The effects of preceding sound and stimulus duration on measures of suppression in younger and older adults^{a)}

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Despite clinically normal audiometric thresholds, some older adults may experience difficulty in tasks such as understanding speech in a noisy environment. One potential reason may be reduced cochlear nonlinearity. A sensitive measure of cochlear nonlinearity is two-tone suppression, which is a reduction in the auditory system's response to one tone in the presence of a second tone. Previous research has been mixed on whether suppression decreases with age in humans. Studies of efferent cochlear gain reduction also suggest that stimulus duration should be considered in measuring suppression. In the present study, suppression was first measured psychoacoustically using stimuli that were too short to result in gain reduction. The potential effect of efferent cochlear gain reduction was then measured by using longer stimuli and presenting tonal or noise precursors before the shorter stimuli. Younger adults (ages 19–22 yr) and older adults (ages 57+ yr) with clinically normal hearing were tested. Suppression estimates decreased with longer stimuli or preceding sound which included the signal frequency, but did not decrease with preceding sound at the suppressor frequency. On average, the older group had lower suppression than the younger group, but this difference was not statistically significant. © 2018 Acoustical Society of America.

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I. INTRODUCTION

It is difficult for anyone to understand speech in a noisy environment, but it is particularly difficult for many older adults. Even older adults with audiometric thresholds within the range of normal hearing often experience difficulty in noise, and this problem can start as young as middle age (e.g., Helfer and Vargo, 2009; Sommers and Gehr, 2010). Many times, middle-aged and older adult patients complain about problems understanding speech in noise prior to any measurable decrease in auditory thresholds (e.g., Helfer and Vargo, 2009). This suggests that there are processes affected by aging that are not reflected in the audiogram and are negatively affecting speech perception in noise. There are several auditory processes or mechanisms that are not tested in the clinic and that may be related to speech perception in noise, and one of these is two-tone suppression.

In the cochlea, a sound of one frequency will reduce the auditory system's response to a neighboring frequency. This phenomenon is called two-tone suppression, and it occurs at the level of the basilar membrane (e.g., Ruggero *et al.*, 1992). Suppression is made possible by the nonlinear properties of the cochlea and is thus due to the activity of the outer hair cells (OHCs), which amplify the motion of the basilar membrane (Ruggero *et al.*, 1992). When lower frequencies suppress higher frequencies, this is known as low-side

suppression, and when higher frequencies suppress lower frequencies, this is known as high-side suppression. The suppressive regions flank the upper and lower edges of the frequency tuning curve (Sachs and Kiang, 1968). The low-side suppressive region starts at mid suppressor intensities [40–50 dB sound pressure level (SPL)] and spreads to frequencies well below the characteristic frequency, and the high-side suppressive region starts at a lower suppressor intensity (10 dB SPL) and cuts off sharply about a half octave above the characteristic frequency (Sachs and Kiang, 1968). With cochlear hearing loss, suppression decreases or is even lost completely, which is likely due to OHC dysfunction (e.g., Thibodeau, 1991; Dubno and Ahlstrom, 2001c). Suppression may help emphasize the regions of higher energy, or formants, in speech, and this emphasis may make the formants more resistant to degradation by background noise (Kates, 1995).

It is possible that suppression decreases as a part of the normal aging process. Two animal studies have investigated whether suppression decreases with age. Both studies investigated suppression using gerbils. For gerbils raised in quiet, defined as a median A-weighted sound level of 35 dB (quiet-aged), the tip-to-tail ratio of tuning curves decreased, particularly in the higher frequencies, but suppressive areas on the low-frequency side were unchanged in frequency and level. On the high-frequency side, the suppressive areas still flanked the tuning curves (Schmiedt *et al.*, 1990; Hellstrom and Schmiedt, 1996). For animals raised in noise, defined as living in a continuous noise field of 85 dBA for 1–2 yr beginning at the age of 8 months (noise-aged), Schmiedt *et al.* (1990) found that high-side suppression areas could be

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missing altogether, suggesting that high-side suppression may be more vulnerable to the detrimental effects of noise. [Schmiedt et al. \(1990\)](#) hypothesized that the quiet-aged effects might reflect a decrease in the endocochlear potential, while the noise-aged effects might also reflect OHC damage.

Several human studies have also investigated the effect of age on suppression. In these studies, two basic forward masking techniques have been used to estimate suppression. One technique uses a tonal masker and suppressor (e.g., [Shannon, 1976](#)). Forward masking by an on-frequency masker is measured. Then forward masking is measured when the on-frequency masker is paired with an off-frequency suppressor. If the masker is being adjusted to find threshold, suppression is indicated by the threshold masker level being higher in the presence of the suppressor. If the masker is fixed and the signal is being adjusted to find threshold, suppression is indicated by the signal threshold being lower in the presence of the suppressor. In the other technique, threshold is measured for a signal following a narrowband noise masker centered at the signal frequency, and then as the noise is extended either below, above, or below and above the signal frequency, with spectrum level kept constant. As the noise is extended in frequency, it should enter suppressive regions that should suppress the frequency region that is causing forward masking of the signal. Suppression is estimated as the difference in signal threshold between the widest and narrowest bandwidths (e.g., [Dubno and Ahlstrom, 2001a](#)).

The majority of the human studies have found that suppression was lower in older listeners than in younger listeners, with both groups having hearing within the clinically normal range ([Dubno and Ahlstrom, 2001b,c](#); [Sommers and Gehr, 1998, 2010](#)). These studies found that both low-side ([Dubno and Ahlstrom, 2001a,b](#)) and high-side suppression can decrease with age ([Dubno and Ahlstrom, 2001b,c](#); [Sommers and Gehr, 2010](#)). In contrast, [Gifford and Bacon \(2005\)](#), who measured only low-side suppression, did not find a difference with age.

Although the animal studies have shown that suppression is still present with age, they differ from the human studies in that they did not find the magnitude of suppression in terms of reduction in gain. This could be affected by the amount of gain present. Since the quiet-aged animals typically had tuning curves with elevated tips, it appears that they had lower gain, which could reduce the magnitude of suppression measured in a masking task. However, in the human studies, effects of hearing loss have been minimized by choosing listeners matched in various ways. These range from clinically normal hearing ([Dubno and Ahlstrom, 2001a,b,c](#)), thresholds below 15 dB hearing level (HL; [Sommers and Gehr, 2010](#)), or matching older and younger subjects on audiometric thresholds ([Gifford and Bacon, 2005](#)). However, even matching listeners fairly well on audiometric thresholds has led to conflicting results. [Gifford and Bacon](#) found no significant difference in suppression in younger and older groups using a low-side band-widening procedure. In contrast, [Sommers and Gehr \(2010\)](#) found significantly less high-side suppression in older than younger listeners using the tonal forward masking technique.

The [Gifford and Bacon \(2005\)](#) results suggest that rather than just matching quiet thresholds, it is important to have a measure of cochlear function for each listener. [Yasin and Plack \(2003, 2007\)](#) used a tonal forward masking technique called a temporal masking curve to measure suppression. In this technique, the signal is fixed in level, and the threshold masker level to mask the signal is measured as a function of signal delay from masker offset. One masker frequency is set at the signal frequency, and another is set approximately an octave below the signal frequency. The off-frequency masker provides a linear reference that should only show the rate of decay of forward masking, while the on-frequency masker should also be affected by the compression at the signal frequency. By comparing on- and off-frequency masker levels as a function of signal delay, an estimate of the cochlear input/output (I/O) function may be derived, including an estimate of gain. [Yasin and Plack](#) also tested multiple masker frequencies to derive psychoacoustic tuning curves (PTCs). They then paired low-side or high-side suppressors of 40–70 dB SPL with the maskers, and derived I/O functions and PTCs. Their results were parallel to physiological suppression data in that the tip of the tuning curve was raised by the suppressors but not the tail, and the gain of the I/O function was decreased. Their subjects had audiometric thresholds within the normal range. Subject ages were not provided.

A subset of these techniques could be used to optimize the measurement of suppression while also obtaining an estimate of gain in younger and older listeners. Signal level could be fixed, and the masker set at the signal frequency, and approximately one octave below the signal frequency. This would provide a measure of gain and also a sparse low-side tuning curve so that a low-side suppressor level could be chosen. Likewise, a masker on the high-frequency side could be chosen that was at a ratio of 1.2 to the signal frequency, which is a frequency ratio that has been shown to produce suppression (e.g., [Shannon, 1976](#)). This would provide the high-frequency side of the tuning curve, and also allow the high-side suppressor level to be chosen. In this way, suppressor levels would be optimized to each subject, which is important in determining whether suppression is present or not. At the same time, it would give a measure of gain, which should be sensitive to cochlear status, and be expected to affect the magnitude of suppression.

Since gain is an important factor to consider in the measurement of suppression, another aspect that should be considered is the duration of the stimuli used to measure suppression. There is both physiological and psychoacoustic evidence that the peripheral auditory system may decrease gain in response to sound by the action of the medial olivocochlear reflex (MOCR). The MOCR is a sound-elicited feedback loop that decreases amplification, or gain, in the cochlea. The acoustic signal causes a response that is sent through the auditory system toward the brain, passing through the superior olivary region of the brainstem (e.g., [Cooper and Guinan, 2006](#)). Collateral neurons medial to the medial superior olivary complex travel back to the cochlea and synapse onto the OHCs, hyperpolarizing them, which in turn decreases cochlear gain (e.g., [Cooper and Guinan,](#)

2006). It takes approximately 25 ms after onset or offset of a sound for cochlear gain to be affected (James *et al.*, 2005; Backus and Guinan, 2006).

It is possible that age can decrease MOCR strength. Several human and animal studies have investigated aging effects on MOCR strength, and the majority of the human studies found decreases in strength of the MOCR with age (Castor *et al.*, 1994; Keppler *et al.*, 2010; Kim *et al.*, 2006; Mazelová *et al.*, 2003; Mukari and Mamat, 2008). However, three human studies found no change in MOCR strength with age (Collet *et al.*, 1992; Quaranta *et al.*, 2001; Stenklev and Laukli, 2003). All of the human studies used contralateral suppression of otoacoustic emissions (OAEs) to measure MOCR strength, and it is unknown why some studies found differences with age while others did not. Animal studies on the effects of age on the MOCR have all found significant changes in MOCR strength and physiology with age (Fu *et al.*, 2010; Jacobson *et al.*, 2003; Thompson *et al.*, 2006; Zettel *et al.*, 2007; Zhu *et al.*, 2007). These studies found that the strength of the MOCR decreased prior to any changes in auditory threshold (Jacobson *et al.*, 2003; Zhu *et al.*, 2007).

Psychoacoustic techniques similar to those used in the Yasin and Plack (2003, 2007) studies described above have been used to show that preceding sound may decrease gain in the cochlea. Short maskers and signals have been used to measure I/O functions and PTCs without the influence of the MOCR. Then, preceding sound (a precursor) has been added, intended to elicit the MOCR. Following a precursor, PTCs broaden (Jennings *et al.*, 2009; Jennings and Strickland, 2012) and the gain of the I/O function is decreased (Krull and Strickland, 2008; Roverud and Strickland, 2010; Yasin *et al.*, 2014). Modeling has shown that these results are consistent with gain reduction, but not consistent with additivity of masking (Jennings *et al.*, 2009; Jennings and Strickland, 2012). This decrease in gain has been seen for tonal precursors at the signal frequency (Krull and Strickland, 2008; Roverud and Strickland, 2010; Jennings *et al.*, 2009), approximately an octave below the signal frequency (Roverud and Strickland, 2014) and for noise precursors (Yasin *et al.*, 2014; Milvae and Strickland, 2018). Jennings and Strickland (2010) showed that the tuning for the precursor was approximately the same as the tuning measured by PTCs for frequencies above and below the signal frequency.

Physiological studies of the tuning for the elicitor of the MOCR have not provided definitive evidence for tuning for the elicitor frequency. Based on the tuning properties of medial olivocochlear (MOC) fibers and the innervation patterns of MOC fibers to OHCs measured in cats, Winslow and Sachs (1987) hypothesized that the MOCR was a fairly frequency-specific system. Studies in humans have been done using stimulus frequency otoacoustic emissions (SFOAEs). These studies suggest that the tuning may be different for contralateral than for ipsilateral elicitors, and increases with the bandwidth of the elicitor (Lilaonitkul and Guinan, 2009a,b, 2012). Here, only the tuning for ipsilateral elicitors measured post-elicitor will be considered, as this is most directly relevant to the stimulus configurations in the present study. Lilaonitkul and Guinan (2012) found that the tuning for the elicitor depends on which measure of SFOAE

change is used. If measured as the derived stimulus frequency otoacoustic emission with medial olivocochlear reflex elicitation (nSFOAEmoc) the change is more sharply tuned at the SFOAE frequency than when measured by the change in stimulus frequency otoacoustic emission (Δ SFOAEn), in which case it may be broad and produce the largest decrease for frequencies below the probe frequency. The change in the phase of the nSFOAEmoc is less sharply tuned. Lilaonitkul and Guinan noted that it is not clear which measure of the MOCR is most relevant for perception. Also, since only the Δ SFOAEn measure has been used in previous studies examining the effects of stimulus bandwidth, it is not clear whether broadband noise (BBN) is a stronger elicitor than tones with the nSFOAEmoc measure. Therefore it is of interest to measure tuning for the precursor in the suppression task in the current study.

The fact that gain reduction can be seen with tonal precursors suggests that long-duration maskers and suppressors might themselves reduce gain, which would also be expected to reduce the amount of suppression. Only one study has directly addressed masker and suppressor duration for very short durations. Champlin and Wright (1993) found that suppression measured using the tonal forward masking technique decreased slightly as masker and suppressor duration increased. However, they measured suppression by simply fixing the masker and suppressor in level, and increasing the duration. As pointed out by Bacon (1996), with the paradigm used, it is difficult to disentangle the effects of masking and suppression. Yasin and Plack used short maskers and suppressors in one study (Yasin and Plack, 2003) and longer maskers and suppressors in another study (Yasin and Plack, 2007) and appear to have found slightly more maximum suppression with the shorter stimuli.

Two physiological studies in cats suggest that suppression decreases when gain has been reduced by MOCR elicitation. Both studies measured the combined effects of suppression and gain reduction on auditory-nerve responses. Kawase *et al.* (1993) measured the response of a nerve fiber to a BBN as a function of the level of a tone presented below the characteristic frequency (CF). They observed suppression and then excitation by the tone. They then elicited the MOCR with contralateral noise and found that cochlear gain decreased, suppression began at a higher tone level, and the amount of suppression decreased compared to conditions where the MOCR was not elicited. Winslow and Sachs (1987) measured suppression of a tone at CF by tonal suppressors either below or above CF. They elicited the MOCR with electrical stimulation of the crossed medial olivocochlear bundle, and found that suppression began at a higher suppressor level and the amount of suppression decreased compared to conditions where the MOCR was not elicited. They hypothesized that the decrease in suppression could either correspond to the decrease in gain at the suppressor frequency or, alternatively, could depend only on the frequency of the suppressor relative to CF.

Physiological data show that OHC lesions basal to the CF of an auditory-nerve fiber may decrease high-side suppression (Dallos, 1996). This is consistent with a model described by Patuzzi (1996) that high-side suppression may

be due to the suppressor “jamming” the active process of the signal frequency place. Therefore, the effect of a precursor on suppression might not only depend on gain at the signal frequency place. It is possible that a tonal precursor presented above the signal frequency, or a BBN precursor, would reduce suppression of the signal by a suppressor above the signal frequency by reducing gain at the suppressor frequency.

The potential effects of gain reduction will be assessed in two ways in the present study. One is by measuring the effect of masker and suppressor duration on the estimate of suppression. This is relevant for comparison with the previous studies, and for determining whether duration is important in these types of suppression measurements. The second way will be to use noise and tonal precursors before short suppressors and maskers in a more direct parallel to previous gain reduction studies. Using these methods, it will be possible to determine whether suppression decreases as gain is decreased. Tonal precursors will be at the signal frequency as well as at the suppressor frequencies, since as noted above the tuning to a precursor in this task is not fully known. As noted above, in OAE studies, noise precursors have been found to be more effective elicitors of gain reduction than narrow-band stimuli (e.g., Lilaonitkul and Guinan, 2009b), and would decrease gain at all frequencies, including the signal and suppressor frequencies. The goal of the present study is to re-examine the effects of aging in measures of suppression. The suppression measurement will be optimized by measuring a sparse PTC to select suppressor levels, and also to get measure of cochlear status. Suppression will be measured for short stimuli, which are expected to show the most suppression. Suppression will also be measured for longer sounds and with precursors to assess potential effects of gain reduction by preceding sound.

II. METHODS

A. Participants

Eight younger listeners (six female, ages 19–22 yr) and eight older listeners (five female, ages 57–69 yr) participated in the experimental conditions. The right ear or better ear of each participant was tested. Audiometric thresholds were tested at octave frequencies from 0.25 to 8.0 kHz. The audiometric thresholds were measured with pulsed tones of at least 200 ms each, using a one-interval yes/no task with a criterion of 50% correct. The modified Hughson-Westlake method (Carhart and Jerger, 1959) was used, which is an adaptive procedure in which 10-dB steps are used to reduce the level, and 5-dB steps are used to increase the level. All participants had auditory thresholds within the normal range (≤ 25 dB HL) at 2 kHz, no air-bone gap, normal tympanograms (type A) and acoustic reflex thresholds, and no significant history of noise exposure. The audiograms for each group are shown in Fig. 1. The older adults showed a wider range of thresholds than the younger adults, along with high-frequency hearing loss in some of the participants. A two-way analysis of variance (ANOVA) with age group (younger vs older) and frequency (six frequencies) as factors found no significant effect of frequency [$F(5,70) = 0.78, p = 0.57$], but a significant effect of age group [$F(1,14) = 9.54, p < 0.01$]

and a significant age group by frequency interaction [$F(5,70) = 7.71, p < 0.001$]. A *t*-test found no significant difference between the groups in audiometric thresholds at 2 kHz [$t(14) = -1.15, p = 0.27$]. Distortion-product otoacoustic emissions (DPOAEs) at 2 kHz were measured with a Bio-logic system (Natus Medical Incorporated, Pleasanton, CA). They were present for all of the younger adults measured and six of the eight older adults [minimum criteria of -6 dB SPL distortion product, and 6 dB signal-to-noise ratio (SNR)]. Measurements were not available for one younger adult due to a problem sealing the probe in the ear canal. The average DPOAE level was significantly lower for the older adults [$M = 13.43$, standard deviation (SD) = 3.35] than for the younger adults ($M = 5.68$, SD = 7.89) [$t(11) = 2.38, p = 0.04$].

Cognition was assessed by the Montreal Cognitive Assessment (MoCA), and all listeners scored within the normal range ($\geq 26/30$). Participants were recruited by word-of-mouth or fliers posted around the Purdue University campus, and all participants were compensated for their time.

B. Stimuli and conditions

Schematics of the stimuli used in the short and long suppression conditions are shown in Fig. 2. The signal was a 2-kHz, 10-ms pure tone with 5-ms onset and offset ramps (no steady-state duration). This signal frequency has been used in previous studies investigating age effects on suppression (Sommers and Gehr, 1998; Dubno and Ahlstrom, 2001a,b,c; Gifford and Bacon, 2005; Sommers and Gehr, 2010), and was chosen in the present study because there was not a significant difference in audiometric thresholds between the younger and older groups. The signal duration and 5-ms ramps were chosen to minimize spectral splatter (Bacon and Viemeister, 1985). In preliminary testing, a signal level of 10 dB sensation level (SL) was too low when precursors were presented, so the signal was fixed at 20 dB SL in relation to threshold in quiet for the 2-kHz, 10-ms pure tone for each participant. The threshold masking level was measured for an on-frequency masker (2 kHz) as well as off-frequency maskers at frequencies that will later be used to measure suppression (1.2 and 2.4 kHz). The forward maskers were 20 and 70 ms in duration, including 5-ms onset and offset ramps. There was zero delay between the masker offset and the signal onset at the zero-voltage points.

The short masker durations have been used in previous studies examining gain reduction (e.g., Jennings *et al.*, 2009; Roverud and Strickland, 2010) based on the time course of the MOCR, which is schematized by the curve labeled “gain” below the stimuli. As noted in the Introduction, the onset and offset delays of the MOCR from elicitor onset and onset are approximately 25 ms (James *et al.*, 2005; Backus and Guinan, 2006). Therefore in the short condition, the stimuli are chosen so that any gain reduction induced by the masker will occur after presentation of the signal.

For the short suppression conditions, the suppressor was either a 1.2- or 2.4-kHz pure tone with a duration of 20 ms, including 5-ms onset and offset ramps. These suppressor frequencies were chosen for several reasons. First, as noted in the Introduction, finding the masking thresholds for these frequencies traced a sparse tuning curve for each participant,

FIG. 1. Group audiograms for the younger and older adult participants. Audiograms are plotted in the traditional format with better thresholds near the top of the plot and poorer thresholds near the bottom.

including an estimate of gain. This tuning curve also allowed suppressor levels to be set below the level where they would produce excitatory forward masking. Several studies have used tonal suppressors at a ratio of 1.15–1.2 times the signal frequency because this ratio has been found to produce maximum suppression under certain conditions (e.g., Shannon, 1976; Yasin and Plack, 2003). However, since the growth of excitation at the signal frequency place to a tone of this ratio to the signal frequency may be compressive, it might be affected by gain reduction, which is tested in some of the conditions. For this reason, and also to test low-side suppression, a suppressor of 1.2 kHz was also tested. This masker/suppressor frequency should have an approximately linear

response at the signal frequency place, and should be unaffected by gain reduction (Cooper and Guinan, 2006). High-side and low-side suppressors were also chosen because previous studies of suppression in younger and older adults showed different results with high- and low-side suppressors. Gifford and Bacon (2005) did not see a difference in suppression with age using a low-side suppression measure, but Sommers and Gehr (2010) did using a high-side suppression measure. The on-frequency masker and suppressor were presented simultaneously. The signal and suppressor levels were fixed, and the masker level was varied to find threshold. The signal was presented at 20 dB SL, and the suppressor level was fixed approximately 2 dB below the threshold masking level for each suppressor frequency. This suppressor level was chosen to avoid forward masking by the suppressor, yet find an estimate of the maximum amount of suppression, because suppression tends to increase with suppressor level (Duifhuis, 1980; Yasin and Plack, 2007). To estimate the amount of suppression, the threshold masker level with a suppressor was subtracted from threshold masker level without a suppressor.

For the long suppression conditions, the masker and precursor durations were increased to 70 ms, including 5-ms onset and offset ramps. The additional 50 ms was chosen to match the duration of the precursor condition below. Thresholds were re-determined with these longer on- and off-frequency maskers. For most listeners there was little change in the masker threshold with the longer duration, but for some listeners the threshold masker level changed by a few dB in some conditions. The suppressor levels were again chosen to be less than the level that produced forward masking of the signal. As shown in Fig. 2, these stimuli are long enough that gain reduction induced by the onset of the masker/suppressor complex could affect the masker and/or suppressor. Gain reduction could decrease the output level of the signal or the on-frequency masker within the signal frequency channel. A reduction in gain could also decrease suppression of the on-frequency masker by the suppressor. To estimate the amount of suppression, the on-frequency masker threshold level was again compared between conditions with and without a suppressor.

Figure 3 shows the relationship between the threshold for the on-frequency (2 kHz) and off-frequency (1.2 and 2.4 kHz) maskers compared to the presentation level of the

FIG. 2. (Color online) Schematics of stimuli for the forward maskers and the short and long suppression conditions. The signal was a 2-kHz, 10-ms pure tone, and the masker was a 2-kHz pure tone with a duration of 20 ms (short) or 70 ms (long). The suppressor was a 20- or 70-ms pure tone at either 1.2- or 2.4-kHz. The line underneath the stimuli depicts the temporal pattern of gain reduction by the MOCR. Gain starts at 100% and decreases approximately 25 ms after onset of the stimulus. Gain begins to recover approximately 25 ms after the offset of the stimulus.

suppressor. The thresholds in Fig. 3 are data from a younger participant. The masker thresholds plot out a sparse psycho-physical tuning curve. The suppressive regions lie just outside of the tuning curve.

The long suppression condition is important in directly comparing whether masker/suppressor duration affects the amount of suppression measured, and for comparing the results of this study to previous studies, which almost all used longer durations. However, from a gain reduction perspective, it is a complicated condition. In the long suppression conditions, gain could be reduced by the masker and/or suppressor. Also, it is possible that suppression may be reduced by a reduction in gain at the signal frequency or suppressor frequency. Since the masker level is varied to find threshold, the amount of gain reduction could also vary with masker level. Therefore, suppression was also measured with fixed-level tonal and noise precursors presented prior to the short suppression condition. The tonal precursors were presented either at the signal frequency or suppressor frequency since, as noted above, suppression may depend on gain at frequencies other than the signal frequency. BBN should reduce gain at all frequencies. This condition also provided a direct parallel with previous experiments measuring gain reduction with a tonal precursor at the signal frequency (e.g., Krull and Strickland, 2008; Jennings *et al.*, 2009; Roverud and Strickland, 2010) or with noise precursors (Yasin *et al.*, 2014; Milvae and Strickland, 2018). In previous studies in this laboratory, 50 ms has been found to be the optimal duration for an on-frequency tonal precursor for producing gain reduction effects with a 20-ms forward masker (Roverud and Strickland, 2014). Using fixed precursors should result in a fixed amount of gain reduction across different conditions.

To establish that these listeners did show gain reduction following a precursor, as has been found in previous studies, this was tested for each listener. A preliminary experiment was done on two of the younger and three of the older listeners using two different methods. In the first method, the level of a

FIG. 3. Thresholds for the on-frequency (2 kHz) and off-frequency (1.2 and 2.4 kHz) short-duration maskers trace a sparse tuning curve. The data are for younger participant A2. Suppressor presentation levels (triangles) were chosen to fall into the suppressive regions of the tuning curve with the goal of producing the greatest amount of suppression for that individual.

1.2-kHz, 20-ms masker was determined that shifted threshold by 5 dB above quiet threshold. This masker frequency is used because it should have a linear response at the signal frequency place and should not be affected by gain reduction. The signal level chosen should place it on the lower leg of the input-output function, where a shift in signal threshold should estimate gain reduction in dB (e.g., Roverud and Strickland, 2010). Next, a 50-ms BBN precursor (250–8000 Hz) was presented at 50 dB SPL immediately prior to the 1.2-kHz masker. This precursor level was chosen because it is within the range of levels that have produced gain reduction in a previous study that used a BBN precursor (Yasin *et al.*, 2014), and because it is close to the highest level used in the later experiments. The masker and precursor levels were fixed and the signal level was varied to find threshold. Gain reduction was measured as the difference in signal threshold with and without the precursor, as in previous studies (Roverud and Strickland, 2010, 2014; Milvae and Strickland, 2018). As noted in the Introduction, previous studies have shown that this threshold shift is consistent with gain reduction and not with temporal integration (additivity of masking) because the precursor decreases frequency selectivity (Jennings *et al.*, 2009; Jennings and Strickland, 2012). In the second method, signal threshold was measured in the presence of the same precursor with a 20-ms precursor-signal gap in place of the 1.2-kHz masker. Gain reduction was again measured as the dB difference in signal threshold with and without the precursor. A paired-samples *t*-test found no significant difference in gain reduction estimate between method one ($M = 6.95$, $SD = 2.79$) and method two ($M = 5.43$, $SD = 4.02$); $t(4) = 0.60$, $p = 0.58$. This agreement in amount of gain reduction measured by both methods was also found by Milvae and Strickland (2018). Therefore, all of the other participants were tested using the second method, which was the gain reduction estimate without the masker present, to reduce the amount of testing time required to complete the experiment.

In the precursor conditions, a 50-ms precursor, including 5-ms onset and offset ramps, was presented before the 20-ms masker/suppressor complex (Fig. 4). There was no delay between the precursor offset and onset of the masker/suppressor complex. The precursor was either a tone at the frequency of the signal or suppressor, or a BBN (250–8000 Hz). In the precursor conditions, the signal, suppressor, and precursor levels were fixed, and the masker level was varied to find threshold (suppressor present, Fig. 4). These conditions were compared to control conditions with the precursor, masker, and signal, but without the suppressor (suppressor absent, Fig. 4), to estimate the amount of suppression.

Stimuli were generated digitally using custom MATLAB (release 2012a, The Mathworks, Inc., Natick, MA) software (Bidelman *et al.*, 2015) at a sampling rate of 44.1 kHz, sent to a LynxTWO-B sound card (Lynx Studio Technology, Costa Mesa, CA), and sent through a headphone buffer (TDT HB6, Tucker-Davis Technologies, Alachua, FL) before being delivered through ER-2 insert earphones (Etymotic Research, Inc., Elk Grove Village, IL). The ER-2 earphones have a flat frequency response at the eardrum from 250 to 8000 Hz. Data analysis was performed using R (R Core Team, 2013).

FIG. 4. (Color online) Schematics of stimuli for the conditions with a precursor. The line under the stimuli depicts the temporal pattern of gain reduction. Gain starts at 100% and decreases approximately 25 ms after onset of the stimulus. Gain begins to recover approximately 25 ms after the offset of the stimulus. The signal was a 2-kHz, 10-ms pure tone, and the masker was a 2-kHz, 20-ms pure tone. The suppressor was a 20-ms pure tone at either 1.2- or 2.4-kHz. The 50-ms precursor consisted of either BBN or a 2.0-kHz pure tone.

C. Procedure

Participants were seated in a double-walled, sound-attenuating booth and responded using a computer mouse and keyboard. A three-interval forced-choice task was used. Stimuli were presented simultaneously with visual markers corresponding to each of the three stimulus intervals. Participants were instructed to select the interval that sounded different from the other two. Visual feedback indicated whether the answer was correct or incorrect. Following two correct responses, the masker level was decreased, and it was increased following one incorrect response. An estimate of 70.7% correct on the psychometric function was produced through this procedure (Levitt, 1971). The step size for the first three reversals was 5 dB, followed by a step size of 2 dB for the remainder of the trial. The threshold for each trial consisted of the average of the last eight reversals. The threshold for each data point consisted of the average of the last two trials. Trials with SDs greater than 5.3 dB were discarded and re-done. Across each session, conditions with fixed precursor levels were presented from low to high levels to avoid possible detrimental effects that exposure to a higher level may have on responses to subsequent lower levels (Strickland, 2001). The maximum output level was limited by the experimental program, and this level was determined by finding the maximum level at which the output did not produce distortion. This level was just below 94 dB SPL. If the stepping rule would have exceeded this level, the track immediately stopped. Participants were instructed to stop the track if the level of the stimuli became uncomfortable. Although participants received this instruction, at no time during the experiment did any participants report that the level was uncomfortably loud. The procedures were performed in accordance with the Purdue University Institutional Review Board, which approved all procedures.

Quiet thresholds for the 2-kHz signal were determined first. Then threshold masking levels for 1.2-, 2-, and 2.4-kHz maskers were determined with the signal fixed at 20 dB SL. Half of the participants started with the 1.2-kHz suppressor conditions, and the other half started with the 2.4-kHz suppressor conditions. Masker thresholds were also measured in the presence of a suppressor preceded by tonal

or BBN precursors. The short suppression condition was measured next, and the order of the long suppression and precursor conditions was randomized across listeners.

While some previous studies of suppression have addressed the issue of confusion, this was not directly addressed in the currently study. Neff (1986) did not find evidence of confusion in forward masking for a tonal masker. In addition, Sommers and Gehr (2010) directly tested for confusion, and found no effects of presenting a contralateral noise cue with the forward masker.

III. RESULTS

A. Quiet thresholds, gain, and gain reduction estimates

Quiet thresholds for the 2-kHz signal were lower for the younger adults ($M = 30$, $SD = 3.66$) than for the older adults ($M = 37$, $SD = 9.05$). A t -test found that this difference was not significant [$t(14) = -2.14$, $p = 0.051$]. This is closer to a significant difference than was seen for the audiometric thresholds. It is possible that the difference in signal duration and measurement technique used made the differences smaller for the audiometric thresholds.

Cochlear gain was estimated as the dB difference in the threshold levels of the 1.2- and 2-kHz short-duration maskers needed to mask the 2-kHz signal fixed at 20 dB SL (Plack *et al.*, 2004; Yasin *et al.*, 2014). This is not an estimate of total gain but rather an estimate of gain for the signal level and masker frequency used in this experiment. Due to the signal level of 20 dB SL, a threshold could not be obtained for the 1.2-kHz masker for four younger adults and three older adults because the masker level reached the limits of the system. In these cases, the highest level possible (93 dB SPL) was used as the estimate of the off-frequency masker level. This may slightly underestimate the gain for these subjects. However, the gain estimate was significantly correlated with the DPOAE level for $F2$ near 2 kHz, which should be related to gain, for the 14 participants for which this was available ($r = 0.68$, $n = 14$, $p < 0.01$). The average gain estimates are shown in Fig. 5. A t -test was conducted to determine whether gain estimates differed between the two age groups. The younger adults ($M = 41.55$, $SD = 5.95$) were found to have significantly greater gain estimates than the older adults ($M = 31.31$, $SD = 9.19$), [$t(14) = 2.64$, $p = 0.02$]. A Pearson product-moment correlation coefficient was conducted, and no significant correlation was found between the cochlear gain estimate and audiometric threshold at 2 kHz ($r = -0.42$, $n = 16$, $p = 0.11$). However, using the same test, a significant correlation was found between gain and threshold for the short 2-kHz tone ($r = -0.74$, $n = 16$, $p < 0.01$). This is consistent with results reported by Plack *et al.* (2004), wherein gain decreased as quiet threshold increased.

The gain reduction estimates are shown in Fig. 6. The left panel shows the signal threshold with no precursor, and the middle panel shows the threshold with a precursor. The difference between these two thresholds is the gain reduction estimate shown in the right panel. Gain reduction estimates were significantly greater for younger ($M = 7.57$, $SD = 1.71$) than older ($M = 4.02$, $SD = 2.86$) adults [$t(14) = 3.02$, $p < 0.01$]. This is because thresholds were higher for the

FIG. 5. On-frequency (left) and 1.2-kHz (middle) masker levels needed to mask the 20 dB SL, 2-kHz signal. The difference between these thresholds is the estimate of gain (right).

older participants with no precursor and showed less change with a precursor. A Pearson product-moment correlation coefficient was conducted, and there was a significant negative correlation between audiometric threshold at 2 kHz and gain reduction ($r = -0.64$, $n = 16$, $p < 0.01$). Using the same test, a significant positive correlation was found between gain reduction and cochlear gain ($r = 0.57$, $n = 16$, $p = 0.02$), and a significant negative correlation with threshold for the short 2-kHz tone ($r = -0.72$, $n = 16$, $p < 0.01$).

B. Suppression estimates with short and long stimuli

Suppression was measured using the forward masking paradigm described in Sec. II (Methods). The threshold masker level to mask a 2-kHz signal at 20 dB SL was measured for maskers at each suppressor frequency (1.2 and 2.4 kHz). The suppressor level was fixed approximately 2 dB below this level, and the on-frequency masker level was varied to find threshold. Suppressor levels for each condition and subject are shown in Table I. Many previous studies of suppression that have used a forward masking paradigm have fixed both the masker and suppressor levels to be the same for all subjects and varied the signal to find threshold. This technique assumes that the suppressor is not causing excitatory forward masking of the signal. In the present study, the suppressor level was determined on an individual basis for the fixed signal level in an attempt to reduce excitatory forward masking of the signal, which may artificially reduce the estimated amount of suppression.

Suppression was estimated as the difference in masker levels needed to mask the signal with and without the

suppressors present. Suppression estimated with short stimuli in the younger and older adults is shown in Fig. 7.

Suppression was also measured using a 70-ms masker/suppressor complex immediately prior to the 10-ms signal. This duration should be long enough to elicit gain reduction that could affect the end of the masker/suppressor complex and/or the signal (Roverud and Strickland, 2010). Furthermore, this condition can be used as a comparison with other studies of suppression that used longer stimuli. Low-side and high-side suppression estimated with long stimuli in younger and older adults is shown in Fig. 7.

C. Suppression following a precursor

To further investigate a decrease in suppression with gain reduction, 50-ms precursors were presented prior to the short suppression condition. This fixes the amount of gain reduction across masker levels. Precursors were pure tones at the signal or suppressor frequencies and BBN. These were presented immediately prior to the 20-ms masker/suppressor complex, which was followed by the 10-ms, 2-kHz signal (see Fig. 4). In these conditions, the precursor should elicit gain reduction, possibly decreasing suppression. The short suppression condition was predicted to result in the greatest amount of suppression because gain should be highest in this condition. Precursor levels were initially presented at 30 dB SPL for two trials and increased over the next trials until the task could no longer be completed. The final threshold was the average of the last two trials with the final precursor level. This procedure was done in an attempt to decrease gain, and possibly decrease suppression, maximally for each

FIG. 6. Threshold for the 2-kHz signal with no precursor (left), and with a 50-ms noise precursor at 50 dB SPL presented with a 20-ms gap before the signal (middle). Gain reduction (right) is the difference between these two thresholds.

TABLE I. Suppressor levels for younger (A) and older (B) participants in each condition. Suppressor levels were approximately 2 dB below threshold level for excitatory forward masking.

Participant	Low-side short	High-side short	Low-side long	High-side long
A1	84	84	78	80
A2	82	84	80	84
A3	78	66	72	80
A4	76	75	65	72
A5	75	78	65	78
A6	74	80	68	74
A7	82	84	72	76
A8	76	78	74	80
B1	80	82	77	82
B2	72	80	64	78
B3	75	80	74	78
B4	68	80	68	78
B5	74	80	70	80
B6	82	86	84	86
B7	74	80	75	80
B8	80	80	80	78

individual. Table II shows the mean levels for each of the precursors for the younger and older adults. There were no significant differences in precursor level between the younger and older adults.

For most of the listeners, gain reduction had been measured with the BBN precursor levels shown in Table II. For all listeners, gain reduction had been measured for at least two levels, and a linear fit was used to determine the growth of gain reduction with noise level so that the amount of gain reduction at the precursor level could be extrapolated from the data. These measurements are described in the Appendix. Gain reduction was not measured for the tonal precursors due to a lack of time. The amount of gain reduction from the tonal precursor levels used is estimated in the Appendix.

It is important to note that thresholds for the on-frequency masker with no suppressor did not change significantly with the addition of a precursor. That is, the signal was still audible. Recall from Sec. II (Methods) that this is why the signal was set at 20 dB SL. Previous studies have also shown that precursors do not produce a change in

FIG. 7. Low-side and high-side suppression measured with short and long stimuli for the younger and older participants. Error bars are SDs.

masking for an on-frequency masker when the signal is at low levels (Jennings *et al.*, 2009; Jennings and Strickland, 2012; Milvae and Strickland, 2018).

The results for the younger adults are shown in Fig. 8. Figure 9 shows the results for the older adults. The results for the short and long conditions are identical to the values in Fig. 7.

A repeated-measures ANOVA with factors of age group (younger adults and older adults), condition (short, long, noise precursor, signal-frequency precursor, suppressor-frequency precursor), and high-side vs low-side was performed on all of the results. This showed a significant effect of condition [$F(4,135) = 13.52$, $p < 0.0001$], but no significant effect of age group [$F(1,14) = 2.15$, $p = 0.16$] or high-side vs low-side [$F(1,135) = 0.17$, $p = 0.68$]. The interaction between age group and condition was not significant [$F(4,135) = 1.62$, $p = 0.17$]. *Post hoc* tests (marginal contrasts with a Tukey adjustment using the “lmeans” function in R) were used to compare all pairs of conditions, collapsing across low-side and high-side. The results of these tests are shown in Table III. The short condition was significantly different from the long, noise precursor, and signal-frequency precursor conditions, but not from the suppressor-frequency precursor condition. The long, noise precursor and signal-frequency precursor conditions were not significantly different from each other. The long and signal-frequency precursor conditions were significantly different from the suppressor-frequency precursor condition, but the noise precursor condition was not.

With cochlear hearing loss, suppression is often reduced or even eliminated (e.g., Schmiedt and Zwislocki, 1980; Harrison *et al.*, 1981; Mills, 1982; Dubno and Ahlstrom, 2001a). Therefore, it was hypothesized that the audiometric threshold, short-duration threshold, or the DPOAE level for $F2$ near 2 kHz would correlate with the amount of suppression for the short condition, which is the maximum estimate of suppression for the conditions tested. Suppression in the short condition was not significantly correlated with audiometric threshold at 2 kHz [low-side ($r = -0.26$, $n = 16$, $p = 0.34$), high-side ($r = -0.29$, $n = 16$, $p = 0.27$)], with threshold for the short-duration 2-kHz tone [low-side ($r = -0.37$, $n = 16$, $p = 0.25$), high-side ($r = -0.48$, $n = 16$, $p = 0.06$)], or with DPOAE level for $F2$ near 2 kHz tone [low-side ($r = 0.26$, $n = 13$, $p = 0.38$), high-side ($r = 0.40$, $n = 13$, $p = 0.18$)]. The measures of gain and of suppression shared a common component of on-frequency masker threshold, and so could not be compared.

IV. DISCUSSION

The goal of the present study was to examine suppression as a function of aging and, as part of this, optimize the measures of suppression. One of these optimizations was to individually choose suppressor levels to maximize the amount of suppression. Another was to look at the effects of shorter suppressor/masker complexes, as compared to longer suppressor/masker complexes, or preceding stimulation by a signal-frequency tone, suppressor-frequency tone, or noise. The clearest outcome of the study is that suppression decreases with preceding sound that includes the signal

TABLE II. Levels for tonal and noise precursors for younger (A) and older (B) participants in each condition.

Participant	Low-side suppression			High-side suppression		
	Noise precursor	Signal frequency precursor	Suppression frequency precursor	Noise precursor	Signal frequency precursor	Suppression frequency precursor
A1	40	35	45	50	40	50
A2	50	40	75	50	50	75
A3	45	35	50	50	40	45
A4	40	35	40	35	35	40
A5	45	25	50	45	30	45
A6	30	30	40	30	30	45
A7	50	30	55	40	30	45
A8	55	35	60	60	35	60
B1	40	35	40	45	45	45
B2	40	30	30	35	35	35
B3	35	30	45	35	35	40
B4	55	55	50	55	50	50
B5	35	35	40	35	30	35
B6	55	55	55	55	55	50
B7	50	40	35	40	35	45
B8	55	40	50	55	40	50

frequency. Since suppression is the measure used to compare the younger and older groups, the measure of suppression will be considered first.

A. Optimization of measurement of suppression

The magnitude of suppression depends critically on the parameters used in measuring it. In the current study, the measurements were optimized in several ways. The signal level chosen was low, placing it in the region where gain would change the most with suppression (Yasin and Plack, 2003, 2007). The suppressor levels were chosen individually for each subject based on sparse PTCs to produce the most suppression possible. All subjects showed both low-side and high-side suppression.

As noted in the Introduction, several previous studies have used the tonal suppression technique used here. Yasin and Plack (2003) used fairly short (44-ms) maskers and suppressors. The signal frequency was 4 kHz and the suppressor was 4.75 kHz. The suppressor was set at 50 or 60 dB SPL. On average, they found a maximum change in gain of approximately

13 dB at 4 kHz. This is within the range for high-side suppression with short stimuli for the younger listeners in the present study. Yasin and Plack (2007) again used a signal frequency of 4 kHz and 104-ms suppressors of 3 and 4.75 kHz from 40 to 70 dB. They found an average increase in 4-kHz masker level with a suppressor of approximately 20 dB for the 3-kHz suppressor, and approximately 12 dB from the 4.75 kHz suppressor, at the highest suppressor levels. The amount of low-side suppression is greater than that seen in the long condition in the present study. This may be due to the higher signal frequency, since the amount of suppression increases with signal frequency (e.g., Hicks and Bacon, 1999). Sommers and Gehr (2010) used a 2-kHz signal, an on-frequency masker level of 55 dB SPL, and a 2.3 kHz suppressor with a level of 85 dB SPL. The masker and suppressor were 500 ms in duration. They found on average approximately 10 dB of suppression for their young listeners, which is slightly higher than the long-duration results in the present study. However, they found on average no suppression for their older listeners, in contrast to the present study. Dubno and Ahlstrom (2001c) used a 2-kHz

FIG. 8. Suppression measured for the younger participants in different conditions.

FIG. 9. Suppression measured for the older participants in different conditions.

signal and suppressors both above and below the signal frequency. The maskers and suppressors were 200 ms, and were at masker/suppressor levels (dB SPL) of 50/70 and 70/90. Because of large variability across subjects they did not calculate the average amount of suppression for the younger and older subjects, but it appears from their figure that it would be near 0 or negative for both groups. The higher suppressor level would have produced excitatory forward masking for most of the listeners in the present study. The individually selected masker and suppressor levels in the present study may have led to the slightly higher suppression estimates, particularly for the older group. In the present study, low-side suppression was not significantly different from high-side suppression.

When suppression is measured using the band-widening method, the signal level is used to measure suppression, and it is typically at a high level, which would be on the compressive part of the I/O function. If the masker level is decreased by suppression, the decrease in signal output is magnified by the fact that the function is compressive. Therefore, the estimates of suppression in the band-widening studies are larger than those seen in the present study. Dubno and Ahlstrom (2001c) found that suppression measured by band-widening was a maximum of approximately 15 dB when the band was widened to the lower side for their younger listeners and approximately 7 dB

for their older listeners. No suppression was seen for noise widened to the higher side. This may be due to the larger size of the suppressive area below in contrast to above the signal frequency. Using a band-widening technique only to the low-frequency side, Gifford and Bacon (2005) saw an average of 23.1 dB of suppression for a signal frequency of 2.4 kHz for their younger listeners and 20.9 dB for their older listeners.

B. Effects of masker/suppressor duration

In the present experiment, the amount of suppression significantly decreased when the stimuli were increased from 20 to 70 ms in duration. The exact levels of the masker and suppressor also changed slightly between these conditions because of the optimization of the parameters. In general, the suppressor level either stayed the same or decreased slightly in the long-duration condition. All other studies that have looked at the effects of duration have used fixed masker and suppressor levels and measured changes in signal threshold. As noted in the Introduction, Champlin and Wright (1993) performed a somewhat similar study with a 20-ms 2-kHz signal, but the on-frequency masker and 2.3 kHz suppressor were fixed at 60 and 80 dB SPL, respectively. They saw only a small amount of suppression in their listeners (mean age 21 yr), but it increased slightly when the masker and suppressor durations were increased together. The results of the present study show that this could be consistent with a suppressor level that was somewhat effective in the short-duration condition, but became more effective in the long-duration condition. Two other studies have examined suppression conditions in which the suppressor was lengthened beyond the masker duration. Thibodeau (1996) used a 2-kHz signal, and suppressor frequencies which produced the most suppression (2.2 or 2.3 kHz). Levels were fixed at 60 dB for the masker and 80 dB for the suppressor. The 2-kHz masker was fixed at 100 ms. As suppressor duration was increased before the onset of the masker (with both stimuli ending together) suppression decreased by up to 10 dB. This was larger than the increase in masking from the suppressor with duration. In contrast, Fletcher *et al.* (2015) measured suppression using a 4-kHz signal and on-frequency masker and a 4.75 kHz suppressor. The masker level was set at 25 dB SL, and the suppressor level was chosen that just masked the masker. Suppression was initially measured for maskers

TABLE III. Marginal contrasts performed on the results of the ANOVA using the “lsmeans” function in *R* with a Tukey adjustment for number of contrasts. The standard error and degrees of freedom were 1.102 and 135, respectively. Contrasts that are significant at the 0.05 level are shown in bold.

Contrast	Estimate	<i>t</i> ratio	<i>P</i> value
Short – Signal Frequency Precursor	6.960	6.318	<0.0001
Short–Long	4.441	4.031	<0.001
Short–Noise Precursor	3.955	3.590	0.004
Short–Suppressor Frequency Precursor	0.683	0.620	0.972
Signal Frequency Precursor–Noise	–3.004	–2.727	0.055
Long–Signal Frequency Precursor	2.519	2.286	0.156
Long–Noise Precursor	–0.486	–0.441	0.992
Long–Suppressor Frequency Precursor	–3.758	–3.411	0.008
Signal Frequency Precursor–Suppressor Frequency Precursor	–6.276	–5.697	<0.0001
Noise–Suppressor Frequency Precursor	–3.272	–2.970	0.029

and suppressors of 12.5 ms. Then a precursor was added at the suppressor frequency at the same level as the suppressor. Suppression did not decrease with the precursor. In a response to the Champlin and Wright study, Bacon (1996) pointed out that increasing duration of maskers and suppressors can lead to complex interactions between masking and suppression. When gain reduction is taken into account as well, the results are even more complex. As gain is reduced, fixed-level suppressors may change from suppressive to excitatory. In the present study, where the suppressor levels were optimized, the levels were either unchanged or reduced in the long-duration condition. In contrast to most of the previous studies discussed above, suppression was significantly lower in the long-duration conditions than in the short-duration conditions.

C. Suppression following a precursor

Estimates of suppression significantly decreased following noise or signal-frequency precursors. This was not due to additional excitatory forward masking by the precursor. The threshold for the on-frequency masker was not significantly different with and without a precursor. If the precursor produced additional forward masking of the signal, it would be expected that the threshold for the on-frequency masker would decrease. PTCs with a 4-kHz signal have been measured with on-frequency tonal precursors in previous studies (Jennings *et al.*, 2009; Jennings and Strickland, 2012). These have shown that threshold for an on-frequency masker typically does not change with the presence of a precursor. A decrease in suppression with the precursor would be consistent with the decrease in gain seen with a precursor in previous studies.

The signal-frequency precursor, noise precursor, and long conditions produced amounts of suppression that were statistically significantly lower than the short condition but not statistically significant from each other. In contrast, the suppressor-frequency precursor condition produced suppression that was not significantly different from the short condition, and was significantly higher than the signal-frequency precursor and long conditions. The suppressor-frequency condition did not differ significantly from the noise precursor condition. Taken together, the results suggest that suppression decreases with preceding sound at the signal frequency. The noise precursor condition had higher suppression (although not statistically significantly so) than the long and signal-frequency precursor conditions, despite the fact that it should reduce gain at both the signal and suppressor frequencies.

Roverud and Strickland (2014) modeled gain reduction for tonal precursors at and below the signal frequency by assuming that the precursors were processed through the signal frequency channel. In that analysis, only precursors that caused excitation within that signal frequency channel would cause gain reduction, and this predicted the observed data well. This is consistent with some data from Lilaonitkul and Guinan (2012), who measured the effect of tonal precursor frequency on reduction of SFOAEs. They found sharp tuning for the precursor around the elicitor frequency if the magnitude of the SFOAE produced after an elicitor (the nSFOAEmoc) was used as the metric.

In the present study off-frequency precursors at the suppressor frequencies did not cause significant effects at the levels used (below 65 dB SPL). This would be consistent with the model used by Roverud and Strickland (2014), which would require that the suppressor produce excitation within the signal frequency channel to cause gain reduction. The conflicting results seen in Sec. IV B (the duration section) may be pertinent here. Thibodeau (1996) found that precursors at the suppressor frequency also produced forward masking on their own. That study found that suppression decreased with suppressor duration. Fletcher *et al.* (2015) used a precursor at the suppressor frequency that did not produce forward masking, and found that it did not decrease suppression. It may be that preceding stimulation at a suppressor frequency only decreases suppression when it also produces excitatory forward masking of the signal, meaning it produces excitation in the signal-frequency channel. A more detailed study would be required to answer this interesting question.

D. Age and cochlear status

This study follows up on previous studies that have examined suppression as a function of age. Because hearing loss often accompanies aging, this study and preceding studies have attempted to separate the effects of hearing thresholds outside the clinically normal range from suppression. In the present study, this was done by choosing older listeners whose audiometric thresholds at the signal frequency were within the clinically normal range and not significantly different from those of the younger listeners. This is a more stringent criterion than was adopted by Dubno and Ahlstrom (2001a,b,c). Their older listeners had audiometric thresholds within the normal range, but thresholds were higher in the older group than in the younger group. The criterion in the present study was not quite as stringent as that adopted by Sommers and Gehr (2010), who required thresholds <15 dB HL. Gifford and Bacon (2005) required thresholds ≤ 15 dB HL, but also matched the younger and older listeners on thresholds. In the present study, the older listeners did not differ significantly from the younger listeners on thresholds for short or long 2-kHz tones.

In the present study, gain was significantly lower in the older group than the younger group, but nearly half of the listeners reached the ceiling for the off-frequency masker. In future studies it would be better to measure gain with the signal at a lower SL to avoid this problem. However, the lower gain is consistent with the lower DPOAE levels in the older group. Despite the difference in gain, there was not a significant difference between the groups on the suppression measures. Gifford and Bacon (2005) found no significant difference in suppression between their younger and older groups, who were matched on quiet thresholds for long and short tones. They also examined two suprathreshold measures of cochlear function, auditory filter shape, and compression. The two groups did not differ significantly on these measures. Sommers and Gehr (2010) used a criterion of audiometric thresholds of 15 dB HL or better. Thresholds were marginally higher for the older group than for the younger group. Thresholds were significantly higher for the older group than for the younger group for the short signal. They

found less suppression in the older group than in the younger group. [Sommers and Gehr \(1998\)](#) measured notched-noise tuning curves in simultaneous masking for younger and older listeners who had equivalent (and low) auditory thresholds at 2 kHz. They found less difference between simultaneous and forward masked auditory filter shapes for the older listeners, which they interpreted as less suppression. In the [Dubno and Ahlstrom \(2001a,b,c\)](#) studies, the older group had significantly higher thresholds for long tones than the younger group and also showed less suppression.

It is important to consider that the question being asked in the present study is different than that being asked in previous studies. Previous studies have examined whether under a given set of signal and suppressor conditions, older adults show the same amount of suppression as younger adults. The current study asks how much suppression each group shows when the conditions have been set to maximize suppression. Although the older group did, in general, show lower amounts of suppression than the younger group, this was not statistically significant, and may be more related to lower amounts of gain than to some other age effect.

Another effect of age that could play a role in the current study is the finding that older listeners may perform more poorly on temporal tasks than younger listeners (e.g., [Fitzgibbons and Gordon-Salant, 2001, 2004](#)). While we cannot rule out that possibility in the current tasks, the older listeners did not require any more training on the tasks than the younger listeners, and the pattern of results across the different duration and precursor conditions was the same for the older listeners as for the younger listeners.

The results of previous studies suggest that younger and older groups may differ in suppression when they differ in threshold for short tones and/or suprathreshold measures of cochlear function ([Dubno and Ahlstrom, 2001b,c](#); [Sommers and Gehr, 2010](#)). This means that matching age groups solely on the basis of audiometric threshold for long tones is not a sufficient metric to separate effects of hearing from effects of age. The results of the present study suggest that decreased cochlear function is not necessarily associated with a significant decrease in suppression if the measurement of suppression is optimized. Given this lack of a significant difference, the results also do not suggest any particular effects of age independent of cochlear function, but also do not rule them out.

In the present study the younger and older listeners all had measureable suppression both below and above the signal frequency. These results would be consistent with the suppression data from quiet-aged gerbils, which showed that suppressive areas were still present but that the tip-to-tail ratio was reduced. The reduced tip to tail ratio would be consistent with the reduced gain seen in the present study. When considered in terms of magnitude of suppression, reduced gain would be expected to result in a smaller estimate of suppression because gain is already reduced. Results of the other studies of aging and suppression are also broadly consistent with the hypothesis that they are primarily due to aging and not noise exposure, which may abolish high-side suppression ([Schmiedt et al., 1990](#)).

The older group showed significantly less gain reduction to a 50 dB SPL BBN precursor than the younger group. This is consistent with the older group having significantly less gain

to adjust. A similar effect has been found in a simultaneous masking phenomenon known as overshoot, in which threshold SNR is lower for a signal presented at a delay from the onset of a noise relative to near the onset of a noise. Studies of overshoot have found smaller effects in listeners with mild cochlear hearing impairment than in listeners with normal hearing ([Bacon and Takahashi, 1992](#); [Strickland and Krishnan, 2005](#)). [Strickland and Krishnan \(2005\)](#) found that the lower the estimate of gain, the lower the estimate of gain reduction, as was found in the present study. This was true within and across ears for the same listeners, which controls for the effects of age. The average age of the listeners in the [Strickland and Krishnan \(2005\)](#) study was 51 yr, as compared to 27 yr for the listeners from a previous study ([Strickland, 2001](#)), who were used as a comparison group. [McFadden and Champlin \(1990\)](#) found a reduction in overshoot when listeners took high doses of aspirin that caused an increase in quiet threshold for long-duration tones of 5–16 dB. These studies together show that even small decreases in gain may decrease gain reduction. As noted in the Introduction, there is also evidence from some studies that MOCR may be lower in older than younger adults ([Castor et al., 1994](#); [Keppler et al., 2010](#); [Kim et al., 2006](#); [Mazelová et al., 2003](#); [Mukari and Mamat, 2008](#)).

V. CONCLUSIONS

- (1) With optimized conditions, low-side and high-side suppression were seen for all younger and older listeners.
- (2) Suppression decreased significantly when the masker/suppressor complex was lengthened or noise or signal-frequency precursors were presented before the short masker and suppressor. This was not due to additional forward masking from the precursor. Suppression did not decrease significantly when the precursor was at the suppressor frequency. These results suggest that suppression may be decreased by preceding sound at the signal frequency, but not at the suppressor frequency, at the low levels used here.
- (3) In general, the older group had less suppression than the younger group, particularly in the short-duration conditions, although this difference did not reach statistical significance. This difference in suppression is consistent with the significantly lower gain in the older group.

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APPENDIX: GROWTH OF GAIN REDUCTION WITH PRECURSOR LEVEL

As noted in Sec. II (Methods), gain reduction with a BBN precursor was measured for all listeners at a precursor level of 50 dB SPL. Gain reduction was measured for at least one other precursor level for all subjects. The values of gain

TABLE IV. Gain reduction in dB for a BBN precursor presented at the levels shown. The noise levels that were used in the experiments are shown by “L” and “H” for the low- and high-side suppressors, respectively. Italicized values are extrapolations from the measured values using the slope values shown in the last column and the intercept value, both calculated using the function “linest” in Excel (Microsoft Corp., Redmond, WA). Values that would have been negative were set to 0 because that is the minimum amount of gain reduction possible.

Precursor level (dB SPL) Subject	30	35	40	45	50	55	60	65	Slope
A1			−0.38 L	3.5	7.63 H				0.8
A2				6	7.63 LH				0.33
A3				5.5 L	6.00 H				0.1
A4		8.46 H	9.63 L	9.13	11.13				0.15
A5				3.5 LH	5.63				0.43
A6	0 LH			4.88	8.5				0.72
A7			1.67 H		6.81 L	9.38			0.51
A8				3.75	7.25	7.75 L	10.25 H		0.4
B1			0 L	1.75 H	2.75	5	8.88	9	0.41
B2		0 H	1.5 L	2.75	5.38	5.75	7.88		0.32
B3		1.64 LH		4.63	6.63	8.5	9.38		0.32
B4					2.88	6.5 LH			0.73
B5		3.54 LH	5.56	6.5	7.5	12.63	11		0.34
B6				−1.25	0	1.25 LH			0.25
B7			0 H	0.25	4.38 L				0.83
B8				3.63	4.38 L	5.13 LH			0.15

reduction are shown as a function of precursor level for all subjects in Table IV. Gain reduction for the precursor levels used in the experiment was estimated either from directly measured values or values extrapolated from a linear fit to the values measured, using slope and intercept values calculated from the “linest” function in Excel (Microsoft Corp., Redmond, WA). When an extrapolated value would have been negative, it was set to 0 as this was the lowest amount of gain reduction possible. The average amount of gain reduction at the levels used was 5.05 dB for the low side and 5.64 dB for the high side for the younger subjects, and 2.99 dB for the low side and 2.48 dB for the high side for the older subjects.

The tonal precursor levels used are, in general, lower than those used in previous experiments at 4 kHz (all with younger adults), which produced up to 10–15 dB of gain reduction (Jennings *et al.*, 2009; Jennings and Strickland, 2012). Data from Roverud and Strickland (2014) show that for a 4-kHz signal, the growth of gain reduction with an on-frequency tonal precursor level is compressive. In that study, for on-frequency, 50-ms precursors at levels of 40, 50, and 60 dB, the average amount of gain reduction was approximately 11, 15, and 18 dB. Using the linest function in Excel, the slope of the least squares fit function is 0.35 dB/dB with an intercept of −2.83. The average level of the on-frequency precursor was 33.75 dB for the low-side suppressor and 36.25 for the high-side suppressor for the young adults. Using the amount of gain reduction and growth rate from the Roverud and Strickland (2014) study, extrapolating to these values and using data from Milvae and Strickland (2018) showing gain reduction at 2 kHz is not significantly different from gain reduction at 4 kHz, the average gain reduction for the young listeners would be estimated at 8.98 and 9.85 dB for the signal-frequency tonal precursor levels for the low and high sides, respectively.

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