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Research Article

Impacts of Diabetes, Aging, and Hearing Loss on Speech-on-Speech Masking and Spatial Release in a Large Veteran Cohort

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Purpose: Type 2 diabetes mellitus (DM2) is associated with impaired hearing. However, the evidence is less clear if DM2 can lead to difficulty understanding speech in complex acoustic environments, independently of age and hearing loss effects. The purpose of this study was to estimate the magnitude of DM2-related effects on speech understanding in the presence of competing speech after adjusting for age and hearing.
Method: A cross-sectional study design was used to investigate the relationship between DM2 and speech understanding in 190 Veterans (M_{age} = 47 years, range: 25–76). Participants were classified as having no diabetes (n = 74), prediabetes (n = 19), or DM2 that was well controlled (n = 24) or poorly controlled (n = 73). A test of spatial release from masking (SRM) was presented in a virtual acoustical simulation over insert earphones with multiple talkers using sentences from the coordinate response measure corpus to determine the target-to-masker ratio (TMR) required for 50% correct identification of target speech. A linear mixed model of the TMR results was used to estimate SRM and separate effects of diabetes group, age, and low-frequency pure-tone average (PTA-low) and high-frequency pure-tone average. A separate model estimated the effects of DM2 on PTA-low.
Results: After adjusting for hearing and age, diabetes-related effects remained among those whose DM2 was well controlled, showing an SRM loss of approximately 0.5 dB. Results also showed effects of hearing loss and age, consistent with the literature on people without DM2. Low-frequency hearing loss was greater among those with DM2.
Conclusions: In a large cohort of Veterans, low-frequency hearing loss and older age negatively impact speech understanding. Compared with nondiabetics, individuals with controlled DM2 have additional auditory deficits beyond those associated with hearing loss or aging. These results provide a potential explanation for why individuals who have diabetes and/or are older often report difficulty understanding speech in real-world listening environments.
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This article addresses the impact of diabetes on speech understanding when there is competing speech. The Centers for Disease Control and Prevention (CDC) estimates that 30.3 million Americans (or 9.4% of the population) currently have diabetes and that an additional 84.1 million have prediabetes (CDC, 2017). One in four (25%) Veterans Affairs (VA) patients has diabetes, making it a serious concern for VA health care. In Veterans who served in the Vietnam Era, diabetes is the fourth most prevalent service-connected disability; regardless of the period of service, diabetes is the most prevalent endocrine disability for all Veterans receiving compensation (Veterans Benefits Administration, 2018).

Diabetes can lead to many serious health conditions, including heart disease, stroke, high blood pressure, kidney disease, blindness, autonomic and peripheral neuropathy, cognitive decline, and loss of limbs, or death (Groop, 1999). The seriousness of this disease dictates that without intervention, having diabetes will result in serious consequences. Therefore, it is not surprising that accumulating evidence suggests that diabetes induces harmful effects along the

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auditory pathway (Baiduc & Helzner, 2019; Bainbridge et al., 2008).

On the basis of the data from the National Health and Nutrition Examination Survey, Bainbridge et al. (2008) estimated the prevalence of mild hearing loss, defined as the average of 0.5, 1, and 2 kHz hearing thresholds greater than 25–40 dB HL, in adults (20–69 years old) with diabetes to be 28%, as compared with 9% in adults without diabetes. Akinpelu et al. (2014) reported that compared with nondiabetic controls, younger (< 65 years old) and older (> 65 years old) individuals with diabetes were 2.1 (credible interval [CI]: 1.2–3.6) and 1.8 (CI: 1.5–2.1) times more likely to have hearing loss, respectively.

Although the effects of Type 2 diabetes mellitus (DM2) on hearing sensitivity have been reported in the literature, little is known about the functional impacts of diabetes-related auditory dysfunction. Investigations of the association between diabetes and speech understanding deficits are comparatively few, and among them, the findings are mixed (Baiduc & Helzner, 2019; Frisina et al., 2006; Konrad-Martin et al., 2015). Frisina et al. (2006) performed a small study comparing 30 participants with DM2 to 30 participants without DM2 using the Hearing in Noise Test (HINT; Nilsson et al., 1994). On average, compared with nondiabetic control participants, those with DM2 had poorer hearing-in-noise thresholds for all conditions on the HINT; differences in threshold performance ranged from 1.6 to 2.5. On the basis of these findings, Konrad-Martin et al. (2015) expected that similar results would be found in their study of 57 Veterans with DM2 compared with 73 participants without DM2 using a different speech-in-noise test, namely, the Quick Speech-in-Noise Test (QuickSIN; Etymotic Research, Inc.). Yet, Konrad-Martin et al. (2015) found that the performance on the QuickSIN was similar for participants with or without diabetes. Possible explanations for the conflicting results between Frisina et al. and Konrad-Martin et al. (2015) include differences in the speech measurements used but could also involve other factors related to the populations they sampled (e.g., Veterans vs. non-Veterans, degree of hearing loss, age) or, simply, sampling variation.

Two important distinctions between most speech-in-noise tests and listening in real-world environments are that the competing sources of noise in real-world environments are typically spatially separated and may or may not be speech. Also, many speech-in-noise tests use a single masker, as is the case with the HINT. When only one masker is used, performance is dominated by the signal-to-noise ratio in the ear farthest from the masker (i.e., the "better ear advantage") and includes smaller effects of "binaural analysis" (see Marrone et al., 2008a, for further discussion). Therefore, from this test alone, it is not clear to what degree the binaural system contributes to performing well on the task. Marrone et al. (2008a) introduced using two symmetrical maskers, so that neither ear had a better signal-to-noise ratio, to create a task that is more likely to be dependent on binaural analysis rather than dominated by the better ear advantage. Jones and Litovsky (2011) developed a computational model that predicts the effects of spatial separation for multiple maskers and is accurate for maskers that are speech or noise. Their model emphasizes (a) the large changes in performance within the first 45° of separation between the target and masker(s) and (b) the importance of the binaural analysis component for spatial release from masking (SRM).

Another important difference between laboratory testing and real-world listening is the presence of reverberation. Marrone et al. (2008b) and Srinivasan et al. (2017) showed that hearing impairment, but not aging, results in a smaller difference between SRM in reverberant and nonreverberant environments. This suggests that there are cues that are distorted by reverberation to which those with hearing loss are less sensitive.

The work by Frisina et al. (2006) shows clear DM2 effects when the degree of separation between the target speech and a single speech-shaped noise masker is large (90° and 270° azimuth). Less established is whether performance with smaller separations between the target and masker or multiple speech maskers, representative of everyday listening environments, has results similar to those seen with larger separations between the target speech and masker(s). Srinivasan et al. (2016) explored this question and found that even small separations of 4° still resulted in substantial benefit to detect the target speech in the presence of two symmetrically separated speech maskers for young, healthy people with normal hearing. Specifically, small spatial separations allowed criterion performance (50% of the time correctly repeating key words) to be achieved with lower target-to-masker ratio (TMR) thresholds compared with the colocated condition.

On the basis of the published work to date, there are many unanswered questions regarding the factors that contribute to poor speech understanding in complex acoustic environments among Veterans with DM2. From a mechanistic perspective, DM2 results in nervous system changes, micro- and macrovascular changes, oxidative stress, and other biological changes. Therefore, a logical question to ask is how disease severity might impact speech understanding. Related questions include whether or not DM2 effects can be attributed to hearing threshold loss or can result in an "accelerated effect of aging." Another important question is how DM2 effects might differ from either hearing loss or age effects, as indicated by residual DM2 effects after accounting for variations in hearing and age across participants.

Therefore, the objectives of this study are to first estimate the age- and hearing loss–adjusted effects of DM2 on the TMR and SRM using speech-on-speech masking. If the blood glucose in an individual with diabetes is not well controlled with diet, exercise, and/or oral medications, the severity of the disease and its complications will often progress. Therefore, we further refine our estimates by grouping individuals according to the severity of DM2 as determined by current glycated hemoglobin (HbA1c) levels: Prediabetes, Controlled DM2, and Uncontrolled DM2. Test conditions include both small (8°) and large (30°) spatial separations,

with and without reverberation. This study design allows for the ability to distinguish the impact of diabetes on speech understanding separately from that of aging and peripheral hearing loss in realistic listening situations. It also allows for the ability to assess the extent to which damage from diabetes can begin before the actual clinical diagnosis at the prediabetes stage when the body's ability to regulate blood glucose becomes impaired, leading to higher than normal levels. Next, we estimate the age-adjusted effects of DM2 on low-frequency hearing because this frequency range provides important spectrotemporal cues for segregating sound sources. We hypothesize that compared with participants without DM2, those with the disease will have more difficulty understanding speech in the presence of competing speech maskers and that among those with DM2, low-frequency hearing loss will be greater. We further hypothesize that diabetes of greater severity, adjusted for age, will be associated with higher thresholds for pure tones.

Materials and Method

Participants

This report is part of a large, prospective diabetes study in Veterans in which participants were recruited and tested at the VA National Center for Rehabilitative Auditory Research in Portland, Oregon, from 2014 to 2018. The recruitment process and methods were similar to those found in Konrad-Martin et al. (2015). All 154 Veterans with diabetes who participated in the Konrad-Martin et al. (2015) study were mailed letters informing them about the opportunity to participate in this continuation study. Additionally, permission was obtained to access the VA diabetes registry, a database containing the names of Veterans considered at high risk for developing diabetes or with a diagnosis of diabetes who receive their health care at the VA Portland Health Care System (VAPORHCS). All Veterans in this registry below the age of 55 years were mailed a recruitment letter. Participants in the No DM group were individuals matched by age (within 5 years) and sex to those with DM2; these controls were recruited from our prior study roster and from respondents to study flyers.

A total of 190 Veterans were included in the current analysis. To be eligible, candidates needed to be receiving care at VAPORHCS; be a previous study participant or a newly recruited participant between 19 and 65 years old; and not have neurologic or psychiatric disorders, a history of stroke, cancer, Ménière's disease, or conductive/mixed hearing loss evidenced by clinically significant audiometric air–bone gaps. Participants were categorized into four groups representing different stages of the disease according to their HbA1c levels:

1. Prediabetes (no diagnosis of DM1 [Type 1 diabetes mellitus] or DM2 and HbA1c $\geq$ 5.7%; n = 19)
2. Controlled DM2 (diagnosis of DM2 and HbA1c < 7%; n = 24)
3. Uncontrolled DM2 (diagnosis of DM2 and HbA1c $\geq$ 7%; n = 73)
4. No DM (no diagnosis of DM1 or DM2 and HbA1c < 5.7%; n = 74)

Procedure

Participants provided informed consent prior to any procedures being performed and were compensated for their time and effort; the VAPORHCS Institutional Review Board (IRB) reviewed and approved the study protocol (IRB No. 3422).

Audiologic Evaluation

All procedures were completed in a sound-treated booth by a research audiologist. Routine audiometric air-conduction hearing thresholds were obtained from 0.25 to 8 kHz using a GSI-16 audiometer (Grason-Stadler, Inc.) and ER-3A insert earphones (Etymotic Research Inc.).

Characteristics of Study Participants

Data were obtained from questionnaires, medical chart review, and interviews. Group assignment was determined according to the diagnosis of DM2 in the medical chart and corroborating evidence from HbA1c levels as well as self-report based on the Diabetes Baseline and Follow-Up Surveys. The HbA1c levels were obtained from blood samples collected on the day testing was performed or extracted from the medical record if available within a month of our auditory testing. The Diabetes Baseline Survey, a questionnaire developed for this longitudinal study, was used to capture demographic information, education level completed, diabetes history, and overall health status. Foot sensation loss (yes, no) was also determined by a research audiologist trained in the procedure, who used a 10-g nylon monofilament applied to each participant's 10 toes. Amputated toes resulting from diabetes complications were counted as having sensation loss. Participants' medical charts were reviewed to capture recent ophthalmological examination findings. Diabetic retinopathy was obtained from participants' medical records and is reported as absent, nonproliferative, or proliferative. For some participants, the presence or absence of clinically significant macular edema was also noted in the medical record.

SRM

This test of speech-on-speech masking and spatial release is based on the work of Gallun et al. (2013) and is available in both laboratory and portable formats (Srinivasan et al., 2020). The version tested was the laboratory implementation, described in Srinivasan et al. (2016, 2017). The portable and laboratory versions both employ automated presentation of stimuli and scoring of responses. The laboratory program presents three different sentences spoken by three different male talkers in each trial. Sentences are drawn from the coordinate response measure (CRM) corpus, "Ready (CALL SIGN) go to (COLOR) (NUMBER) now," and listeners are instructed to use a touch screen to

select the color and number associated with a specific call sign. In each trial, one CRM sentence is designated as the target due to the inclusion of the call sign "Charlie," and two masking sentences are randomly chosen with the requirement that all three sentences contain different call signs and key words. Stimuli are presented binaurally over ER-3A insert earphones, and as described in Srinivasan et al. (2016, 2017), a virtual acoustical simulation is created by a convolution with nonindividualized head-related impulse responses. The simulation includes three spatial configurations: (a) colocated, with all three sentences presented at 0° azimuth, and (b and c) spatially separated, with the target CRM sentence at 0° azimuth and the masking sentences at either ±8° azimuth or ±30° azimuth. All three conditions were tested in a simulated anechoic environment and in a simulated room with a reverberation time of 1,000 ms (for details of the reverberation simulation, see the "ALL" condition described in Srinivasan et al., 2017).

To ensure that the stimuli were similarly audible across all participants, target sentences were presented at 30 dB SL (relative to the speech reception threshold), and masker levels were progressively adjusted across presentations, as described in Gallun et al. (2013). Progressive tracking starts with maskers that are 10 dB lower in level than the target (a TMR of 10 dB), and after every two trials, the masker level increases by 2 dB. Across 20 trials, this results in presentations of TMRs from 10 to −8 dB. Threshold performance in decibels is estimated by subtracting the number of trials on which both key words were correctly identified from 10 dB, following the work of Gallun et al. This procedure results in a threshold TMR value estimated for each spatial condition. An example of how TMR is estimated is found in the work of Jakien and Gallun (2018, p. 532):

> For example, if a listener answered all 20 presentations correctly, the threshold would be estimated at −10 dB, whereas if all of the answers were incorrect, the estimate of TMR at threshold would be 10 dB. A listener who answered half of the presentations correctly would be assigned a threshold of 0 dB TMR.

Additionally, SRM is obtained by subtracting the TMR in the spatially separated condition (8° or 30°) from the TMR in the colocated condition. The TMR is an estimate of the relative target and masker levels at which a person gets approximately 50% of the responses correct. The target level is held constant. Hence, SRM in decibels represents the increase in masker level that can be introduced in the spatially separated conditions without changing the intelligibility of the target speech relative to performance in the colocated condition. Positive values indicate that the same 50% correct performance could be achieved with higher masker levels in the spatially separated conditions compared with the colocated conditions. Negative SRM values would mean that performance actually became worse with spatial separation such that the masker levels would need to be increased relative to the colocated condition to correctly recognize the target speech 50% of the time.

Statistical Considerations

On the basis of the literature, we expect to see that individuals with DM2 will have poorer pure-tone thresholds compared with controls. However, we also expect that the impact of having impaired hearing will be the same whether or not a person has DM2. It is important to ensure that the estimated relationship between DM2 and speech-on-speech masking was not solely attributable to their mutual association with peripheral hearing sensitivity. This adjustment allowed us to identify possible central effects of the disease. We also sought to identify and adjust for effects of age and its potential interaction with DM2.

Bayesian multilevel logistic regression was used to estimate the relationship between DM2, age, and hearing loss as predictors as well as speech understanding in complex listening environments, the TMR, as the outcome. The model also estimates the effects of listening conditions (three spatial configurations presented in two simulated environmental settings: anechoic and reverberant) on mean TMR. The Bayesian approach is distinguished from classical approaches by probabilistically characterizing our uncertainty about different effect sizes, conditional on the data and the fitted model. The result is a set of Bayesian "90% credible intervals," which, in a crucial distinction from classical confidence intervals, define the interval within which we are 90% confident the true effect size lies (McMillan & Cannon, 2019).

A separate Bayesian multilevel logistic regression is used to estimate the diabetes-related excess low-frequency hearing loss for the sample after adjusting for age. The technical details of the modeling and Bayesian approach are in Supplemental Material S1.

Results

Participant Characteristics

Demographic, hearing, and educational characteristics of the diabetes and control groups are presented in Table 1. All participants were Veterans, and the sample was predominantly male (87%). Twenty-five participants in this study (13% of the total sample) also contributed data to the earlier study reported by Konrad-Martin et al. (2015). These individuals are listed in Table 1 by diabetes group as identified in this study. Study participants ranged in age from 25 to 76 years (M_{age} = 47). Overall, race/ethnicity is representative of the metropolitan area from which the sample was drawn.

Table 1 also provides a low-frequency pure-tone average (PTA-low; 0.5, 1, and 2 kHz) and a high-frequency pure-tone average (PTA-high; 3, 4, 6, and 8 kHz) by group. Audiometric hearing thresholds ranged between normal to moderately impaired in the lower frequency range and normal to severely impaired in the higher frequency range. Figure 1 displays individual pure-tone hearing thresholds for each ear (thin lines) and average pure-tone hearing thresholds (thick lines) for each group (panels). The control group (i.e., No DM) had better average PTA-low or PTA-high of approximately 1–4 dB compared with each of the other groups.

Table 1. Demographic information and characteristics of study participants.

Variable		No DM	Prediabetes	Controlled DM2	Uncontrolled DM2	All
N		74	19	24	73	190
Number of subjects who participated in Konrad-Martin et al. (2015)		11	2	4	8	25
Sex						
Male	*N*	66	16	19	64	165
	%	89.2	84.2	79.2	87.7	86.8
Female	*N*	8	3	5	9	25
	%	10.8	15.8	20.8	12.3	13.2
Age	*M*	45.9	48.3	49.0	47.6	47.2
	Min	28	34	32	25	25
	Max	73	76	76	71	76
Low-frequency pure-tone average (0.5, 1, and 2 kHz)	*M*	12.3	16.2	16.7	15.7	14.5
	Min	0	4	5	4	0
	Max	26	34	28	42	42
High-frequency pure-tone average (3, 4, 6, and 8 kHz)	*M*	19.0	20.1	23.0	20.2	20.1
	Min	1	2	3	3	1
	Max	56	56	64	66	66
Ethnicity						
Asian	*N*	1	0	0	5	6
	%	1.4	0	0	6.8	3.2
Black	*N*	4	5	6	3	18
	%	5.4	26.3	25.0	4.1	9.5
Caucasian	*N*	60	13	15	51	139
	%	81.1	68.4	62.5	69.9	73.2
Hispanic	*N*	4	0	2	8	14
	%	5.4	0	8.3	11.0	7.4
Middle Eastern	*N*	0	1	0	0	1
	%	0	5.3	0	0	0.5
Native American	*N*	1	0	1	3	5
	%	1.4	0	4.2	4.1	2.6
Pacific Islander	*N*	0	0	0	1	1
	%	0	0	0	1.4	0.5
Prefer not to answer	*N*	2	0	0	0	2
	%	2.7	0	0	0	1.1
Other	*N*	2	0	0	2	4
	%	2.7	0	0	2.7	2.1
Education						
Some high school	*N*	3	1	0	1	5
	%	4.1	5.3	0	1.4	2.6
Completed high school	*N*	2	2	2	5	11
	%	2.7	10.5	8.3	6.8	5.8
Post–high school vocational training	*N*	2	1	1	6	10
	%	2.7	5.3	4.2	8.2	5.3
Some college	*N*	31	6	11	38	86
	%	41.9	31.6	45.8	52.1	45.3
Completed college	*N*	36	9	10	23	78
	%	48.6	47.4	41.7	31.5	41.1

Note. No DM = participants with no diabetes; Prediabetes = participants with prediabetes; Controlled DM2 = participants with controlled Type 2 diabetes mellitus; Uncontrolled DM2 = participants with uncontrolled Type 2 diabetes mellitus.

Health characteristics for each group are provided in Table 2. Years with diabetes, HbA1c, the method of metabolic control, and common comorbidities associated with the disease indicate disease severity; those with higher HbA1c values, with longer disease duration, and who are dependent on insulin had greater severity of diabetes. A greater percentage of the participants with uncontrolled DM2 were insulin dependent compared to those with controlled DM2, despite similar mean ages across the two groups. A greater percentage of those with uncontrolled DM2 also took oral medications and used diet and exercise to help manage their diabetes and had common diabetes-related comorbidities such as loss of sensation in toes and retinopathy, compared with the Controlled DM2 group.

Unadjusted Speech-on-Speech Masking and Spatial Release Results

In this section, all figures depict unadjusted results. In the next section, all figures are based on the results of the statistical modeling to estimate the relationship among DM2, age, hearing loss, and speech understanding as measured by the TMR and SRM. The importance of summarizing the raw data is to show the impacts of hearing loss,

Figure 1. Individual audiometric pure-tone hearing thresholds (thin lines) and mean pure-tone hearing thresholds (thick lines) in dB HL are displayed in separate panels for each group: No DM (participants with no diabetes), Prediabetes (participants with prediabetes), Controlled DM2 (participants with controlled Type 2 diabetes mellitus), and Uncontrolled DM2 (participants with uncontrolled Type 2 diabetes mellitus). Hearing thresholds range from within normal limits to severely impaired in the higher frequencies.

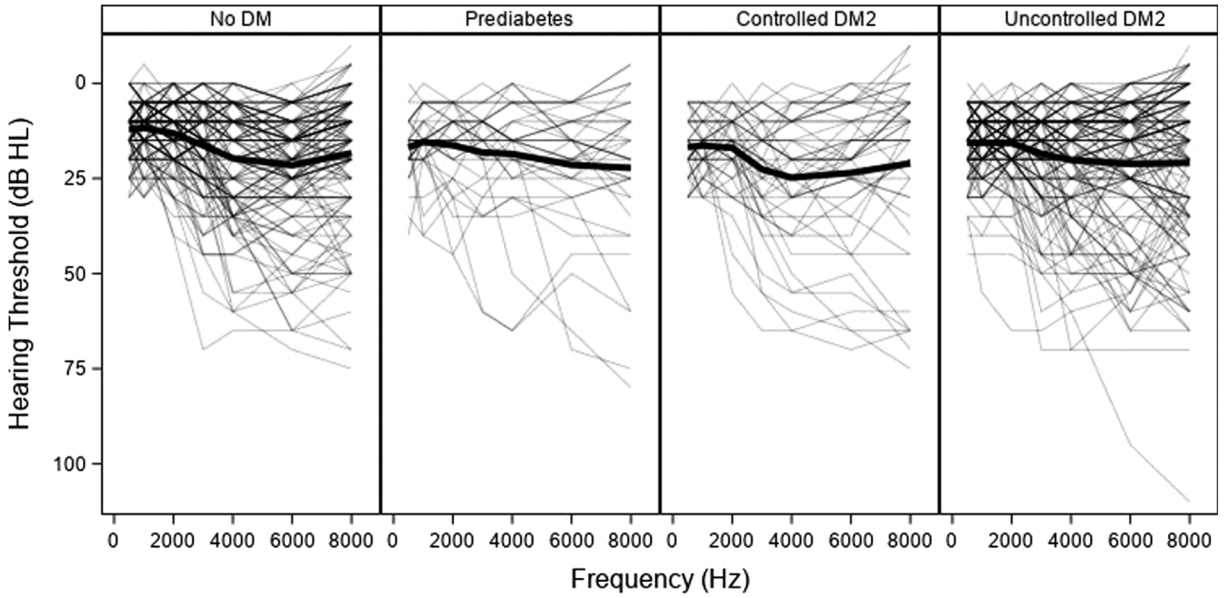


Table 2. Diabetes and overall health characteristics of the sample.

Variable	No DM	Prediabetes	Controlled DM2	Uncontrolled DM2	All
Total number of participants per group	74	19	24	73	190
HbA1c, *M* (range)	5.3 (4.6–5.6)	6.2 (5.7–7.5)	6.2 (4.8–6.9)	9.1 (7.0–14.0)	6.9 (4.6–14.0)
Years with DM2, *M* (range)	n/a	n/a	6.1 (0–18)	8.3 (0–26)	7.7 (0–26)
Treatment for diabetes, *N* (%)					
Insulin-dependent	n/a	0 (0)	7 (29.2)	34 (46.6)	41 (35.3)
Oral medications	n/a	3 (15.8)	15 (62.5)	62 (84.9)	80 (69.0)
Diet/exercise	n/a	2 (10.5)	14 (58.3)	56 (76.7)	72 (62.1)
No treatment	n/a	1 (5.26)	2 (8.3)	0 (0)	3 (2.6)
Foot sensation loss: right or left foot, *N* (%)	0 (0)	0 (0)	0 (0)	3 (4.2)	3 (1.7)
Retinopathy: right eye,[a] *N*					
Data not available in EMR	73	17	6	4	100
Retinopathy absent	1	2	16	58	77
Mild nonproliferative	0	0	2	8	10
Moderate nonproliferative	0	0	0	2	2
Retinopathy: left eye,[a] *N*					
Data not available in EMR	73	17	6	4	100
Retinopathy absent	1	2	17	58	78
Mild nonproliferative	0	0	1	7	8
Moderate nonproliferative	0	0	0	3	3
Moderate proliferative	0	0	0	1	1

Note. No DM = participants with no diabetes; Prediabetes = participants with prediabetes; Controlled DM2 = participants with controlled Type 2 diabetes mellitus; Uncontrolled DM2 = participants with uncontrolled Type 2 diabetes mellitus; HbA1c = glycated hemoglobin; DM2 = Type 2 diabetes mellitus.

[a]Retinopathy data were obtained from the electronic medical record (EMR). Data for this common DM2 comorbidity were missing for four (5.6%) participants with uncontrolled DM2 and 26 (25%) participants with controlled DM2. Additionally, the retinal images could not be evaluated for the right eye in one participant with uncontrolled DM2. Thus, to reduce confusion, only the *N* is presented for the retinopathy data.

age, and DM2 combined. The importance of summarizing the model-based results is to quantify the separate impacts of these variables. Figure 2 shows box plots of the unadjusted TMR (y-axis) by diabetes group in the anechoic setting for each spatial condition (x-axis). Spatial condition (maskers at 0°, ±8°, and ±30° azimuth) represents no separation, a small separation, and a large separation from the target, which is fixed at 0° azimuth. The interquartile (box) and the 90% confidence interval (whiskers) reflect the uncertainty of each estimate of the average TMR value for each group (symbols). A value of 0 (horizontal line) indicates that each of the two maskers was at the same level as the target speech to achieve 50% correct performance on the task. Positive values indicate that the level of the maskers has to be lower relative to the level of the target speech to achieve 50% correct performance on the task, whereas negative values indicate that 50% correct performance on the task is achieved when the masker is higher in level than the target. All groups had median TMR values of 0 dB or greater at 0° and 8° azimuth, whereas for 30°, the groups differed. For the No DM and Prediabetes groups, the median TMR value was lower, meaning higher masker levels are tolerated by these groups, for maskers located at 30° compared with those at 0° and 8° azimuth. Supplemental Materials S2–S9 show the reverberant environmental setting results.

Figure 3 shows SRM by diabetes group for each stimulus condition. The horizontal line indicates zero spatial release, meaning that the TMR at the spatially separated condition is identical to the TMR at the colocated condition, implying that there was no change in speech intelligibility when the maskers were spatially separated from the target. Responses greater than 0 suggest improved speech intelligibility when the maskers are separated from the target. Results show improved speech intelligibility with greater separation of the maskers at 30° compared with small separations of 8°.

From these unadjusted data, it is unclear whether the apparent diabetes group differences were due to variations in hearing or age of the participants or attributable to the central effects of the disease. A model-based approach allows us to estimate the adjusted effects of diabetes severity, age, and hearing loss on the TMR and SRM. A separate model estimates the amount of excess low-frequency hearing loss that can be attributable to DM2.

Figure 2. Relationship between the target-to-masker ratio (TMR) and simulated spatial location of the maskers by diabetes group. This figure shows box plots of the TMR in decibels. Symbols show the median TMR for the groups of participants with no diabetes (No DM), with prediabetes (Prediabetes), with controlled Type 2 diabetes mellitus (Controlled DM2), and uncontrolled Type 2 diabetes mellitus (Uncontrolled DM2). The target sentence was always presented at 0° azimuth, and the masking sentences were either colocated (0° azimuth) or spatially separated (8° and 30° azimuth) symmetrically from the target. Boxes indicate the interquartile range and whiskers indicate the 90th percentile for each group. The horizontal line indicates a TMR threshold of 0, meaning that criterion performance was achieved when the levels of the target speech and maskers were equal. Responses higher on the plots indicate that the level of the maskers had to be lowered relative to the level of the target speech to achieve 50% correct performance on the task (i.e., worse performance).

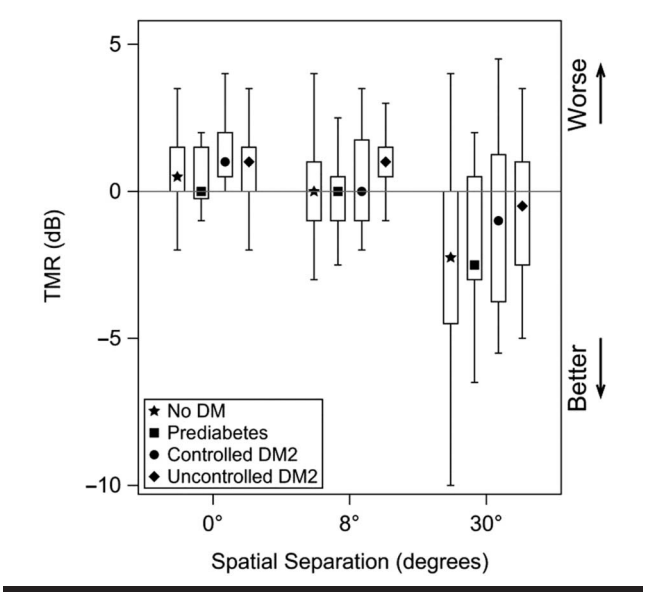
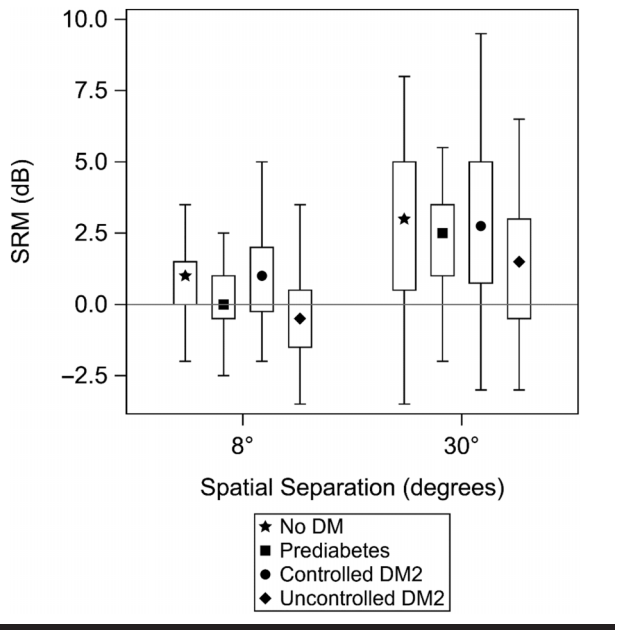


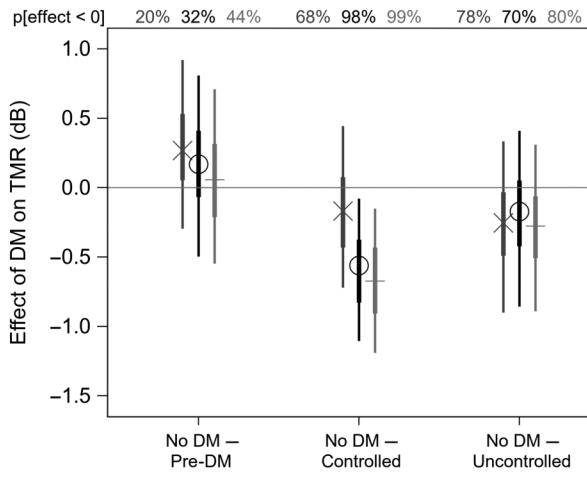
Figure 3. Unadjusted spatial release from masking (SRM) by diabetes group. The target-to-masker ratio data presented in Figure 2 are replotted here, displaying SRM in decibels. Results are plotted using the same format as for Figure 2. The horizontal line indicates zero spatial release; that is, no benefit in intelligibility is achieved by separating the maskers from the target. Responses higher on the plot indicate that the participants achieved 50% performance with masker levels increased in the spatially separated conditions compared with the colocated condition, which is the definition of SRM (i.e., better performance). Responses lower on the plot indicate that spatially separating the maskers from the target speech did not improve intelligibility of the speech. No DM = participants with no diabetes; Prediabetes = participants with prediabetes; Controlled DM2 = participants with controlled Type 2 diabetes mellitus; Uncontrolled DM2 = participants with uncontrolled Type 2 diabetes mellitus.



Model-Based Speech-on-Speech Masking and Spatial Release Results

Figure 4 shows the model-based difference in mean TMR between the No DM control group and each other diabetes severity group (i.e., contrasts). Because the level of the target speech is held constant (at 30 dB SL), these TMR differences correspond to group differences in the level of the competing maskers needed to achieve 50% correct performance on the speech understanding task. Symbols indicate the best point estimate of each effect, that is, the median of the posterior distribution of the mean group difference in decibels. The length of the interquartile (thick bar) and the 90% confidence interval (thin bar) reflect the uncertainty of each estimate, that is, the range of the posterior distribution. The horizontal line indicates a 0-dB mean difference in the TMR relative to the No DM control group. Negative values correspond to a situation where the control group can achieve 50% correct performance with, on average, more intense competing maskers than the comparison groups with diabetes. The Bayesian point estimate and confidence intervals are also shown in the table at the bottom of the figure. Small absolute values of the point estimate and confidence intervals that straddle 0 dB suggest weak and/or imprecisely estimated Group × Condition effects.

Figure 4. Model-based differences in mean target-to-masker ratio (TMR) for each diabetes group relative to the No DM control group. This figure shows the posterior distribution of the model-based mean difference in the TMR for each diabetes group compared with the No DM control group at each spatial separation of the maskers from the target at 0°, 8°, and 30°, respectively. Symbols indicate the median of the posterior distribution, and bars indicate the posterior interquartile (thick bars) and 90% credible interval (thin bars). The horizontal line indicates a 0-dB mean difference relative to controls. The table at the bottom shows the numeric values for the median of the posterior distribution of the mean difference (labeled "Estimate") and the 90% posterior credible interval. For example, with maskers positioned at 30° from the target speech, participants with controlled Type 2 diabetes mellitus needed the competing maskers to be 0.2–1.2 dB quieter than did participants with no diabetes, to achieve 50% correct performance on the speech understanding task. The "p[effect < 0]" at the top of the figure is the posterior probability that the population mean difference is below 0. For the example mentioned, this posterior probability is 99%. No DM = participants with no diabetes; Pre-DM = participants with prediabetes; Controlled = participants with controlled Type 2 diabetes mellitus; Uncontrolled = participants with uncontrolled Type 2 diabetes mellitus; UCL = upper credible limit; LCL = lower credible limit.



90% Posterior intervals

90% UCL	0.9	**0.8**	0.7	0.4	**−0.1**	−0.2	0.3	**0.4**	0.3
Estimate	0.3	**0.2**	0.1	−0.2	**−0.6**	−0.7	−0.3	**−0.2**	−0.3
90% LCL	−0.3	**−0.5**	−0.5	−0.7	**−1.1**	−1.2	−0.9	**−0.9**	−0.9

Results indicate that the adjusted diabetes effect on the TMR was small for both Prediabetes and Uncontrolled DM2 groups (the maximum absolute value of the associated point estimates shown in Figure 3 is less than 0.5 dB, and the confidence intervals for these contrasts straddled 0 dB across conditions and contrasts). The effects of controlled DM2 were comparatively larger after accounting for the other variables in the model. For example, with maskers positioned at 30° from the target speech, participants in the Controlled DM2 group needed the competing maskers to be 0.7 dB less intense on average (with a 90% CI of −0.2 to −1.2 dB) than did participants in the No DM group to achieve 50% correct performance on the speech understanding task. The "p[effect < 0]" shown at the top of the figure is the posterior probability that the population mean difference is below 0. Values show there is at least 98% posterior probability that the mean TMR in the No DM group population was less (i.e., higher masker levels could be tolerated) than that in the Controlled DM2 group population at both spatially separated conditions.

Figure 5 shows the model-based difference in mean SRM for each of the diabetes groups compared with the No DM control group. The figure format is the same as in Figure 4. Recall that SRM represents the increase in masker level over the colocated condition that can be introduced in a spatially separated condition while maintaining 50% correct speech understanding. The horizontal line indicates a 0-dB mean difference in SRM relative to the No DM control group. If the contrast is less than 0 dB, it means that SRM for the No DM group is larger than that for the other diabetes group in question. That is, a negative contrast value indicates that the No DM control group can sustain higher relative masker levels in the spatially separated condition, over the colocated condition, than the comparison group. The mean SRM values were approximately 0.5 dB less for the Controlled DM2 group than for the No DM group. This contrast presumably reflects disease-related variation in the ability to access spatial cues to identify the target speech that are unrelated to variations in PTA-low and PTA-high as well as left–right ear asymmetries, which are accounted for in the model along with age. The confidence intervals for the remaining DM group contrasts in the other conditions largely straddled 0 dB, suggesting weak and/or imprecisely estimated Group × Condition effects.

Figure 6 shows the model-based estimates of the effect of increasing age by 10 years on mean TMR. The model (Equation 1 in Supplemental Material S1) includes an Age × Diabetes Group interaction so that the age effects are shown for each diabetes group; also, the age effect is adjusted for

Figure 5. Model-based differences in mean spatial release from masking (SRM) for each diabetes group relative to the No DM control group. This figure shows the posterior distribution of the model-based mean difference in SRM in decibels for each diabetes group compared with the No DM control group. Recall that SRM in decibels is the masker level change required due to spatially separating the target and masker while maintaining 50% correct performance. Data are shown for SRM at 8° and 30°, respectively. Symbols indicate the median of the posterior distribution, and bars indicate the posterior interquartile (thick bars) and 90% credible interval (thin bars) of the difference in mean SRM compared with the No DM control group. The horizontal line indicates a 0-dB mean difference relative to controls. The table at the bottom shows the numeric values for the median of the posterior distribution of the mean difference (labeled "Estimate") and the 90% posterior credible interval. Negative values indicate that the difference in masker levels between the spatially separated and collocated conditions (i.e., SRM) is reduced for a given group relative to the No DM control group, suggesting reduced access to spatial cues to correctly identify the target speech. No DM = participants with no diabetes; Pre-DM = participants with prediabetes; Controlled = participants with controlled Type 2 diabetes mellitus; Uncontrolled = participants with uncontrolled Type 2 diabetes mellitus; UCL = upper credible limit; LCL = lower credible limit.

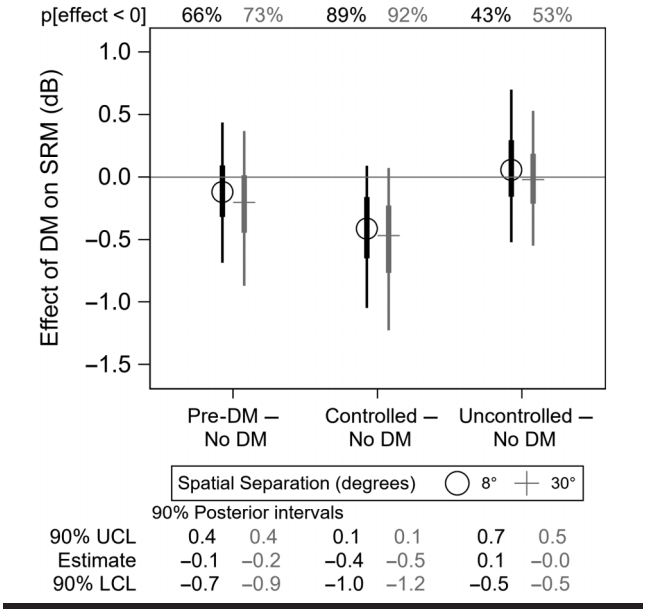
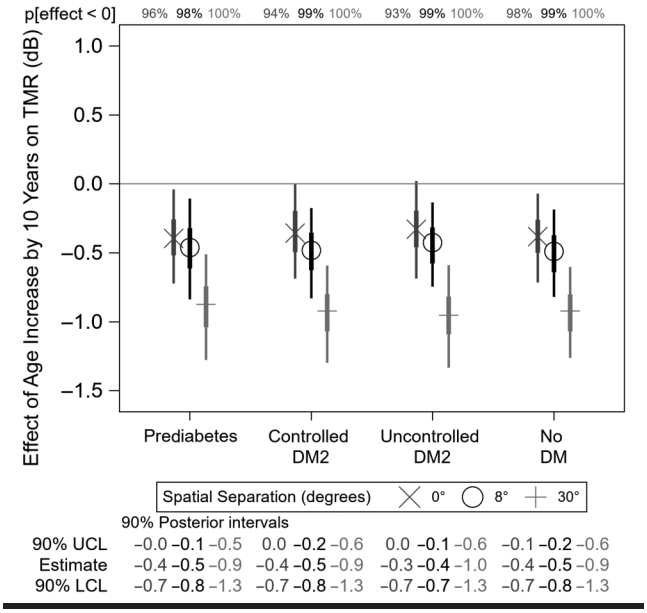


Figure 6. Model-based estimates of the effect of increasing age by 10 years on mean target-to-masker ratio (TMR). This figure shows how a decade of aging impacts the TMR for each group for maskers located at 0° (X's), 8° (circles), and 30° (crosses). Symbols indicate the median of the posterior distribution, and bars indicate the posterior interquartile (thick bars) and 90% credible interval (thin bars). The horizontal line indicates a 0-dB mean difference relative to controls. The table at the bottom shows the numeric values for the median of the posterior distribution of the mean difference (labeled "Estimate") and the 90% posterior credible interval. Results show that increasing age by 10 years negatively impacted mean TMR, such that masking levels needed to be reduced, particularly in 30° spatially separated conditions, to maintain speech intelligibility. A decade of aging impacts TMR performance similarly across groups. Prediabetes = participants with prediabetes; Controlled DM2 = participants with controlled Type 2 diabetes mellitus; Uncontrolled DM2 = participants with uncontrolled Type 2 diabetes mellitus; No DM = participants with no diabetes; UCL = upper credible limit; LCL = lower credible limit.



PTA-low and PTA-high as well as left–right ear asymmetries. The values on the *y*-axis correspond to the change in masker level required to achieve 50% correct speech understanding after a 10-year "increase" in age. In other words, results show the estimated mean TMR for participants – mean TMR for the same participants "aged" by 10 years. The general impression shown in Figure 6 is that 10 years of aging resulted in an average increase in TMR of 0.2–1 dB depending on the spatial separation between the target and masker(s). There was little difference in the magnitude of the age effect between 0° and 8° of spatial separation, although there was a jump in the age effect at 30° of spatial separation. This pattern across degrees of spatial separation was consistent across diabetes groups.

Figure 7 shows the model-based estimates of the effect of increasing age by 10 years on mean SRM. The values on the *y*-axis correspond to the adjusted mean SRM for participants – mean SRM for the same participants "aged" by 10 years. Negative values indicate that the higher masker levels tolerated in the spatially separated condition, over the colocated condition, need to be reduced as participants get older. Ten years of aging impacted mean SRM similarly across diabetes groups. On average, 10 years of aging required about a 0.5-dB reduction of the spatially separated masker levels to achieve the same 50% speech understanding as in the colocated condition.

Figure 8 shows the model-based estimates of the effect of increasing PTA-low (0.5–2 kHz) and PTA-high (3–8 kHz) by 10 dB on mean TMR. The values on the *y*-axis correspond to the change in masker level resulting in 50% correct speech understanding after a 10-dB "increase" in pure-tone averages. Changes to PTA-low resulted in relatively large reductions in the TMR compared with changes to PTA-high for all spatially separated conditions.

The effect of "increasing" PTA-low by 10 dB was a reduction of about 0.4–1.0 dB for participants to achieve

Figure 7. Model-based estimates of the effect of increasing age by 10 years on mean spatial release from masking (SRM). This figure shows how a decade of aging impacts SRM for each group for maskers located at 8° (circles) and 30° (crosses). Symbols indicate the median of the posterior distribution, and bars indicate the posterior interquartile (thick bars) and 90% credible interval (thin bars). The horizontal line indicates a 0-dB mean difference relative to controls. The table at the bottom shows the numeric values for the median of the posterior distribution of the mean difference (labeled "Estimate") and the 90% posterior credible interval. Results show that a decade of aging impacts SRM performance similarly across groups. The negative values in the 30° condition indicate that the masker levels in this spatially separated condition compared with the collocated condition needed to be reduced by 0.4–0.6 dB for participants to achieve 50% correct performance and suggest that a decade of aging reduces access to spatial cues needed to correctly identify the target speech. No DM = participants with no diabetes; Prediabetes = participants with prediabetes; Controlled = participants with controlled Type 2 diabetes mellitus; Uncontrolled = participants with uncontrolled Type 2 diabetes mellitus; UCL = upper credible limit; LCL = lower credible limit.

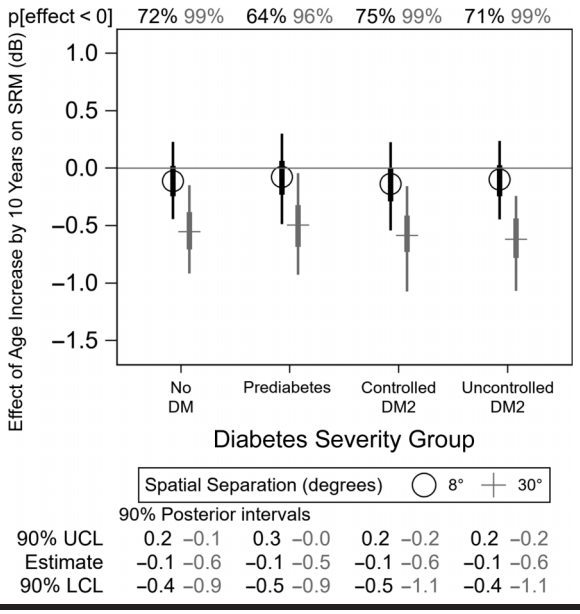
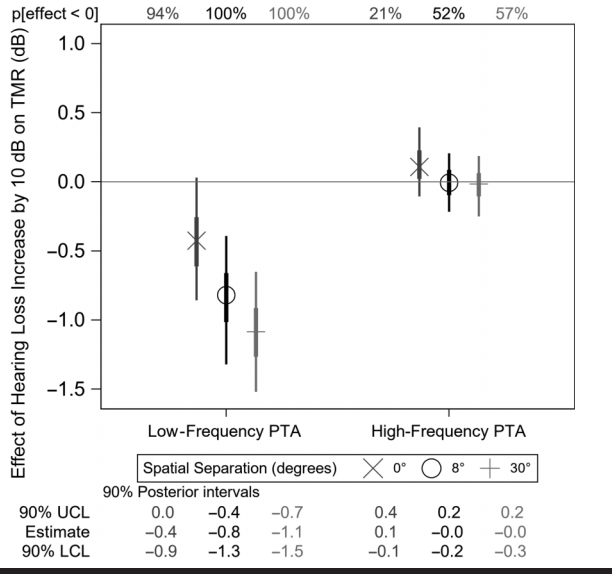


Figure 8. Model-based estimates of the effect of increasing hearing loss on mean target-to-masker ratio (TMR). Each panel shows how 10 dB of hearing loss in the low frequencies (left) and high frequencies (right) impacts TMR performance for maskers located at 0° (X's), 8° (circles), and 30° (crosses). Symbols indicate the median of the posterior distribution, and bars indicate the posterior interquartile (thick bars) and 90% credible interval (thin bars). The horizontal line indicates a 0-dB mean difference in the TMR when pure-tone average (PTA) is increased. The table at the bottom shows the numeric values for the median of the posterior distribution of the mean difference (labeled "Estimate") and the 90% posterior credible interval. Results show a negative impact of low-frequency, but not high-frequency, hearing loss. A 10-dB increase in the low-frequency PTA is associated with a mean reduction in the TMR of greater than 1 dB in the 30° condition. The low-frequency hearing effect is less for maskers separated from the target by 8°; however, the true effect is likely substantial even at 8° azimuth. In contrast, a 10-dB increase in the high-frequency PTA has little or no effect on the TMR, indicating that this speech understanding task is mediated by low-frequency cues. UCL = upper credible limit; LCL = lower credible limit.



50% correct performance on the speech task. The effect of elevating high-frequency hearing thresholds by 10 dB was negligible, essentially 0 dB for all contrasts, given PTA-low as well as other effects in the model (see Equation 1 in Supplemental Material S1).

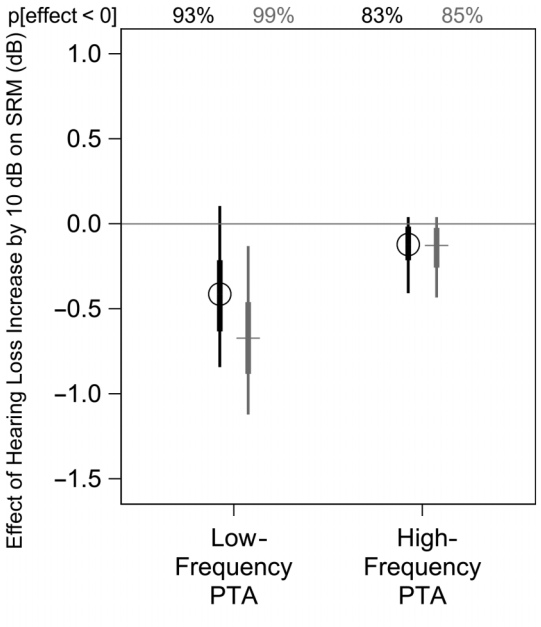
Figure 9 shows the model-based estimates of the effect of elevating PTA-low and PTA-high by 10 dB on mean SRM. Again, this effect was most pronounced when PTA-low was "increased" by 10 dB, showing an average reduction in SRM of 0.4 dB for 8° and 0.7 dB for 30° of spatial separation between the target and masker(s). The effect of increasing PTA-high on mean SRM was very small, at most less than half a decibel with a point estimate of 0.1 for both spatially separated masker conditions.

To evaluate group effects on PTA-low, we fit a model with a linear age effect, a DM group effect, and a subject-specific random effect to account for unmodeled variation in PTA-low across subjects. The model results are plotted in Figure 10. The symbols represent the model-based estimate of the population mean PTA-low; the thin lines show the 90% CI. These results show that PTA-low was elevated for each of the diabetes groups compared with the No DM control group, after adjusting for age. This indicates that DM2 affects low-frequency hearing in our sample, even among participants with prediabetes.

Discussion

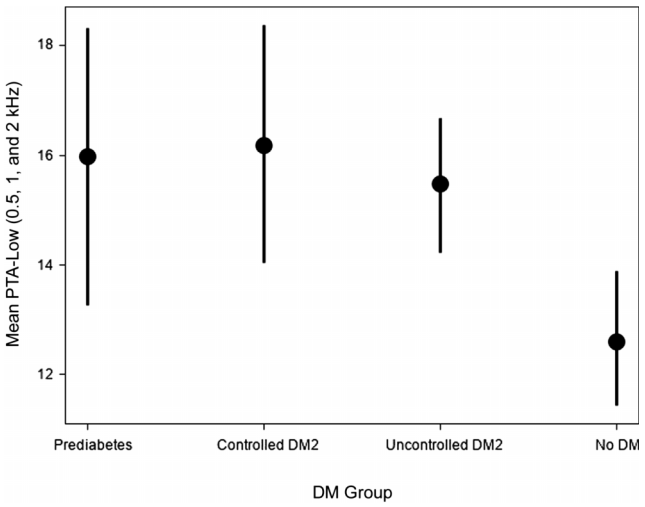
In complex auditory environments, listeners use spectro-temporal differences between the voices of different talkers and spatial cues associated with different sound source locations to improve speech-in-noise understanding (Gallun & Best, 2020). TMRs in this study provide an indication of the difficulty listeners experienced in understanding speech in the presence of competing speech maskers. SRM provides an indication of the improvement in speech-in-noise understanding due to spatial separation of the maskers

Figure 9. Model-based results of low- and high-frequency hearing loss on mean spatial release from masking (SRM). This figure shows how 10 dB of hearing loss impacts SRM by spatial location for maskers located at 8° (circles) and 30° (crosses). Symbols indicate the median of the posterior distribution, and bars indicate the posterior interquartile (thick bars) and 90% credible interval (thin bars). Hearing loss effects are shown separately for low-frequency (left) and high-frequency (right) pure-tone averages (PTAs). The horizontal line indicates a 0-dB mean difference. The table at the bottom shows the numeric values for the median of the posterior distribution of the mean difference (labeled "Estimate") and the 90% posterior credible interval. For example, a 10-dB hearing loss in the low frequencies shows an average reduction in SRM of 0.4 dB for 8° and 0.7 dB for 30° of spatial separation. UCL = upper credible limit; LCL = lower credible limit.



90% Posterior intervals				
90% UCL	0.1	−0.1	0.0	0.0
Estimate	−0.4	−0.7	−0.1	−0.1
90% LCL	−0.8	−1.1	−0.4	−0.4

Figure 10. The posterior distribution of the model-based mean low-frequency pure-tone average (mean PTA-low; 0.5, 1, and 2 kHz) in dB HL for each diabetes group: Prediabetes (participants with prediabetes), Controlled DM2 (participants with controlled Type 2 diabetes mellitus), Uncontrolled DM2 (participants with uncontrolled Type 2 diabetes mellitus), and No DM (participants with no diabetes). Circles indicate the median of the posterior distribution, and lines indicate the 90% credible interval.



from the speech and is thought to be due to a combination of binaural and spectrotemporal analysis and "better ear" hearing (Arbogast et al., 2002; Best et al., 2006; Freyman et al., 1999; Kidd et al., 1998; Marrone et al., 2008a). This study aimed to determine if DM2 was associated with reduced ability to access these important cues in a manner similar to what has been reported due to hearing loss and aging.

In this large cohort of 190 Veterans, DM2, age, and low-frequency hearing loss were each shown to negatively impact speech understanding in complex listening environments. Moreover, the Veterans with prediabetes or diagnosed diabetes had worse low-frequency hearing. Overall, results show that participants with DM2, compared with controls, needed competing speech levels to be less intense to recognize the target speech command. Another way to describe this effect is to think of a scenario of trying to hold a conversation in a noisy restaurant. Imagine two tables with people sitting all around them talking. At Table 1 is a person with diabetes trying to understand 50% of what the person across from him is saying. At Table 2 is a person without diabetes trying to understand 50% of what the person across from him is saying. On the basis of the TMR data from Figure 4, both the person with diabetes and the person without diabetes can understand about 50% of what the person across from them is saying when the competing talkers are not spatially separated from the talker of interest (0° condition) so long as the competing speech is not much more intense than the speech of interest. The competing speech must be less intense (by up to 0.5 dB on average) for a person with controlled DM and on the order of 0.25 dB for a person with uncontrolled DM. Furthermore, there is high certainty in the direction of these DM-related effects (see Figure 3 p[effect < 0] results toward the top of the graph). On the basis of the SRM data from Figure 5, when the competing talkers move 30° away from the person who has controlled diabetes, say to other chairs, that alone is not enough to improve intelligibility of speech from the person across from them, as it is for the person without diabetes. The person with controlled diabetes also needs the competing talkers to be at least a half decibel less intense than the person without diabetes to understand 50% of what the person across from them is saying. These results suggest that separating the maskers from the target speech alone did not result in improving the intelligibility of the target speech as would normally be expected.

While half a decibel is not necessarily going to have a huge impact on speech intelligibility, these data provide clear evidence that diabetes can reduce complex auditory processing through its impacts on the central auditory

system. Moreover, the results of this study show that diabetes can impair low-frequency hearing, which is crucial for speech intelligibility in this sample. Thus, diabetes appears to impact speech intelligibility indirectly by producing excess hearing loss and directly by altering central processes not attributable to hearing loss. In a Veteran population, it is likely that these effects related to diabetes further compromise an auditory system already damaged by noise exposure. Further work is needed to determine how often diabetes results in impairment that falls in the range for which rehabilitation is appropriate.

The extent to which DM2-related auditory dysfunction depends on disease severity may provide an indication of whether the effects can be preventable. Prior work suggests that better metabolic control may help mitigate DM2-related excess hearing loss (Horikawa et al., 2013; Konrad-Martin et al., 2015). In this study, controlled blood sugar among diabetics was not protective of DM2-related central changes in the TMR or SRM. Classification error is possible for the Controlled DM and Uncontrolled DM groups because the HbA1C values used to categorize diabetes control and severity are taken at one time point whereas the diabetes diagnoses occurred at least 2 years prior to study participation for most of the sample. However, this result is broadly consistent with our previous findings in a large VA cohort that central auditory evoked potentials were similar among individuals with diabetes who were insulin dependent or not (Konrad-Martin et al., 2016). Our results also show that participants with uncontrolled DM2 were more likely to be on oral medications (generally some form of metformin) compared with those with controlled DM2. Metformin is a known neuroprotectant, and thus, its use may have prevented some of the diabetes-related impacts on the TMR and SRM in the group of participants with uncontrolled DM2 (see Table 2). In this study, individuals with prediabetes were included in the sample to investigate the effects of an earlier and/or a less severe stage of DM2. Participants with prediabetes had worse low-frequency hearing compared with nondiabetic controls; however, their speech intelligibility was comparable to controls after adjusting for age and hearing differences. This could indicate that the central nervous system of individuals with DM2 is less vulnerable to the effects of DM2, as compared with the peripheral hearing organ. Currently, there is very little information on the appropriate ways to provide rehabilitation for those with small amounts of hearing loss (Koerner et al., 2020) or on which diagnostic approaches are the most appropriate. These results suggest that SRM may be one effective diagnostic approach but, even more importantly, suggest that more work is needed to fully understand the auditory dysfunction present in those with diabetes and how it develops as the disease progresses.

For this study, the model-based results show that 10 years of "aging" negatively impacted the TMR to the same degree for all groups, that is, about 0.25–0.75 dB on average for both spatial conditions. Therefore, in this sample of Veterans, there is no evidence of accelerated aging among the participants with diabetes. This finding is consistent with normative data published by Jakien and Gallun (2018) showing a 0.5 dB poorer TMR associated with a decade of aging in both colocated and 45° of spatial separation conditions. In respect to SRM, this study showed that 10 years of "aging" required reducing the masker levels in the spatially separated conditions by more than 1 dB to achieve 50% speech understanding, compared with performance in the colocated condition. The age effects can be used to put the DM2-related effects on both the TMR and SRM into context; the largest DM2 effect sizes are similar in magnitude to the effects of 10 years of aging.

After accounting for the other effects in the model (see Equation 1 in Supplemental Material S1), this study found that "increasing" low-frequency hearing loss by 10 dB had a detrimental effect on the TMR and SRM, separate from diabetes or aging. These findings are again similar to normative data published by Jakien and Gallun (2018) who showed that with greater spatial separations than used in this study, that is, that of 45° between the target and speech maskers, a 10-dB increase in hearing loss negatively influenced performance in the spatially separated condition by approximately 1.7 dB. Recent findings reported by Baltzell et al. (2020) also demonstrate that low-frequency hearing loss can reduce SRM ability. The overarching implication is that SRM is mediated by low-frequency temporal cues and that even small amounts of low-frequency hearing loss can impair binaural sensitivity and reduce access to timing cues needed to understand speech in noisy environments (Bernstein & Trahiotis, 2016).

Results in animal models provide a plausible biological basis for the association of DM2 with altered auditory function at the peripheral and central levels. In CBA/CaJ mice fed with a high-fat diet to induce DM2, Wave I of the auditory brainstem response exhibited threshold elevations across the entire hearing range in middle age, when presbycusis affected only high-frequency hearing in age-matched controls (Vasilyeva et al., 2009). The Wave 1 amplitudes were also significantly lower in mice with DM2 compared with controls. In contrast, near-field recordings from the dorsal and ventral inferior colliculus of the diabetic mice exhibited better thresholds of about 15–25 dB compared with controls, and response amplitudes were similar across the two groups. This suggests that the auditory midbrain compensates for the reduced peripheral input in mice with DM2, presumably through a loss of central inhibition and/or an increase in excitation (Vasilyeva et al., 2009). A growing body of evidence indicates that changes in central gain in response to reduced peripheral input impair temporal resolution crucial for understanding speech (e.g., Lobarinas et al., 2020).

Limitations

The model-based approach used in this study to estimate multiple effects separately showed average estimates of less than 1 dB; it is possible that this approach underestimates the individual effects of DM2, hearing loss, and age. Additionally, we found larger group differences in listening conditions that were ostensibly easier for the participants; the performance improvement seen for healthy, young listeners between the most and least difficult conditions is reduced for those

who are older and/or have hearing problems. It is possible that using easier conditions, such as 45° between the target and speech maskers, would have yielded larger effects. Finally, the participants in this sample were mostly middle-aged Veterans receiving care through VAPORHCS. Although any impairment in higher level auditory processing has negative consequences on speech intelligibility when combined with peripheral hearing loss, the effects of DM2 and age may be larger in a cohort that includes younger individuals without military noise exposures. In particular, damage to the auditory periphery and any correlated central changes might be expected to be less in a younger, better hearing, nondiabetic control group.

Conclusions

This study is one of the first to address the separate effects of DM2, age, and hearing loss in a large cohort of Veterans using a speech task that is representative of real-world listening environments. Results show that individuals with prediabetes or diagnosed DM2 have worse low-frequency hearing compared with nondiabetics. Model-based results indicate that older age and small amounts of low-frequency hearing loss have independent effects that combine to reduce the ability to understand speech in complex listening environments. However, there is also evidence, particularly among participants with controlled disease, that DM2 negatively impacts auditory function and possible cognitive resources as well, which are used to distinguish sound sources. These results provide a potential explanation for why individuals who have diabetes and/or are older often report difficulty understanding speech in real-world listening environments even when hearing is relatively normal.

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