Adaptation to Noise in Human Speech Recognition Depends on Noise-Level Statistics and Fast Dynamic-Range Compression

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Human hearing adapts to background noise, as evidenced by the fact that listeners recognize more isolated words when words are presented later rather than earlier in noise. This adaptation likely occurs because the leading noise shifts (“adapts”) the dynamic range of auditory neurons, which can improve the neural encoding of speech spectral and temporal cues. Because neural dynamic range adaptation depends on stimulus-level statistics, here we investigated the importance of “statistical” adaptation for improving speech recognition in noisy backgrounds. We compared the recognition of noised-masked words in the presence and in the absence of adapting noise precursors whose level was either constant or was changing every 50 ms according to different statistical distributions. Adaptation was measured for 28 listeners (9 men) and was quantified as the recognition improvement in the precursor relative to the no-precursor condition. Adaptation was largest for constant-level precursors and did not occur for highly fluctuating precursors, even when the two types of precursors had the same mean level and both activated the medial olivocochlear reflex. Instantaneous amplitude compression of the highly fluctuating precursor produced as much adaptation as the constant-level precursor did without compression. Together, results suggest that noise adaptation in speech recognition is probably mediated by neural dynamic range adaptation to the most frequent sound level. Further, they suggest that auditory peripheral compression per se, rather than the medial olivocochlear reflex, could facilitate noise adaptation by reducing the level fluctuations in the noise.

Key words: auditory compression; dynamic range adaptation; medial olivocochlear reflex; speech recognition; statistical adaptation

Significance Statement

Recognizing speech in noise is challenging but can be facilitated by noise adaptation. The neural mechanisms underlying this adaptation remain unclear. Here, we report some benefits of adaptation for word-in-noise recognition and show that (1) adaptation occurs for stationary but not for highly fluctuating precursors with equal mean level; (2) both stationary and highly fluctuating noises activate the medial olivocochlear reflex; and (3) adaptation occurs even for highly fluctuating precursors when the stimuli are passed through a fast amplitude compressor. These findings suggest that noise adaptation reflects neural dynamic range adaptation to the most frequent noise level and that auditory peripheral compression, rather than the medial olivocochlear reflex, could facilitate noise adaptation.

Introduction

Accurate speech recognition is necessary for human communication and socialization (Higgins and Semin, 2001) but can be challenging in noisy environments. Normal-hearing listeners presented with speech in noise, however, adapt out of the simultaneous noise and can recognize up to 28% more isolated words or syllables when the speech tokens are presented in continuous noise than when the tokens start at the same time as the noise (Ainsworth and Meyer, 1994; Cervera and Gonzalez-Alvarez, 2007). Noise adaptation likely occurs because the leading noise

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adapts the dynamic range of auditory neurons depending on the noise level (Ainsworth and Meyer, 1994), but the physiological processes underlying noise adaptation remain unclear.

Like visual (Ohzawa et al., 1982) or somatosensory neurons (Garcia-Lazaro et al., 2007), auditory neurons adapt their response dynamic range to the current environment. For short tones in continuous, steady noise, neurons shift their discharge rate-level functions toward the noise level (Evans, 1974; Costalupes et al., 1984; Gibson et al., 1985; Phillips and Hall, 1986; Rees and Palmer, 1989). In steady noise, neural dynamic range adaptation (DRA) toward the mean noise level can increase the accuracy with which auditory neurons encode sound intensity, which might improve the encoding of the speech envelope (Fig. 1A) (Marrufo-Pérez et al., 2018) and/or the speech spectrum as represented in the auditory nerve (Fig. 1B) (Ainsworth and Meyer, 1994).

Auditory neurons, however, do not simply adapt their dynamic range to the mean sound level but to the most probable levels in the stimulus (Dean et al., 2005). Indeed, when the stimulus (noise or tone) level varies every 50 ms according to a statistical distribution of sound levels, and a set of levels is presented 80% of the time (defined as “high probability region”), neurons shift their rate level functions toward the “most commonly occurring sound levels” (Dean et al., 2005, 2008; Watkins and Barbour, 2008, 2011; Wen et al., 2009, 2012). When the stimulus level is distributed in two high-probability regions, neurons do not adapt to the mean level (which lays between the two regions). Instead, some neurons shift their dynamic range toward one level region and other neurons shift it toward the other region (Dean et al., 2005). These adjustments improve the coding precision of levels near the high probability region in the neural population (Dean et al., 2005; Wen et al., 2009; but see Rocchi and Ramachandran, 2018). Most auditory neurons adapt with a time course of 100–400 ms (Dean et al., 2008; Wen et al., 2012), and DRA has been observed in the auditory nerve (Wen et al., 2009, 2012), the inferior colliculus (Dean et al., 2005, 2008; Robinson et al., 2016; Bakay et al., 2018), and the auditory cortex (Watkins and Barbour, 2008, 2011) of animals, as well as in the human auditory cortex (Herrmann et al., 2018, 2019).

The aim of the present study was to investigate how noise adaptation in human speech recognition depends on the noise level distribution. We compared adaptation for noise-masked words preceded by adapting noise precursors with different noise level distributions, going from steady, to mildly fluctuating to highly fluctuating. Neural DRA was expected to be less for the highly fluctuating precursor because it does not provide a “most common” level to which neurons can adapt their dynamic ranges. We also investigated the effects of fast-amplitude compression on noise adaptation. Fast-amplitude compression could facilitate adaptation by turning a highly fluctuating sound into a less fluctuating one, thus allowing auditory neurons to adapt to a prevailing level. Fast compression occurs at multiple auditory processing stages, is often reduced in impaired hearing, and is applied by many hearing devices (see Bacon et al., 2004). If it facilitates adaptation, this might shed light on why speech-in-noise recognition is more challenging for hearing-impaired than for normal-hearing listeners, even in aided conditions (e.g., Glasberg and Moore, 1989; Johannesen et al., 2016).

Material and Methods

Experimental design

We compared the signal-to-noise ratio (SNR) at 50% word recognition (termed the speech reception threshold [SRT]) for

Figure 1. Effects of DRA on the encoding of the speech envelope (A) and the speech spectrum (B). **A**, The shift of the neuronal dynamic range toward the noise level can enhance the coding of the speech envelope. A given envelope (black trace next to the abscissa) would be better represented in the discharge rate of the adapted auditory neuron (blue envelope) than in the discharge rate of the nonadapted neuron (red envelope). Figure adapted with permission from Marrufo-Pérez et al. (2018). **B**, Top, In quiet, the speech spectrum is faithfully encoded in the auditory nerve rate profile. For speech in noise, however, many auditory nerve fibers would be saturated at high intensities because of their limited dynamic range. This would result in a degradation of the speech spectrum as coded in the auditory nerve rate profile (red representation). Conversely, the speech spectrum would be more faithfully encoded by the noise-adapted neurons because their responses would saturate at higher intensities (blue). F, Acoustic frequency; CF, auditory nerve characteristic frequency. Figure adapted with permission from Ainsworth and Meyer (1994).

noise-masked words in the presence and in the absence of an adapting noise precursor (1.5 s in duration). The long-term spectra of the (simultaneous) masking noise and the precursor noise were identical and equal to the long-term spectrum of speech (speech-shaped noise [SSN]). The SRT improvement in the precursor relative to the no precursor condition was regarded as the amount of adaptation to noise.

To investigate the effect of precursor-level statistics on noise adaptation, SRTs were measured without the adapting precursor and with three precursor types: steady (with a constant level of 65 dB SPL), mildly fluctuating (the precursor level changed every 50 ms and 80% of the 50 ms segments were at 65 dB SPL), or highly fluctuating (with only 20% of the 50 ms segments at 65 dB SPL). We hypothesized that the less fluctuating the precursor

level is, the greater the amount of adaptation to noise. The change in precursor-level statistics resulted in the mildly and highly fluctuating precursors having mean levels 1.5 and 3.7 dB higher than the level of the steady precursor, respectively. We investigated how this difference in mean level affected noise adaptation by measuring adaptation for a steady precursor with a mean level equal to that of the highly fluctuating precursor.

To investigate the effects of amplitude compression on noise adaptation, we measured SRTs without a precursor as well as with a highly fluctuating precursor, and stimuli were passed through a broadband, instantaneous amplitude compressor before presenting them to the listeners. This compression was expected to distort the speech tokens and thus to worsen SRTs overall, but it was also expected to facilitate (even reinstate) noise adaptation by reducing the level fluctuations in the adapting precursor noise. Measurements were obtained for two different compression ratios (2:1 and 4:1 dB/dB).

Speech signals are filtered by the cochlea and decomposed into several bandpass-filtered signals, each of which can be separated in an envelope (that represents the slow amplitude fluctuations over time) and the temporal fine structure (the rapid fluctuations with a rate close to the center frequency of the bandpass filter) (Rosen, 1992). Noise adaptation in word recognition is more obvious for words processed (“vocoded”) to maintain only the envelope cues in speech than for natural (unprocessed) words (Marrufo-Pérez et al., 2018). For this reason and to better reveal the hypothesized effects of noise level statistics and compression on noise adaptation, SRTs were measured for vocoded as well as natural (unprocessed) words.

The processes responsible for neuronal DRA toward the sound-level statistics are unclear, but DRA might be mediated to some uncertain extent by the medial olivocochlear reflex (MOCR) (Dean et al., 2005, 2008), an efferent pathway that projects from the auditory midbrain to the cochlea (for review, see Guinan, 2006; Lopez-Poveda, 2018). A control experiment was conducted to investigate the potential involvement of the MOCR on noise adaptation. MOCR activation hyperpolarizes outer hair cells (OHCs) (Cooper and Guinan, 2003), which linearizes cochlear mechanical responses by turning down the gain of the cochlear amplifier for low-to-mid level sounds at or near the characteristic frequency (Murugasu and Russell, 1996; Dolan et al., 1997; Cooper and Guinan, 2003, 2006; Guinan, 2006). This is expected to reduce the level of otoacoustic emissions, a byproduct of a nonlinear cochlea (Collet et al., 1990; Berlin et al., 1993; Guinan, 2006). Here, we measured the change in the level of click evoked otoacoustic emissions (CEOAEs) for steady and highly fluctuating contralateral noises and compared the pattern of this change with the pattern of noise adaptation in the word recognition tests. Mertes (2018) showed that contralateral broadband steady noise produced statistically similar suppression of CEOAEs as did speech-modulated noise. Furthermore, ipsilateral broadband noise is as effective as contralateral broadband noise in activating the MOCR (Lilaonitkul and Guinan, 2009). Therefore, if the contralateral steady and highly fluctuating noises suppressed CEOAEs equally but adaptation in speech recognition occurred only for the steady noise, this would undermine the notion that noise adaptation is mediated by the MOCR.

Methods were approved by the Ethics Committee of the University of Salamanca (Spain).

Noise adaptation in speech recognition

Participants. Twenty-eight human listeners (9 men) with normal hearing (NH) participated in the main experiment (mean $\pm$

SD age = 26.6 ± 8.3 years). Twenty-five of them had audiometric thresholds ≤ 20 dB hearing level (HL) in the test (left) ear at octave frequencies between 125 Hz and 8 kHz (American National Standards Institute, 1996). Three participants had audiometric thresholds equal to 25 dB HL at one or two audiometric frequencies. Fourteen listeners were tested with natural and vocoded words, 13 listeners were tested with only natural words, and 1 listener was tested with only vocoded words. In total, 27 and 15 participants were tested with natural and vocoded words, respectively.

All participants were native speakers of Spanish. They were volunteers and not paid for their services. All of them signed an informed consent to participate in the study.

Stimuli. Stimuli were presented monaurally to the left ear of the participants. Thirty-five disyllabic words were used to measure each SRT. The first 10 words were always the same but were presented in random order. They were used to give participants the opportunity to become familiar with the test condition. The last 25 words corresponded to one of the nine phonetically balanced lists from Cárdenas and Marrero (1994). Test words were presented in random order across test conditions to minimize the possibility that participants remembered the words.

The vocoder included a high-pass pre-emphasis filter (first-order Butterworth filter with a 3 dB cutoff frequency of 1.2 kHz); a bank of 12, sixth-order Butterworth bandpass filters whose 3 dB cutoff frequencies followed a modified logarithmic distribution between 100 and 8500 Hz; and envelope extraction via full-wave rectification and low-pass filtering (fourth-order Butterworth low-pass filter with a 3 dB cutoff frequency of 400 Hz). The envelope for each frequency channel was used to modulate the amplitude of a sinusoidal carrier at the channel center frequency, and the modulated signals were sample-wise added to obtain the vocoded speech.

In the no-precursor condition, the simultaneous noise masker started 50 ms before the word onset and finished 50 ms after the word offset (including 10 ms onset and offset ramps) (Fig. 2A). In the precursor conditions, the noise precursor started 1500 ms before the word onset. The simultaneous masking noise was steady, and its level was fixed at 65 dB SPL. By contrast, the level of the precursor noise varied every 50 ms depending on the precursor type. For the steady precursor, the level was constant at 65 dB SPL (Fig. 2B). For the mildly fluctuating precursor, the level of 80% of the 50 ms segments was at 65 dB SPL and the level of the remaining 20% of the segments varied uniformly between 20 and 80 dB SPL in 5 dB steps (Fig. 2C). For the highly fluctuating precursor, the level of 20% of the 50 ms segments was at 65 dB SPL and the level of the remaining 80% of the segments varied uniformly between 20 and 80 dB SPL in 5 dB steps (Fig. 2D). The different sound levels were presented randomly throughout the duration of the precursor. To generate the fluctuating precursors, a steady SSN of 65 dB SPL was multiplied by the desired envelope, whose amplitude varied in 50 ms segments. Different masking and precursor noises were generated for each word (i.e., noises were not “frozen”).

The level of the steady precursor was 65 dB SPL, thus equal to the level of the simultaneous masking noise, but the change in precursor-level statistics resulted in the mildly and highly fluctuating precursors having mean levels of 66.5 dB SPL (± 1.9 SD) and 68.7 dB SPL (± 0.8 SD), respectively, thus different from the level of the simultaneous masking noise. A complementary experiment was performed to investigate whether this difference in the mean level may affect the amount of noise adaptation (see below).

Figure 2. Example stimuli used to measure the effect of precursor-level statistics on noise adaption. Top, Stimulus waveforms for conditions with no precursor (**A**), steady precursor (**B**), mildly fluctuating precursor (**C**), and highly fluctuating precursor (HFP) (**D**), and compressed highly fluctuating precursor with a compression ratio 2:1 (**E**) or 4:1 (**F**). **C–F**, The precursor level fluctuated every 50 ms, but words (depicted in black for illustration purposes) were masked by simultaneous steady noise. Bottom, Precursor-level distributions. The probability was calculated by considering each 50 ms segment as 1 unit. **B–F**, Precursor level distributions before (red) and after (blue) applying amplitude compression. a.u., arbitrary unit.

The effects of instantaneous amplitude compression on noise adaptation were assessed by measuring SRTs without and with a highly fluctuating precursor but passing stimuli through a broad-band, instantaneous amplitude compressor before presenting them to the listeners. Two compression ratios were used (2:1 and 4:1 dB/dB). The instantaneous amplitude of the compressed stimulus, $y[i]$, was calculated as follows:

$$y[i] = \text{sign}(x[i]) \cdot b \cdot |x[i]|^c \quad (1)$$

where i denotes sample number, c is a parameter that determines the amount of compression (i.e., 0.25 and 0.5 for compression ratios 4:1 and 2:1, respectively), $x[i]$ is the instantaneous amplitude of the uncompressed stimulus, and b was set so that an input level of 65 dB SPL corresponded to an output level of 65 dB SPL. This resulted in sound levels <65 dB SPL being amplified, levels equal to 65 dB SPL not changing, and levels >65 dB SPL being attenuated (Fig. 3). Figure 2E,F shows example compressed stimuli.

Procedure. To measure an SRT, the speech level varied adaptively using a one-down, one-up adaptive rule (i.e., the level decreased after a correct response and increased after an incorrect response). The SRT was thus defined as the SNR giving 50% correct word recognition in the psychometric function (Levitt, 1971). The initial SNR was 10 dB, and the speech level changed in 4 dB steps between words 1 and 14, and in 2 dB steps between words 14 and 35. The SRT was calculated as the mean of the SNRs for the final 20 words. Feedback was not given to the participants on the correctness of their responses.

SRTs were measured in eight conditions: four without and four with compression. The conditions without compression included one without precursor, one with a steady precursor, one with a mildly fluctuating precursor, and one with a highly fluctuating precursor (the same no-precursor condition was taken as the reference to calculate the amount of adaptation). The four conditions with compression involved one without precursor and one with a highly fluctuating precursor times two compression ratios (2:1 and 4:1 dB/dB). Conditions without and with compression were administered in two separate blocks. The four conditions within each block were administered in random

Figure 3. Compressor input/output functions for the two compression ratios used in the study.

order. Blocks with and without compression were alternated, and participants received a brief break after each block.

Three SRTs were obtained for each of the eight conditions, and their mean was taken as the SRT for that condition. An SRT measurement was discarded, and a new measurement was obtained when the SD within the measure was >4 dB. A fourth SRT was sometimes obtained and averaged when the experimenter deemed that the first three SRT measurements were too variable (no objective criterion was applied). To train subjects in the task with vocoded words, four SRTs were measured at the beginning of the experiment (conditions chosen at random) and discarded from the analyses.

During the measurements, participants were seated in a double-wall, sound-attenuating booth, and the presentation of each word was controlled by the experimenter, who was sitting outside the booth without visual interaction with the participant. A sound cue (1 kHz pure tone with 500 ms duration) was presented 500 ms before the stimulus onset to warn the listener about the stimulus presentation and to focus his/her attention on the speech recognition task.

Controlling for the effects of mean precursor level. The mean levels of steady and highly fluctuating precursors were different

(65 vs ~69 dB SPL, respectively). This difference would make it hard to know whether any differences in adaptation for the steady and the highly fluctuating precursor were related to their different level distributions or their different mean level. To elucidate this issue, we performed a complementary control experiment on 14 NH listeners (4 males, mean $\pm$ SD age: 29.2 ± 9.3 years). Audiometric thresholds were ≤ 20 dB HL at octave frequencies between 0.25 and 8 kHz in the test (left) ear of all but 2 participants. One participant had a 25 dB HL threshold at 0.25 kHz, and another had a 25 dB HL threshold at 8 kHz. Only 1 of these subjects had participated in the main experiment with vocoded words (described above).

The experiment was performed for vocoded words presented in the left ear. It included three conditions: one without precursor, one with steady precursor at 65 dB SPL, and one with steady precursor at 69 dB SPL (the same mean level as the highly fluctuating precursor in the main experiment). The level of noise presented simultaneously with the word was fixed at 65 dB SPL. No compression was applied. We hypothesized that similar adaptation would occur for steady precursors of 65 and 69 dB SPL. This would support that a difference in adaptation for the steady and the highly fluctuating precursor in the main experiment would be related to differences in the level distributions rather than to the difference (~4 dB) in mean levels.

The measurement procedure was as for the main experiment.

Apparatus. Stimuli were digitally stored and presented through custom-made MATLAB software version 2017 (The MathWorks; RRID:SCR_001622). Stimuli were played via an RME Fireface UCX soundcard at a sampling rate of 44.1 kHz with 24 bit resolution. Stimuli were presented to the listeners using ER2 insert earphones (Etymotic Research), designed to give a flat frequency response at the eardrum from 250 to 8000 Hz. Sound pressure levels were calibrated by placing the earphones in a Zwislocki DB-100 coupler connected to a sound level meter (Brüel Kjaer, mod. 2238). Calibration was performed at 1 kHz, and the obtained sensitivity was used at all other frequencies.

Statistical analyses. Statistical analyses were performed with SPSS Statistics, version 23 (IBM; RRID:SCR_002865). The Shapiro-Wilk test of normality revealed that the SRTs followed a Gaussian distribution for vocoded but not for natural words. For vocoded words, a one-way repeated-measures ANOVA was used to test for the effect of precursor type on SRTs for conditions without compression. For conditions with compression, paired Student's *t* tests were used to compare mean SRTs with and without the highly fluctuating precursor. Separate tests were applied for each compression ratio. Friedman and Wilcoxon signed ranks tests (the nonparametric equivalents to repeated-measures ANOVA and Student's *t* tests) were used to analyze SRTs for natural words. Differences in the amount of adaptation between natural and vocoded words and the possible interaction between word type and precursor type were tested with a two-way repeated-measures ANOVA (including word type and precursor type as factors).

To analyze the data of the control experiment aimed at investigating the effects of mean precursor level on noise adaptation, we performed a one-way repeated-measures ANOVA with the three conditions as a factor.

Post hoc pairwise comparisons (in the repeated-measures ANOVAs or the Friedman tests) were conducted using Bonferroni corrections for multiple comparisons. An effect was regarded as statistically significant when the null hypotheses could be rejected with 95% confidence (two-tailed, $p \leq 0.05$).

CEOAEs

Participants. We attempted to measure CEOAEs for 18 participants, but results from 7 participants were discarded because (1) CEOAE levels for 6 participants did not meet the SNR criterion (see below), and (2) the contralateral noise was erroneously presented at ~55 dB SPL instead of 65 dB SPL for 1 participant. Therefore, reliable CEOAEs were measured for 11 participants, 2 of whom had participated in the main speech recognition tests. The mean $\pm$ SD age of the participants was 30.5 ± 9.9 years. They had normal audiometric thresholds (≤ 20 dB HL at octave frequencies between 125 Hz and 8 kHz in both ears), except 1 participant whose audiometric thresholds were 25 dB HL at 125 and 250 Hz in the left ear.

Stimuli. Clicks were presented to the left ear. CEOAEs were measured without contralateral acoustic stimulation (CAS), with a steady contralateral SSN, and with a highly fluctuating contralateral SSN. Clicks were presented at 60 dB SPL peak equivalent. The steady and highly fluctuating contralateral noises had mean levels of 65 and ~69 dB SPL, respectively, the same levels as those used in the speech recognition task. Clicks were presented at a rate of 43.5/s. The use of rates ≥ 31.25 /s probably activates the ipsilateral MOCR (Boothalingam and Purcell, 2015). Hence, we probably assessed the effects of ipsilateral and contralateral MOCRs.

Procedure. Each measurement involved the presentation of 1000 stimulus trials. The nonlinear protocol was used (Kemp et al., 1990), and so each trial involved presenting three identical clicks of one polarity followed by a single click of three times the amplitude and opposite polarity. Twelve measures were obtained in total: four without CAS, four with contralateral steady noise, and four with contralateral highly fluctuating noise. Conditions were randomized. The mean CEOAE level across the four measures was taken as the CEOAE level for that condition. The recording probe remained in the participant's ear throughout the 12 measures to minimize the possible variance in the measure from altering the position of the probe in the ear canal. A measure was regarded as valid only when the CEOAE level was at least 6 dB above the noise floor ($\text{SNR} \geq 6$ dB).

Apparatus. Participants sat in a double-wall sound booth during testing. CEOAEs were measured with an Eclipse system (Interacoustics), suite version 1.0.1. The contralateral noise was digitally stored and presented through custom-made MATLAB software, played via an RME Fireface UCX soundcard at a sampling rate of 44.1 kHz and with 24 bit resolution, and presented to the listeners using ER2 insert earphones.

Analyses. CEOAE amplitude was calculated over an analysis time window 4–20 ms after the click offset. The change in CEOAE amplitude, ΔCEOAE , was calculated as follows (Backus and Guinan, 2007; Mishra and Lutman, 2013; Bhatt, 2017; Boothalingam et al., 2019):

$$\Delta\text{CEOAE}[\%] = 100 \times \frac{\text{CEOAE}_{\text{CTR}}[\text{Pa}] - \text{CEOAE}_{\text{CAS}}[\text{Pa}]}{\text{CEOAE}_{\text{CTR}}[\text{Pa}]} \quad (2)$$

where $\text{CEOAE}_{\text{CTR}}$ and $\text{CEOAE}_{\text{CAS}}$ denote CEOAE pressure amplitude in the control and CAS conditions, respectively, in units of Pascal.

The Shapiro-Wilk test of normality revealed that CEOAE values conformed to a Gaussian distribution. A one-way repeated-measures ANOVA with the three conditions (no CAS, steady CAS, highly fluctuating CAS) was used to test for the statistical significance of CAS on CEOAE amplitude.

Figure 4. The effect of precursor-level statistics on SRTs and on noise adaptation. **A**, SRTs for natural words ($N = 27$) measured without precursor and with steady, mildly fluctuating, and highly fluctuating precursors. Dots and squares represent individual and mean scores, respectively. Each dot indicates the mean of at least three measures. **B**, Adaptation to noise for natural words calculated as the difference between SRTs measured with and without precursor. Positive values indicate better (lower) SRTs in the condition with precursor than in the condition without precursor. Bottom, middle, and top lines in each box plot indicate the 25th, 50th (median), and 75th percentiles, respectively. Crosses represent mean values. Dots indicate individual results. **C**, **D**, The same as in **A** and **B**, but for vocoded words ($N = 15$). $*p \leq 0.05$, $**p \leq 0.01$.

Results

Effects of precursor-level statistics on noise adaptation

To investigate how the precursor-level distribution affected noise adaptation, we measured SRTs for noise-masked words presented without precursor as well as with precursors with different level statistics (steady, mildly fluctuating, and highly fluctuating). Figure 4A shows SRTs for natural (unprocessed) words in these conditions. There was a significant effect of precursor type on SRTs (Friedman $\chi^2_{(3)} = 9.8$, $N = 27$, $p = 0.020$). *Post hoc* pairwise comparisons revealed that SRTs tended to be better (lower) with the steady precursor than without precursor ($p = 0.059$). SRTs also tended to be better for the steady than for the highly fluctuating precursor ($p = 0.050$). The mean amount of adaptation was 0.50 dB (± 0.8 SD), 0.44 dB (± 1.1 SD), and 0.02 dB (± 1.2 SD) for steady, mildly fluctuating, and highly fluctuating precursors, respectively (Fig. 4B). This indicates that greater fluctuations in the noise precursor generated less noise adaptation.

Figure 4C shows SRTs for vocoded words for the same conditions as described above. There was a significant effect of precursor type on SRTs (repeated-measures ANOVA $F_{(3,42)} = 8.2$, $N = 15$, $p < 0.001$). *Post hoc* pairwise comparisons revealed significantly better SRTs with the steady precursor than without

precursor ($p = 0.005$). SRTs were also better with the steady precursor than with the mildly fluctuating precursor ($p = 0.037$) or with the highly fluctuating precursor ($p = 0.008$). The mean amount of adaptation was 1.69 dB (± 1.5 SD), 0.51 dB (± 1.3 SD), and 0.36 dB (± 1.4 SD) for steady, mildly fluctuating, and highly fluctuating precursors, respectively (Fig. 4D). In other words, as it occurred for natural words, noise adaptation was greatest for the constant-level precursor.

One might think that the envelope fluctuations in the highly fluctuating precursor could mask (or interfere with) those of the words, and thus hinder word recognition in a way similar to how an amplitude modulated (AM) precursor hinders the detection of an AM probe when both have the same modulation rate (Oxenham and Dau, 2001; Wojtczak and Viemeister, 2005; Wojtczak et al., 2011). This, however, did not seem to be the case because mean SRTs with the highly fluctuating precursor were not statistically different from SRTs without precursor (Fig. 4). In other words, the highly fluctuating precursor did not hinder word recognition and thus cannot be regarded as an “interferer.”

Effects of instantaneous amplitude compression on noise adaptation

To investigate the effects of instantaneous amplitude compression on noise adaptation, we measured SRTs for noise-masked words presented with and without a highly fluctuating precursor. Stimuli were passed through a broadband, instantaneous amplitude compressor before presenting them to the listeners. Because instantaneous compression reduces precursor-level fluctuations (Fig. 2E,F), it was expected to facilitate noise adaptation. Figure 5A shows SRTs for natural words for the two precursor conditions (none and highly fluctuating) and for the two compression ratios tested (2:1 and 4:1). For the compression ratio 2:1, SRTs were not significantly different with and without precursor (Wilcoxon test $Z = -1.29$; $p = 0.196$). For the compression ratio 4:1, however, SRTs were better with than without precursor (Wilcoxon test $Z = -2.2$; $p = 0.028$). Adaptation was, on average, 0.25 dB (± 1.0 SD) and 0.55 dB (± 1.2 SD) for the compression ratios 2:1 and 4:1, respectively (Fig. 5B).

Figure 5C shows corresponding SRTs for vocoded words. SRTs were better with than without precursor for the compression ratio of 2:1 (paired Student's t test: $t_{(14)} = 5.92$; $p < 0.001$) as well as for the compression ratio of 4:1 ($t_{(14)} = 3.56$; $p = 0.003$). The mean adaptation was 2.16 dB (± 1.4 SD) and 2.47 dB (± 2.7 SD) for the compression ratios 2:1 and 4:1, respectively, and it was not significantly different for the two compression ratios ($t_{(14)} = -0.44$; $p = 0.664$).

In addition to the findings just reported, SRTs were overall worse with than without compression (compare Fig. 4A vs Fig. 5A or Fig. 4C vs Fig. 5C). In other words, compression deteriorated intelligibility as expected.

Comparison of noise adaptation for natural and vocoded words

Figure 6A compares noise adaptation for natural and vocoded words across all tested conditions. Only data for the 14 participants tested with natural and vocoded words were analyzed to make an intrasubject comparison. Adaptation was overall greater for vocoded than for natural words (repeated-measures ANOVA: $F_{(1,13)} = 16.5$, $p = 0.001$). The interaction between word type and test condition was also significant ($F_{(4,52)} = 3.5$, $p = 0.013$). *Post hoc* analyses revealed that adaptation was greater for vocoded than for natural words in the conditions with the steady precursor ($p = 0.023$), with the highly fluctuating precursor compressed with a ratio 2:1

Figure 5. The effect of fast-amplitude compression on SRTs and on noise adaptation. **A**, SRTs for natural words ($N = 27$) measured without precursor and with a highly fluctuating precursor. Both words and noise were compressed with compression ratios of 2:1 or 4:1, as indicated at the top. Dots and squares represent individual and mean scores, respectively. **B**, Adaptation to noise for natural words calculated as the difference between SRTs with and without precursor. Positive values indicate better (lower) SRTs in the condition with precursor. **C**, **D**, SRTs and adaptation for vocoded words ($N = 15$). The layout is as for **A** and **B**. * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. n.s.: not significant.

Figure 7. Effects of precursor mean level on SRTs (**A**) and on noise adaptation (**B**) for vocoded words. **A**, Individual (dots) and mean (squares) SRTs. ** $p \leq 0.01$, *** $p \leq 0.001$. **B**, Comparison of adaptation for steady precursors at 65 and 69 dB SPL. Points below the dashed line indicate greater adaptation for the 65 than for the 69 dB SPL precursor.

($p = 0.004$), and with the highly fluctuating precursor compressed with a ratio 4:1 ($p = 0.012$). The greater adaptation for vocoded than for natural words was consistent with the findings of our previous study (Marrufo-Pérez et al., 2018).

Figure 6. Mean adaptation for natural and vocoded words (**A**) and mean precursor level (**B**) for all tested conditions. **A**, Group mean scores for those participants tested with natural and vocoded words ($N = 14$). Error bars indicate SEM. * $p \leq 0.05$, ** $p \leq 0.01$. **B**, Mean precursor level for each condition. Error bars indicate SD. HF, Highly fluctuating; CR, Compression ratio.

The effect of mean precursor level on noise adaptation

When stimuli were not compressed, participants showed adaptation when the precursor was steady but not when it was fluctuating (Fig. 6A). It is uncertain whether this was because of the difference in level fluctuations or because of the difference in mean level across precursor types (Fig. 6B). To elucidate the reason, we measured adaptation for vocoded words for a steady precursor at 69 dB SPL, the same level as that of the highly fluctuating precursor in the main experiment. For completeness, we also measured adaptation for a steady precursor level at 65 dB SPL, the same level as that of the simultaneous masking noise.

Figure 7 shows the individual and mean SRTs. Analyses revealed better SRTs with than without precursor [repeated-measures ANOVA: $F_{(2,26)} = 19.5$, $p < 0.001$]. *Post hoc* analyses revealed that SRTs were better with the steady precursor of 65 dB SPL than without precursor ($p < 0.001$). SRTs were also better with the steady precursor of 69 dB SPL than without precursor ($p = 0.012$). Figure 7B shows adaptation for each participant. Most subjects showed slightly greater adaptation with the 65 dB SPL precursor than with the 69 dB SPL steady precursor (1.65 vs 1.27 dB), but the difference was not statistically significant ($p = 0.129$).

In summary, there was adaptation for steady precursors but not for highly fluctuating precursors with equal mean levels (69 dB SPL). This shows that precursor-level distribution is important for noise adaptation. In addition, the slightly greater adaptation with the 65 dB SPL precursor than with the 69 dB SPL

Figure 8. The effect of CAS on CEOAE levels. **A**, CEOAE levels for 11 participants measured without CAS, with contralateral steady SSN, and with contralateral highly fluctuating SSN. NF, Noise floor (mean = −5.5 dB SPL). Error bars indicate 1 SD. **B**, CEOAE suppression calculated using Equation 2. * $p \leq 0.05$, ** $p \leq 0.01$.

steady precursor demonstrated that the mean precursor level (relative to the simultaneous noise) may be important for noise adaptation.

CEOAE suppression by steady and highly fluctuating noise

To investigate the potential role of the MOCR in noise adaptation, we measured the suppression of CEOAEs by contralateral steady and highly fluctuating noises. The effect of contralateral steady and highly fluctuating noises on CEOAE levels is depicted in Figure 8A. There was a significant effect of CAS on CEOAE levels [repeated-measures ANOVA: $F_{(2,20)} = 22.6$, $p < 0.001$]. *Post hoc* pairwise comparisons revealed that both the steady noise and the highly fluctuating noise suppressed CEOAEs ($p = 0.002$ for the two noise types), but suppression was greater for the steady than for the fluctuating noise (2.1 dB vs 1.5 dB; $p = 0.016$). This difference in suppression (0.6 dB) is similar to that observed by Mertes (2018) (0.5 dB) after using 60 dB SPL contralateral broadband noises with and without being modulated with the envelope of a four-talker babble. The latter modulation resembles the modulation in the present highly fluctuating noise (see Fig. 1 in Mertes, 2018). Figure 8B shows the amount of suppression calculated using Equation 2.

Discussion

We have shown that, for NH listeners, the recognition of noise-masked words improves when words are preceded by steady (constant level) noise but not when they are preceded by highly

fluctuating noise with the same mean level (Figs. 4, 7). In addition, we have shown that instantaneous amplitude compression facilitates adaptation in highly fluctuating noise (Fig. 5) because it reduces the variability in noise level, effectively making a highly fluctuating noise more stationary. Together, the present results indicate that the variability in precursor level is important for noise adaptation to occur, and are consistent with neural DRA toward the most common level in the environment as being the underlying mechanism.

The role of the medial olivocochlear reflex in noise adaptation

MOCR activation can theoretically facilitate speech in noise recognition by (1) enhancing auditory nerve responses to sounds embedded in noise (Nieder and Nieder, 1970a,b; Kawase et al., 1993), (2) restoring the discharge rate range of auditory nerve fibers in noise to values observed in quiet (Winslow and Sachs, 1988), and/or (3) adapting the neuronal dynamic range to the sound-level statistics (Dean et al., 2005, 2008). We have shown that a highly fluctuating noise significantly suppressed CEOAEs when presented contralaterally to the test ear but did not improve word recognition when it preceded noise-masked words ipsilaterally. Because ipsilateral broadband noise is as effective as (if not more than) contralateral broadband noise in activating the MOCR (Lilaonitkul and Guinan, 2009), this suggests that the highly fluctuating noise precursor probably activated the MOCR during the present speech tests, and yet it did not produce noise adaptation. In other words, this suggests that the MOCR played little or no role in noise adaptation. This conclusion is supported by two other studies. Wojtczak et al. (2019) showed that AM sensitivity in noise can improve with a precursor even when the precursor does not change basilar membrane responses (i.e., when it does not activate the MOCR). Second, cochlear-implant users show adaptation to noise in word recognition despite lacking MOCR effects (Marrufo-Pérez et al., 2018), which suggests that mechanisms different from the MOCR can facilitate speech-in-noise recognition, at least when the MOCR is absent.

Instantaneous compression facilitates adaptation to noise

We have shown that applying broadband, fast-amplitude compression to the stimuli facilitates noise adaptation. Compression occurs at multiple stages in the auditory system. For example, the velocity of motion of the basilar membrane grows compressively with increasing sound level (Robles and Ruggero, 2001), and the inner hair cell (IHC) applies additional compression (Lopez-Poveda and Eustaquio-Martín, 2006) such that the IHC receptor potential grows with increasing sound level more compressively than does basilar membrane motion (Patuzzi and Sellick, 1983). Cochlear mechanical compression (Vavakou et al., 2019) and IHC compression (e.g., Dallos, 1986) are both fast enough that they could reduce the level fluctuations in the background noise, thereby making the IHC representation of a fluctuating sound less fluctuating than the corresponding acoustic input. Therefore, it is tempting to hypothesize that auditory compression facilitates noise adaptation. The data from Dubno et al. (2012) appear to be consistent with this idea. They did not measure noise adaptation but showed that the recognition of vocoded speech-in-noise at a constant SNR was better at mid-levels (60 dB SPL), where basilar membrane responses are more compressive, than at lower or higher speech levels, where basilar membrane responses are more linear. They also reported that subjects with more compressive basilar membrane responses showed greater changes in recognition scores as speech level

increased. The better recognition scores at mid-levels may have occurred because basilar membrane compression reduced the noise level fluctuations more at mid-levels, and thus induced greater neural DRA to the noise statistics and better speech-in-noise recognition.

Hearing-impaired (HI) listeners show less or no noise adaptation in word recognition (at least for babble maskers) (Ben-David et al., 2012) or AM detection (Jennings et al., 2018). Because hearing loss is typically associated with combined loss or dysfunction of cochlear IHCs and OHCs (Liberman and Dodds, 1984; Lopez-Poveda and Johannesen, 2012; Johannesen et al., 2014), and the MOCR is thought to have antimasking effects (for review, see Guinan, 2006; Lopez-Poveda, 2018), the conventional view is that OHC loss would impair noise adaptation because OHCs are necessary for the MOCR to exert its antimasking effects (Jennings et al., 2018; for review, see Lopez-Poveda, 2018). If this were the case, however, it would be hard to explain why HI listeners show less or no noise adaptation while cochlear-implant users show normal adaptation even though the two listener groups are expected to have impaired or absent MOCR effects (Marrufo-Pérez et al., 2018, 2019). The present findings prompt us to hypothesize a different explanation: listeners with hearing loss (OHC loss) may show less noise adaptation not because they have an impaired MOCR but because they have less or no auditory peripheral compression (Plack et al., 2004; Lopez-Poveda et al., 2005; Johannesen et al., 2014). Reduced or absent compression would make the IHC receptor potential representation more fluctuating than normal, and neurons would not have a prevailing level to adapt to. Cochlear implants, however, include instantaneous compression at the back end of processing to map the wide range of acoustic pressure into a narrower range of electrical current (e.g., Wilson et al., 1991; Lopez-Poveda et al., 2016). This compression reduces the level fluctuations of incoming sounds and probably facilitates neuronal DRA toward a prevailing stimulus level.

Further research is necessary to investigate the potential role of basilar membrane, IHC, or other forms of auditory compression, as well compression in hearing devices, in noise adaptation.

Noise adaptation was less for natural than for vocoded words

Like Marrufo-Pérez et al. (2018), here we also found less noise adaptation for natural than for vocoded words (Fig. 6). Marrufo-Pérez et al. (2018) explained this difference by ceiling effects; that is, they reasoned that adaptation is overall less for conditions where baseline SRTs (without precursor) are better. Consistent with this explanation, here, baseline SRTs were better for natural than for vocoded words. It is uncertain, however, whether other factors can explain or contribute to the reduced adaptation for natural words. For instance, NH listeners use TFS cues in steady noise backgrounds when those cues are available (Hopkins and Moore, 2009) and adaptation mechanisms seem to enhance only envelope cues (Marrufo-Pérez et al., 2018). It is possible that envelope enhancement is less useful when speech recognition relies to some extent in a nonenhanced (e.g., TFS) cue.

Implications

The present findings have several implications. First, we have provided new evidence that noise adaptation is unlikely mediated by the MOCR. This new evidence adds to other recent evidence supporting the same conclusion (Marrufo-Pérez et al., 2018; Wojtczak et al., 2019) and contributes to resolving the long-standing controversy about the role of the MOCR in

facilitating speech-in-noise recognition (for review, see Lopez-Poveda, 2018).

Second, we have demonstrated that instantaneous amplitude compression facilitates noise adaptation. This could be relevant for hearing aid design. For instance, there is no consensus on whether hearing aid release times should be a few or several hundreds of milliseconds (e.g., Jenstad and Souza, 2005; Kowalewski et al., 2018). In fluctuating noise, adaptation would be expected to occur for fast but not for slow release times because the hearing aid would work like a linear amplifier and would not reduce the level fluctuations in the noise in the latter case. Of course, the broadband, fast compressor used here would be inadequate because it distorts the speech, and the negative effects of this distortion outweigh the positive effects of adaptation (i.e., the present SRTs with a highly fluctuating precursor were still overall better without than with compression; Figs. 4, 5). However, it may be possible to design narrowband compressors that are fast enough to facilitate noise adaptation with minimal distortion (e.g., compressors based on basilar-membrane models) (e.g., Lopez-Poveda and Meddis, 2001; Clark et al., 2018).

Third, the lesser noise adaptation for natural than for vocoded words suggests that adaptation may be greater for those listeners who rely on speech envelope cues, such as cochlear-implant users (Shannon et al., 1995; Schatzer et al., 2010), or for those listeners with degraded ability to use TFS cues, such as older listeners with clinically NH (Füllgrabe, 2013). It also suggests that HI listeners might have significant trouble understanding audible speech in noise because, on the one hand, they are less able to use TFS speech cues for speech recognition (Buss et al., 2004; Lorenzi et al., 2006), which makes them more reliant on envelope cues, and on the other hand, they do not benefit from noise adaptation because they show much less or no peripheral compression if their hearing loss involves OHC loss or dysfunction (Plack et al., 2004; Lopez-Poveda et al., 2005; Johannesen et al., 2014).

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