentage correct as a function of serial position for younger (circles) and older (squares) adults in two conditions: combined baseline (filled symbols, as before), and when the words were jittered (unfilled symbols). Visual inspection of this figure suggests that jittering the words reduced performance in older adults but not in younger adults, and that the reduction in memory was larger for the later than for the earlier serial positions for older adults. To confirm these observations we submitted the data to an age (young, old) by jitter condition (unjittered baseline, 100-Hz jitter) by serial position

Figure 6. Average percentage of correctly recalled word pairs and standard errors of the means for word pairs jittered with a 100-Hz bandwidth at 0.5 ms (young adults, circles) and 0.4 ms (older adults, squares). Also shown are recall results for word pairs in the baseline condition (filled symbols), which consists of the combined results for the quiet and between-word babble conditions.

ANOVA with serial position as a within-subject variable and age and jitter conditions as between-subject variables. This analysis confirmed significant main effects of serial position, $F(4, 344) = 104.77$, $MSE = 261.43$, $\eta^2_p = .55$, $p < .0001$, age, $F(1, 86) = 31.31$, $MSE = 1,097.98$, $\eta^2_p = .27$, $p < .0001$, and jitter condition, $F(1, 86) = 4.52$, $MSE = 1,097.98$, $\eta^2_p = .05$, $p = .036$. In addition, there were significant two-way interactions between age and jitter condition, $F(1, 86) = 6.52$, $MSE = 1,097.98$, $\eta^2_p = .07$, $p = .012$, confirming that jitter affected older adults more than younger adults; between serial position and age, $F(4, 344) = 2.58$, $MSE = 261.43$, $\eta^2_p = .03$, $p = .037$, indicating that age affected memory in the early serial positions more than in the later serial positions; and between serial position and jitter condition, $F(4, 344) = 3.26$, $MSE = 261.43$, $\eta^2_p = .04$, $p = .012$, indicating that jitter affected more recent serial positions more than the earlier ones. Indeed, post hoc tests (LSD) revealed that only at the most recent serial position did listeners exhibit a reliable decline in memory performance compared with theunjittered baseline. The lack of a significant three-way interaction, which indicates that the serial position by jitter condition interaction did not differ between younger and older adults, is surprising given the overall pattern of the data and might be due to a lack of power.

The pattern of results seen in Experiment 4 is very similar to that of Experiment 2 (babble gated on and off with word pairs). In fact, when memory performance in both experiments was compared directly in an age (young, old) by auditory condition (word-only babble, 100-Hz jitter) by serial position ANOVA with serial position as a within-subject variable and auditory conditions and age as between-subject variables, the analysis only showed two main effects of serial position, $F(4, 236) = 43.68$, $MSE = 285.93$, $\eta^2_p = .43$, $p < .0001$, and age, $F(1, 59) = 52.05$, $MSE = 1,072.51$, $\eta^2_p = .47$, $p < .0001$, but no effect of auditory condition and no significant interaction (all F s < 1). Hence, both auditory conditions (word-only babble and jitter) led to very similar results in young and older listeners.

EXPERIMENT 5: DISTORTING THE WORDS—PART 2

The last experiment was set up to investigate whether the effect of jitter was specific to the jitter parameters used in Experiment 4, or whether the effect extended to any combination of parameters, as long as they yielded a perceptual accuracy of 91%. We decided to increase the rate-of-change parameter (given by the bandwidth of the noise) to 500 Hz and to adjust the range of change (given by the RMS value of the noise) to achieve the same level of intelligibility as that in previous experiments. As before, to find the parameter combination that yielded 91% accuracy, we first tested 10 young and 10 older adults on an intelligibility task where the RMS value of the jitter changed between lists of 40 words to find the value that would yield 91% accuracy. The procedure followed for intelligibility testing was the same as that in Experiment 4. Based on this procedure values of 0.1 and 0.05 were selected for the memory experiment for 15 younger and 15 older adults, respectively.

Results and discussion

Figure 7 plots the outcome of the memory experiment as percentage correct as a function of serial position for younger (circles) and older (squares) adults in two conditions: combined baseline (filled symbols), and when the words were jittered (unfilled symbols). Visual inspection of Figure 7 suggests that jittering the words at 500 Hz had no effect on performance in either younger or older adults compared to the unjittered quiet baseline condition. An age (young, old) by jitter condition (baseline, 500-Hz jitter) by serial position ANOVA with serial position as a within-subject variable and age and jitter conditions as between-subject variables, confirmed significant main effects of serial position, $F(4, 344) = 103.21$, $MSE = 297.43$, $\eta^2_p = .55$, $p < .0001$, and age, $F(1, 86) = 15.42$, $MSE = 1,203.74$, $\eta^2_p = .15$, $p < .0001$, but not of jitter condition ($F < 1$). The only significant two-way interaction was

Figure 7. Average percentage of correctly recalled word pairs and standard errors of the means for word pairs jittered with a 500-Hz bandwidth at 0.1 ms (young adults, circles) and 0.05 ms (older adults, squares). Also shown are recall results for word pairs in the baseline condition (filled symbols). The baseline consists of the combined results for the quiet and between-word babble conditions (filled symbols).

between serial position and age, $F(4, 344) = 3.92$, $MSE = 297.43$, $\eta^2_p = .04$, $p = .004$, indicating once again that ageing affects the earlier serial positions more than the later ones.

GENERAL DISCUSSION

Effect of age on early serial positions

The results from all three studies (Heinrich et al., 2008; Murphy et al., 2000; the present study) indicate that older adults perform worse than younger adults in the first three serial positions in our version of the Madigan and McCabe (1971) paradigm in all tested experimental conditions. This occurred independent of whether the word pairs were: (a) presented in quiet; (b) acoustically

distorted; or (c) a background babble was present during all or part of the session. Moreover, when the word pairs were presented in quiet (Murphy et al., 2000), with babble in between word pairs (Experiment 1), or jittered at 500 Hz (Experiment 5), the drop in early serial positions was the only effect that differentiated young and older listeners.

The consistently poorer performance of older adults than of younger adults in the first three serial positions is consistent with a resource reduction hypothesis: namely, that older adults have a smaller pool of resources that can be allocated to encoding and consolidating these items in secondary memory.

That older adults can sometimes perform as well as younger adults in the last two serial positions indicates that they can retain recently presented items in working memory when no other significant demands are placed on the processing resources during word presentations. It is also worth noting that presenting babble during the rehearsal period only (Experiment 1) is among the listening conditions for which memory does not differ between young and older adults in later serial positions. This result suggests two conclusions: First, older adults are successful in inhibiting irrelevant sound information during encoding; and second, they can do so without putting an additional strain on processing resources.

Effect of age on later serial positions

Playing babble only during word presentation (Experiment 2) or distorting the words at a rate of 100 Hz (Experiment 4) reduced performance in the last two positions for older adults. This result is particularly interesting because it contrasts with the performance of young adults, who did not show any adverse effect of word-only babble (Heinrich et al., 2008) or jitter (Experiment 4). It is important to note that the age difference in the later serial positions in these two experiments cannot be attributed to differences in word recognition ability, because in all of these instances care was taken to adjust either the SNR when babble was presented, or the amount of distortion when the words were distorted, to ensure that the

probability of recognizing individual words was the same in the young and older participants.

How could word-only babble and 100-Hz BW jitter have affected memory in old listeners? One possibility is that both manipulations distorted the acoustic form of the word and thereby made it more difficult and slower for listeners to match the distorted word with an item in the mental lexicon. That the matching process can be impaired with age and can lead to slower word identification, particularly when acoustic conditions are difficult in any way, was previously shown by Sommers (1996). Slower word identification, in turn, may have left less time to encode the words in working memory. As a result, recall in Serial Positions 4 and 5 suffered. Interestingly, words that were successfully encoded in working memory were then successfully transferred to episodic memory at approximately the same overall rate as that in undistorted conditions.

Effect of age on early and late serial positions combined

A third interesting pattern of results can be observed if one compares older adults' performance in the case of continuous (Murphy et al., 2000) and flanking babble (Experiment 3) with the word-only babble (Experiment 2) and 100-Hz BW jitter (Experiment 4). Because there were no statistical differences in performance between continuous and flanking babble, we collapsed over these two conditions and call it "bracketing babble". Bracketing babble and word-only babble clearly had differential effects on both early and late serial positions in older adults. Interestingly, this pattern does not agree with what might be expected if negative age effects for early and late serial positions were simply added together, but rather shows a complete cross-over interaction (see Figure 8). Recall was better in Positions 4 and 5 for bracketing babble than for word-only babble, with the reverse being true in Positions 1 and 2. This pattern was confirmed by a babble condition (bracketing, word-only masking) by serial position ANOVA (serial position as a within-subject variable,

Figure 8. Average percentage of correctly recalled word pairs and standard errors of the means for word pairs presented to older adults in word-only babble (open squares) and in the combined bracketing babble conditions (filled squares, a combination of continuous babble and word-only babble).

babble condition as between-subject variable), which revealed a main effect for serial position, $F(4, 180) = 37.43$, $MSE = 465.729$, $\eta^2_p = .45$, $p < .0001$ (Greenhouse–Geisser adjusted for violation of sphericity), and a two-way interaction between serial position and babble condition, $F(4, 180) = 5.77$, $MSE = 465.729$, $\eta^2_p = .11$, $p = .002$, Greenhouse–Geisser adjusted for violation of sphericity. The main effect of babble condition was not significant ($F < 1$).

What processes could account for this pattern? We have already argued that cognitive resource limitations may account for the age-related drop in memory for early serial positions in the most favourable listening conditions. We have also argued that the effect on the later serial positions might be the result of slower access to the correct lexical item. Now we would like to suggest that starting the background noise before the target signal facilitates auditory stream

segregation, thereby allowing a better separation and extraction of the target word from the background babble. Exactly how this is accomplished by the listener remains to be investigated by further studies. A more accurate extraction of the target word would allow for a faster and/or more accurate access to the correct lexical item. Faster and more accurate access to the lexicon, in turn, would leave more time for memory consolidation, leading to better recall for word pairs in the later serial positions.

On the flip side, however, is the fact that stream segregation is likely to be attention demanding and consumes attentional resources at the word perception stage that otherwise could be utilized in consolidating words in episodic memory. Moreover, attention-demanding stream segregation processes are likely to be engaged earlier, and for a longer duration, when the babble is continuous or flanking than when it occurs only during word presentations. As a result, words in the bracketing noise conditions are faster and more accurately extracted. However, the stream segregation that allows for these improvements consumes part of the resources otherwise employed to transfer the words to episodic memory. Therefore, episodic memory, as indicated by early serial position recall, suffers.

Why then do we not observe any adverse effect of word-only babble on memory in young listeners? If we assume a more rapid build-up of stream segregation in younger than older adults (Alain & McDonald, 2007; Alain, Ogawa, & Woods, 1996), then the word-only babble condition would combine two positive effects: First, stream segregation supports good lexical access; second, the shorter duration of word-only babble (compared with continuous and flanking noise conditions) leads to a shorter engagement of attentional resources for streaming. As a result, in younger adults, word-only babble would not affect performance in the later serial positions due to good lexical access. It would also not affect performance in the early serial positions because the word-only babble engages attentional resources only relatively briefly thereby leaving sufficient resources for consolidation of early items in

episodic memory. Conversely, continuous or flanking babble requires an earlier and more prolonged engagement of attentional resources for stream segregation in order to allow memory encoding of the words at all. This depletes the pool of resources available for consolidation and adversely affects memory for the early serial positions.

The effects of age and word distortion on memory

Experiments 4 and 5 suggested that older adults' performance in the 100-Hz (but not the 500-Hz BW jitter condition) was equivalent to their performance in word-only babble, a finding that was confirmed by two mixed-measures ANOVAs performed on the data for older adults. The first analysis, which included two perceptual degradation conditions (word-only babble, 100-Hz BW jitter) and five serial positions, only confirmed a main effect of serial position, $F(4, 120) = 18.47$, $MSE = 420.53$, $\eta^2 = .38$, $p < .0001$ (Greenhouse-Geisser adjusted for violation of sphericity), but not of perceptual degradation, $F(1, 30) < 1$, and no interaction between the two, $F(4, 120) = 1.7$, $MSE = 420.53$, $\eta^2_p = .05$, $p = .15$, thereby suggesting that both manipulations affected recall similarly. The second ANOVA compared word babble and 500-Hz BW jitter for all five serial positions and found main effects of serial position, $F(4, 120) = 19.60$, $MSE = 386.00$, $\eta^2_p = .40$, $p < .0001$, and perceptual degradation, $F(1, 30) = 9.70$, $MSE = 882.88$, $\eta^2_p = .24$, $p < .0001$, as well as a two-way interaction between the two, $F(4, 120) = 2.64$, $MSE = 386.00$, $\eta^2_p = .08$, $p = .04$, suggesting that participants performed significantly better in the 500-Hz BW jitter condition than they did with words masked by babble, an effect that was even stronger for later than early serial positions.

Why did 100 Hz but not 500-Hz jitter affect older adults? When words are jittered there is spectral spread; the amount of spectral spread depends on the amplitude of the jitter. To achieve 91% correct word recognition we varied the amplitude of the 100- and 500-Hz low-pass noises that were used to jitter the words. The amplitude parameters

Figure 9. Long-term spectral density functions for a 500-Hz pure tone jittered with a bandwidth of 500 Hz and a root mean square (RMS) level of 0.05 ms (A), and a bandwidth of 100 Hz and a RMS of 0.40 ms (B), respectively.

for older adults were 0.40 ms and 0.05 ms for 100- and 500-Hz bandwidths, respectively. Figure 9 plots the spectrum of a 500-Hz tone jittered with 100- and 500-Hz low-pass noises at amplitudes of 0.40 and 0.05, respectively. This figure shows that in each case the spectrum consists of a single spike at 500 Hz, surrounded by a noise band. Note, however, that the signal-to-noise ratio close to the target frequency is much greater for the 500-Hz bandwidth than it is for the 100-Hz bandwidth. Hence the words jittered at 100 Hz effectively have a lower signal-to-noise ratio for frequencies close to the target than those jittered at 500 Hz. Recall that older adults were severely affected by noise when the babble was presented only during word presentations. Jittering words effectively acts as adding noise only during word presentations. Hence, the fact that older adults are more readily affected by 100-Hz jitter than 500-Hz jitter is consistent with the fact that their memory is very susceptible to signal-to-noise ratio when the noise is gated on and off with the words.

There is, however, another possible explanation of why babble only during word presentations is more deleterious to older than to younger adults.

The level at which the words were presented in all experiments was set to 50 dB above each individual's threshold. Because older adults have higher babble thresholds than younger adults, there remains the possibility that that memory for words masked by babble may be dependent on the sound pressure level at which the words are presented. This possibility will be explored in a later experiment.

In general, the results indicate that memory for heard words is strongly affected by the auditory environment in which they are presented. First, for both younger and older adults, noise in between word presentations has no observable effect on memory. It is only when noise overlaps word presentations that memory is affected. Hence, neither younger nor older adults experienced any difficulty in inhibiting the processing of irrelevant stimuli in an auditory memory experiment provided the irrelevant stimuli do not overlap the target stimuli. Second, the effects of noise or distortion on memory are more deleterious in older than in younger adults, even when word recognition is equivalent in both age groups (as it was in this series of experiments). This contributes to the emerging consensus that comprehension, memory, and other cognitive processes are more severely affected by noise and distractors in older than in younger adults (Schneider, Pichora-Fuller, & Daneman, 2009; Tun, O'Kane, & Wingfield, 2002; Tun & Wingfield, 1999). Third, although the increased opportunity for effective source segregation provided by bracketing babble may improve word recognition, this improvement in speech perception is offset somewhat by the demands that streaming places on attentional resources. Increased opportunities for effective source segregation implies decreased availability of resources for consolidating words in episodic memory for later retrieval. Hence the performance of both younger and older adults in the presence of bracketing babble is adversely affected in the early serial positions because some of the attentional resources required for encoding into episodic memory are diverted to stream segregation. Finally, in older adults, the improved opportunities for effective source segregation

provided by continuous or flanking babble cannot completely compensate for the adverse effects that noise has on memory for recently presented words, as indicated by the fact that word-only noise is more deleterious than either flanked or continuous noise for recently presented words.

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