Auditory and Vestibular Research

Relationship Between Envelope Difference Index and Benefits offered by Digital Noise Reduction Algorithm in Younger and Older Adults with Moderate Sensorineural Hearing Loss

Hemanth Narayan Shetty*[1]Srikar Vijayasarathy[2],

[1] Jagadguru Sri Shivarathreeshwara Institute of Speech and Hearing, Department of Audiology, MG Road, Mysuru- (Karnataka, India). Email: hemanthn.shetty@gmail.com; ORCID IDs: https://orcid.org/0009-0008-2099-7676

[2]All India Institute of Speech and Hearing, Department of Audiology, Manasagangothri, Mysuru- (Karnataka, India). Email: srkrv.y@gmail.com; ORCID IDs: https://orcid.org/0000-0003-0064-3789

***Corresponding Author**
Hemanth Narayana Shetty
Professor in Audiology,
Department of Audiology,
Jagadguru Sri Shivarathreeshwara Institute of Speech and Hearing,
Mysuru, Karnataka, India.
Email: hemanthn.shetty@gmail.com

Highlights

- Digital noise reduction (DNR) benefits were independent of envelope distortion
- DNR improved speech-in-noise recognition in younger listeners
- Listening effort decreased in both age groups with DNR

Abstract

Background and Aim: To investigate if the effectiveness of digital noise reduction (DNR) in improving speech recognition scores and reducing listening effort in younger and older adults with moderate sensorineural hearing loss is associated with envelope distortion caused by the DNR algorithm used in hearing aids.
Methods: Participants included 17 younger adults (18-45 years) and 20 older adults (51-70 years) with flat moderate sensorineural hearing loss (SNHL). The benefit of a modulation-based DNR algorithm was assessed using sentences (0° azimuth) presented in speech noise (180° azimuth) at +4 dB SNR. The Envelope Difference Index was calculated using the algorithm, and correlations between DNR benefits and envelope distortion were analysed.
Results: DNR enhanced speech-in-noise recognition scores for younger adults, but it did not have the same effect for older adults. Listening effort, measured by final-word recall scores,
improved significantly in both younger and older adults in the DNR group. However, there was no significant difference in EDI between the groups. No correlation was found between the magnitude of the envelope difference index and DNR benefits on speech recognition and listening effort in younger and older adults.
Conclusions: Digital noise reduction improved speech recognition in noise for younger adults but not older adults with moderate hearing loss, though both groups showed reduced listening effort, with benefits unrelated to signal envelope distortion.
Keywords: Digital noise reduction, Listening effort, Envelope distortion, speech in noise perception, Ageing.

Introduction

Difficulty understanding speech in noisy environments is one of the most frequent complaints among older adults [1]. Nearly 10% of individuals seeking audiological consultation report speech-in-noise difficulties even without clinically significant hearing loss [2]. Such challenges increase with age, partly because adverse listening conditions impose greater cognitive load and place additional demands on auditory–cognitive integration [3]. When age-related sensorineural hearing loss is present, speech recognition in noise further declines due to degraded bottom-up encoding and reduced efficiency of top-down repair mechanisms [4]. Consequently, older adults with hearing loss remain disproportionately affected by noisy environments even when audibility is restored through amplification [5].

Digital Noise Reduction (DNR) algorithms, typically used alongside directional microphones, are commonly employed to enhance communication in challenging listening environments [6]. Research has demonstrated that DNR processing improves listening comfort, reduces annoyance from background noise, and minimises listening fatigue [7]. These benefits enable users to wear their hearing aids for longer periods without experiencing mental or physical exhaustion. Some studies found that DNR algorithms offer modest improvement in speech recognition, especially in multi-talker or fluctuating noise conditions [8]. Cumulative benefits can lead to increased confidence and greater social engagement by hearing aid users [9]. However, the perceptual benefit of DNR is not uniform; in some conditions—particularly for older adults with sloping sensorineural loss—noise suppression may not enhance speech intelligibility and may occasionally degrade performance in complex environments [10].

A long-standing concern regarding dynamic noise reduction (DNR) processing is the potential alteration of the speech temporal envelope, which is crucial for intelligibility, segmentation, and prosodic cues [11]. During noise reduction, algorithms may become overly aggressive, inadvertently distorting speech sounds [12]. This distortion can cause the speech produced by hearing aids to sound muffled or unnatural, ultimately reducing their overall effectiveness, particularly when the signal's temporal modulations are compromised [13]. The Envelope Difference Index (EDI) is commonly used to quantify temporal-envelope modifications by comparing input and output envelopes of processed speech [14]. EDI directly compares envelopes, sensitivity to temporal modulation, offering a direct and nuanced assessment of distortions vital to speech intelligibility.[13]. EDI effectively measures temporal-envelope differences but has limitations to differentiate linear from nonlinear distortions and may not fully capture perceptual relevance. Modern metrics like the Hearing Aid Speech Perception Index, Hearing Aid Speech Quality Index, and log likelihood ratio incorporate auditory models and modulation analysis, providing valuable insights and are recommended for multi-metric evaluations of hearing aid processing.

Given the mixed findings regarding perceptual outcomes, it remains unclear how DNR-related envelope changes relate to speech recognition and listening effort. The present study addresses this gap by examining the effects of DNR activation on speech recognition and listening effort in young and older adults with moderate sensorineural hearing loss (SNHL). We hypothesised that: (1) DNR activation would improve speech recognition and reduce listening effort, with potentially larger benefits in younger adults; and (2) greater EDI values would be negatively associated with DNR-related perceptual benefits.

Methods

Participants

A total of 37 participants were recruited and grouped based on age. The younger adult group comprised 17 individuals aged 18–45 years (mean = 34.5, SD = 6.4), and the older adult group comprised 20 individuals aged 51–70 years (mean = 65.7, SD = 6.8). The required sample size was determined a priori using G*Power 3.1. To detect a medium-sized interaction effect (f = 0.25, based on our pilot data [11]) in a mixed-design ANOVA ($\alpha = 0.05$, power = 0.80), a minimum of 34 participants was required. All participants had bilateral, symmetrical, flat sensorineural hearing loss (40–55 dB HL) and speech identification scores greater than 60%, with normal middle-ear status confirmed by Type A tympanograms. All were new hearing-aid users and native Kannada speakers. Cognitive screening was conducted in study participants using the Mini-Mental State Examination (MMSE) [15], and only individuals with scores ≥ 24 were included. Institutional review board approval (XXXX/RB/2022/57) was obtained, and written informed consent was obtained prior to data collection.

Hearing Aid Programming and Digital Noise Reduction Algorithm

Participants were fitted with behind-the-ear digital hearing aids (Model S, Siemens Acuris) utilising input compression across 16 channels with the NAL-NL 2 prescriptive formula. Directional microphone technology was disabled, but adaptive feedback cancellation remained active. Two programs were set up: one with maximum noise reduction enabled and another with it disabled.

The DNR technology features two independent algorithms that operate simultaneously across 16 channels on the Siemens Acuris platform. The modulation-based dynamic noise reduction (DNR) algorithms differentiate between speech and noise by analysing the temporal modulation characteristics in each audio channel. They apply gain reduction to the channel with the higher modulation rate and reduced depth. This algorithm has a relatively slow activation time of 5 to 7 seconds and a longer deactivation period of approximately 500 milliseconds. This design approach focuses on preserving speech clarity, enhancing comfort during use, and accepting noise [16].

The second algorithm is based on the Adaptive Wiener filter, which functions as a fast-acting, adaptive noise estimation system inspired by the Wiener filtering technique. This algorithm monitors the short-term signal envelope and continuously evaluates noise levels, allowing for dynamic gain adjustments. It operates with a quick time constant of around 10 milliseconds. The primary objective of this algorithm is to improve the short-term signal-to-noise ratio (SNR) by implementing specific gain reductions on channels when noise levels exceed those of the signal.

Both algorithms are incorporated into the manufacturer's DNR system and are not selectable by the user; thus, activating DNR simultaneously engages both algorithms. The rationale behind this combined system is that the modulation-based algorithm enhances speech comfort and mitigates the annoyance tied to steady-state noise. In contrast, the Wiener-filter-based algorithm provides rapid noise suppression, especially under fluctuating noise conditions. The manufacturer's signal-processing framework merges the outputs of both algorithms at the channel level, ensuring that the final gain reduction in each channel corresponds to the greatest noise suppression suggested by either algorithm at that time, while still conserving the speech envelope.

Stimuli for speech recognition and listening effort

The study used a standardised Kannada sentence list for speech identification and recall experiments [17]. This material comprises 25 lists, each containing 10 sentences. The presentation level for the speech stimulus was fixed at 65 dB SPL. Speech babble from four speakers (equal numbers of male and female) was added to the sentences at a +4 dB signal-to-noise ratio (SNR). The experimental design featured eight blocks, each with five sentences drawn from four different lists. Another set of eight blocks was prepared from four additional lists. These blocks were used to evaluate two conditions: DNR-on and DNR-off. A 5-second interval was provided between the presentation of each sentence. To minimise potential order effects, the sequence of block presentations was randomised for participants in both groups. Testing occurred immediately post-fitting without an acclimatisation period, consistent with protocols evaluating acute processing effects in new users.

Procedure

Sentences were presented from 0° azimuth from a loudspeaker located one metre away from the listener, and speech noise was presented from 180° azimuth at +4 dB SNR through loudspeakers placed one metre from the listener. The signal from the front, and noise from the back paradigm was employed to mimic the most frequently occurring natural listening situation, and the +4dB SNR was chosen based on our pilot study to avoid the floor effects seen at worse SNRs (scores ranged between 30% to 60% with this combination)

We employed a “dual-task paradigm” For the primary task, participants were asked to repeat the final keyword of each sentence verbatim [18]. The dual-task paradigm, with sentence repetition as the primary task and final-word recall as the secondary task, is a validated behavioural measure of listening effort. It quantifies cognitive resource allocation by assessing performance decrements on the secondary task under increased auditory demand.

One point was awarded for every accurately repeated keyword, with a maximum possible score of 40. The recall task required participants to recall the final word of a five-sentence block. Participants were encouraged to repeat these words in the order of presentation and to guess if uncertain. A score of one was given if a word was correctly recalled, regardless of order. Responses were noted online and recorded for later verification.

Envelope Difference Index

The output of the hearing aid fitted to each participant was measured under conditions identical to those of the listening tasks (the target sentence at 0° azimuth and noise at 180° azimuth with a +4 dB SNR). The input and output of the hearing aid (programmed for each patient) in KEMAR (Knowles Electronics Manikin for Acoustic Research) were measured in two conditions: DNR-On and DNR-Off. A total of ten sentences were used in each condition. EDI was computed per sentence, and values were averaged across sentences for each condition. The input and output versions of the stimulus were rectified (full-wave) and low-pass filtered using a 6th-order Butterworth filter at 50 Hz to extract the signal envelope, then downsampled to 6 kHz. The mean amplitude of the sampled envelope was calculated, and each data point was scaled by dividing it by the mean amplitude. Both input and output envelopes were normalised using this procedure, and the resultant envelopes were analysed using the equation. [EDI = $\sum_{n=1}^{N} |\mathrm{Env1n} - \mathrm{Env2n}|/2N$ adopted in MATLAB (version R2014b, MathWorks Inc., USA) to calculate the Envelope Difference Index, a measure of envelope distortion at the output relative to the input [19]. In the equation, 'Env1n' represents the hearing aid output waveform of a sentence, 'Env2n' is the input waveform, and N is the number of samples in each waveform.

Results

Speech recognition in noise

A Mixed ANOVA was conducted to compare speech recognition scores with and without DNR across the two groups (Figure 1). The main effect of DNR was not significant ($F_{(1,35)} = 2.71$, $p = 0.11$, $\eta p^2 = 0.07$). However, a significant interaction was found between DNR condition and Group ($F_{(1,35)} = 17.1$, $p < 0.001$, $\eta p^2 = 0.33$). Further dependent-samples t-tests within each group, comparing speech identification scores in the DNR-on vs DNR-off conditions in each group, revealed different outcomes. In younger adults, scores were significantly higher in the DNR-on condition ($t(16) = -4.8$, $p < 0.001$, $d = 1.16$). In contrast, older adults showed no such difference between the conditions ($t_{(19)} = 1.6$, $p = 0.12$, $d = 0.36$). These findings indicate that DNR improved speech recognition only for younger participants.

Sentence Final-Word Recall – Listening effort

Mixed ANOVA results showed a significant main effect of DNR condition ($F_{(1,35)} = 13.86$, $p = 0.001$, $\eta p^2 = 0.28$), while the interaction between Group and DNR condition was not significant ($F_{(1,35)} = 0.41$, $p = 0.53$, $\eta p^2 = 0.01$). Follow-up dependent t-tests indicated significantly better recall scores in the DNR-on condition relative to the DNR-off condition in both age groups (Figure 2) (Younger adults: $t_{(16)} = -3.6$, $p = 0.002$, $d = 0.87$; Older adults: $t_{(19)} = -2.8$, $p = 0.01$, $d = 0.62$). Thus, DNR reduced listening effort consistently across both age groups.

Envelope difference Index

The envelope difference index (EDI) was lower in the DNR-on condition than in the off condition in each group. A mixed ANOVA results revealed no significant main effect of condition (DNR-on and -off) on EDI [F (1, 35) = 0.115, $p = 0.737$] and group [F (1, 35) = 0.142, $p = 0.708$]. Furthermore, interaction between condition*group on EDI revealed no significant difference [F (1, 35) = 3.101, $p = 0.086$].

Correlation of Envelope Difference Index with Benefit From DNR

The benefit is calculated as the difference in SIS score between the DNR-on and DNR-off conditions. The same method was applied to the final recall score. Pearson product-moment correlations revealed that no correlation was found between the magnitude of envelope difference index and DNR benefits on speech recognition and listening effort in younger ($r = -0.28$, $p = 0.28$; $r = -0.11$, $p = 0.67$) and older adults ($r = 0.37$, $p = 0.11$; $r = 0.28$, $p = 0.23$). (Figure 3). These findings suggest that, under the present conditions, EDI did not account for individual variability in speech or effort benefits.

Discussion

The present study examined the effects of digital noise reduction (DNR) on speech recognition, listening effort, and envelope distortion in younger and older adults with flat, moderate SNHL. The enhancement in speech recognition in noise observed only for younger adults is consistent with some earlier findings [20], although other studies have reported no significant improvements [21]. These inconsistencies across the literature likely arise from methodological variability. A key factor is the spatial configuration of speech and noise. Whereas many studies present both from the same azimuth, the current study used a spatially separated configuration (speech from the front and noise from the back), which provides additional spatial cues that may influence DNR effectiveness. Another methodological difference lies in the signal-to-noise ratio (SNR). The current study used a relatively favourable +4 dB SNR based on pilot data, whereas other studies have used more challenging SNRs [22]. Such differences in SNR can affect the accessibility of speech cues and may partly account for discrepancies in observed DNR benefits.

Older listeners did not improve their speech perception scores despite good SNR and spatial separation, indicating that cognitive factors are crucial for utilising DNR benefits. This aligns with evidence that speech perception in noise relies on cognitive resources like working memory, attention, and executive function [23]. In this context, the DNR can alleviate cognitive load by enhancing the signal-to-noise ratio. While our findings are consistent with the role of age-related cognitive decline, future studies should directly measure working memory and attentional resources in both age groups to confirm this mechanism. Cognitive operations such as auditory scene analysis, linguistic decoding, and memory updating are affected by age-related cognitive decline [24]. Thus, older adults may find it more challenging to harness DNR-mediated improvements despite enhanced audibility [23,24]. Our observation that younger adults experienced greater improvements in speech recognition with DNR than older adults likely stem from the interconnected auditory and cognitive constraints. While cognitive factors likely contributed to the age-related differences we observed, future studies should test this interpretation by incorporating direct, standardised measures of cognitive functioning in both age groups.

In contrast to the speech recognition findings, both younger and older adults showed significantly reduced listening effort—indexed by improvements in final-word recall—when DNR was activated. This benefit replicates and extends earlier work demonstrating that DNR can reduce cognitive demand even when it does not improve speech intelligibility [25]. Most past DNR research has focused on speech recognition and sound quality, with fewer studies on listening effort, particularly in mixed-age clinical samples. Our results show that both younger and older adults with flat moderate SNHL experience reduced listening effort, adding ecological validity to the effectiveness of DNR in real-world clinical settings. The interaction effect shows that DNR benefits listening effort similarly across age groups. Older adults experienced reduced effort without improved speech recognition, indicating stable performance despite decreased cognitive load. [26]. The findings support theories suggesting that listeners employ compensatory strategies to maintain performance under adverse conditions, despite increased cognitive effort [27]. The findings are specific to the implementation of tested modulation-based DNR algorithms. Generalizability to other manufacturers' algorithms requires further validation. The current findings complement previous research by demonstrating significant reductions in listening effort among a mixed-age clinical population with flat moderate hearing loss, a condition that has been less frequently studied in prior DNR research.

Future research would benefit from incorporating physiological indices of listening effort, such as pupillometry and electroencephalography (EEG), alongside behavioural recall measures. These objective metrics could clarify the mechanisms by which DNR influences cognitive load and help dissociate perceptual from cognitive contributions to effort [28]. The current results, while encouraging, highlight the need for multimodal assessments to characterise the benefits of DNR fully.

Regarding the Envelope Difference Index (EDI), the magnitude of envelope distortion was small (around 0.3), consistent with previous reports on modern digital hearing aids [11,29]. Significantly, neither the magnitude of EDI nor its change across DNR conditions correlated with improvements in speech recognition or listening effort. This finding implies that the relatively low level of envelope distortion in these devices is unlikely to impede the perceived or cognitive advantages provided by DNR. On the other hand, EDI has recognised limitations as a metric for assessing fidelity in nonlinear hearing aid processing [30], and it may lack the sensitivity needed to detect subtle envelope modifications in the current context. To clarify the precise reasons for these discrepancies, future research should investigate how higher levels of compression, different dynamic range reduction (DNR) architectures, and directional processing affect envelope fidelity in more complex acoustic environments. Additionally, incorporating metrics beyond the envelope distortion index (EDI)—such as log-likelihood ratio (LLR) or modulation spectral analyses—could provide a more comprehensive understanding of how hearing-aid processing influences speech envelopes and their perceptual effects.

Overall, the present study contributes to the literature by including a clinically typical sample of younger and older adults with moderate flat hearing loss, demonstrating reliable DNR-related improvements in listening effort across age groups, and incorporating EDI as an objective, signal-based index of envelope alteration. The consistent listening-effort benefit observed here reinforces the clinical value of DNR technology, even when speech-recognition gains are limited, and underscores the importance of evaluating multiple outcome domains when assessing hearing-aid performance.

Clinical Implication

The results suggest that, under the specific device settings of the dual-modulation DNR algorithm and the listening conditions tested at a +4 dB signal-to-noise ratio (SNR), we did not observe envelope distortions large enough to affect perceptual outcomes. For individuals with moderate flat hearing loss, DNR can be safely activated without causing speech distortion, particularly in environments where speech originates from the front and noise from the back. Clinically, this supports the routine use of DNR to improve speech recognition and reduce listening effort.

Future Directions

Future work should include direct measures of cognitive resources—such as working memory, attentional capacity, and processing speed—to test the hypothesised cognitive mechanisms underlying age-related differences in DNR benefit. Incorporating physiological indices of listening effort (e.g., pupillometry, EEG) alongside behavioural measures would provide a more comprehensive understanding of how DNR influences cognitive load across age groups. Further research should also employ additional signal fidelity metrics beyond EDI, such as log-likelihood ratio and other envelope- or spectrum-based indices, to more comprehensively characterise how hearing-aid processing modifies speech signals under different noise conditions and algorithmic settings. We assessed listening effort using a single, favourable SNR (+4 dB), which may not reflect DNR effects in more challenging environments, and lacks ecological validity. Future studies should test multiple SNRs to better characterise dose-response relationships. Finally, expanding stimulus conditions to include more challenging SNRs, multi-talker babble, and different spatial configurations will help clarify the extent to which acoustic and cognitive factors interact to shape real-world DNR outcomes. Testing was conducted immediately after the hearing aid fitting, without acclimatisation. While acclimatisation (4–12 weeks) may affect overall benefit perception, it has a limited impact on short-term DNR-specific outcomes in noise tasks. Future research should include follow-up testing after acclimatisation to evaluate potential changes. The data were collected from a single device to avoid confounding variables related to it; however, this approach limits generalizability, and further studies are required to collect data from clients' own hearing aids.

Conclusions

Activation of digital noise reduction improved speech recognition in noise for younger adults but did not yield measurable recognition benefits for older adults with moderate sensorineural hearing loss. Nevertheless, both age groups demonstrated reduced listening effort when DNR was enabled, highlighting its consistent advantage for listening comfort. The magnitude of signal envelope distortion at the hearing-aid output was low and was not associated with DNR benefits in either group. These outcomes suggest that envelope distortion at the levels measured here may not strongly constrain DNR-related benefits, although further work using multiple objective fidelity indices is warranted.

Acknowledgements: We thank the participants in the study for their kind cooperation and patience. We also wish to acknowledge Dr Sharath Kumar for his assistance with hearing aid output recordings.

Ethical statement: The research was approved by the JSS Institutional Ethical Committee (JSSMC/IEC/27102023/40 NCT/2023-24).

Conflicts of interest: No potential conflict of interest was reported by the author(s).

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author's contributions:

HNS: study design, statistical analysis, Interpretation of results, writing - review & editing and drafting the manuscript, **SV:** Conceptualization, Visualization, Methodology, Data acquisition and formal analysis, Writing - original draft.

Reference

1. Le Prell CG, Clavier OH. Effects of noise on speech recognition: Challenges for communication by service members. Hear Res. 2017;349:76-89. [DOI:10.1016/j.heares.2016.10.004]

2. Parthasarathy A, Hancock KE, Bennett K, DeGruttola V, Polley DB. Bottom-up and top-down neural signatures of disordered multi-talker speech perception in adults with normal hearing. Elife. 2020;9:e51419. [DOI:10.7554/eLife.51419]
3. Zekveld AA, Kramer SE, Festen JM. Cognitive load during speech perception in noise: the influence of age, hearing loss, and cognition on the pupil response. Ear Hear. 2011;32(4):498-510. [DOI:10.1097/AUD.0b013e31820512bb]
4. Başkent D, Clarke J, Pals C, Benard MR, Bhargava P, Saija J, et al. Cognitive Compensation of Speech Perception With Hearing Impairment, Cochlear Implants, and Aging: How and to What Degree Can It Be Achieved? Trends Hear. 2016;20:1-16. [DOI:10.1177/2331216516670279]
5. Helfer KS, Wilber LA. Hearing loss, aging, and speech perception in reverberation and noise. J Speech Hear Res. 1990;33(1):149-55. [DOI:10.1044/jshr.3301.149]
6. Brodie A, Smith B, Ray J. The impact of rehabilitation on quality of life after hearing loss: a systematic review. Eur Arch Otorhinolaryngol. 2018;275(10):2435-40. [DOI:10.1007/s00405-018-5100-7]
7. Kumar LMS. Measuring listening effort using physiological, behavioral and subjective methods in normal hearing subjects: Effect of signal to noise ratio and presentation level. [Dissertation]. Harrisonburg: James Madison University; 2020.
8. Kuk F, Peeters H, Lau C, Korhonen P. Effect of maximum power output and noise reduction on speech recognition in noise. J Am Acad Audiol. 2011;22(5):265-73. [DOI:10.3766/jaaa.22.5.3]
9. Dawes P, Emsley R, Cruickshanks KJ, Moore DR, Fortnum H, Edmondson-Jones M, et al. Hearing loss and cognition: the role of hearing AIDS, social isolation and depression. PLoS One. 2015;10(3):e0119616. [DOI:10.1371/journal.pone.0119616]
10. Neher T, Grimm G, Hohmann V, Kollmeier B. Do hearing loss and cognitive function modulate benefit from different binaural noise-reduction settings? Ear Hear. 2014;35(3):e52-62. [DOI:10.1097/AUD.0000000000000003]
11. Chinnaraj G, Shetty HN, Palaniyappan V. Effect of Digital Noise Reduction And Directionality Algorithms in Hearing Aids on Temporal Envelope Distortion and Speech Recognition. J Hear Sci. 2021;11(4):19-29. [DOI:10.17430/JHS.2021.11.4.2]
12. Kim G, Loizou PC. Gain-induced speech distortions and the absence of intelligibility benefit with existing noise-reduction algorithms. J Acoust Soc Am. 2011;130(3):1581-96. [DOI:10.1121/1.3619790]
13. Fukawa T, Jin'no K. Noise Reduction Method Focusing on Spectral Envelopment and Fine Structure of Speech. J Signal Process Syst. 2021;25(6):233-7. [DOI:10.2299/jsp.25.233]
14. Souza P, Hoover E, Gallun F. Application of the envelope difference index to spectrally sparse speech. J Speech Lang Hear Res. 2012;55(3):824-37. [DOI:10.1044/1092-4388(2011/10-0301)]
15. Folstein MF, Folstein SE, McHugh PR. "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res. 1975;12(3):189-98. [DOI:10.1016/0022-3956(75)90026-6]
16. Mueller HG, Weber J, Hornsby BW. The effects of digital noise reduction on the acceptance of background noise. Trends Amplif. 2006;10(2):83-93. [DOI:10.1177/1084713806289553]
17. Geetha C, Kumar KSS, Manjula P, Pavan M. Development and Standardisation of the Sentence Identification Test in the Kannada Language. J Hear Sci 2014;4(1):18-26. [DOI:10.17430/890267]
18. Pichora-Fuller MK, Schneider BA, Daneman M. How young and old adults listen to and remember speech in noise. J Acoust Soc Am. 1995;97(1):593-608. [DOI:10.1121/1.412282]
19. Fortune TW, Woodruff BD, Preves DA. A new technique for quantifying temporal envelope contrasts. Ear Hear. 1994;15(1):93-9. [DOI:10.1097/00003446-199402000-00011]
20. Wu YH, Stangl E, Chipara O, Hasan SS, DeVries S, Oleson J. Efficacy and Effectiveness of Advanced Hearing Aid Directional and Noise Reduction Technologies for Older Adults With Mild to Moderate Hearing Loss. Ear Hear. 2019;40(4):805-22. [DOI:10.1097/AUD.0000000000000672]
21. Brons I, Houben R, Dreschler WA. Acoustical and Perceptual Comparison of Noise Reduction and Compression in Hearing Aids. J Speech Lang Hear Res. 2015;58(4):1363-76. [DOI:10.1044/2015_JSLHR-H-14-0347]
22. Peeters H, Kuk F, Lau CC, Keenan D. Subjective and objective evaluation of noise management algorithms. J Am Acad Audiol. 2009;20(2):89-98. [DOI:10.3766/jaaa.20.2.2]
23. Lawrence BJ, Jayakody DMP, Henshaw H, Ferguson MA, Eikelboom RH, Loftus AM, et al. Auditory and Cognitive Training for Cognition in Adults With Hearing Loss: A Systematic Review and Meta-Analysis. Trends Hear. 2018;22:2331216518792096. [DOI:10.1177/2331216518792096]
24. Rönnberg J, Lunner T, Zekveld A, Sörqvist P, Danielsson H, Lyxell B, et al. The Ease of Language Understanding (ELU) model: theoretical, empirical, and clinical advances. Front Syst Neurosci. 2013;7:31. [DOI:10.3389/fnsys.2013.00031]
25. Rudner M. Cognitive Spare Capacity as an Index of Listening Effort. Ear Hear. 2016;37 Suppl 1:69S-76S. [DOI:10.1097/AUD.0000000000000302]
26. Sarampalis A, Kalluri S, Edwards B, Hafter E. Objective measures of listening effort: effects of background noise and noise reduction. J Speech Lang Hear Res. 2009;52(5):1230-40. [DOI:10.1044/1092-4388(2009/08-0111)]
27. Hornsby BW. The effects of hearing aid use on listening effort and mental fatigue associated with sustained speech processing demands. Ear Hear. 2013;34(5):523-34. [DOI:10.1097/AUD.0b013e31828003d8]
28. Zekveld AA, Koelewijn T, Kramer SE. The Pupil Dilation Response to Auditory Stimuli: Current State of Knowledge. Trends Hear. 2018;22:2331216518777174. [DOI:10.1177/2331216518777174]
29. Arehart K, Souza P, Kates J, Lunner T, Pedersen MS. Relationship Among Signal Fidelity, Hearing Loss, and Working Memory for Digital Noise Suppression. Ear Hear. 2015;36(5):505-16. [DOI:10.1097/AUD.0000000000000173]
30. Kates JM. Limitations of the Envelope Difference Index as a Metric for Nonlinear Distortion in Hearing Aids. Ear Hear. 2020;41(2):356-61. [DOI:10.1097/AUD.0000000000000768]

Figures

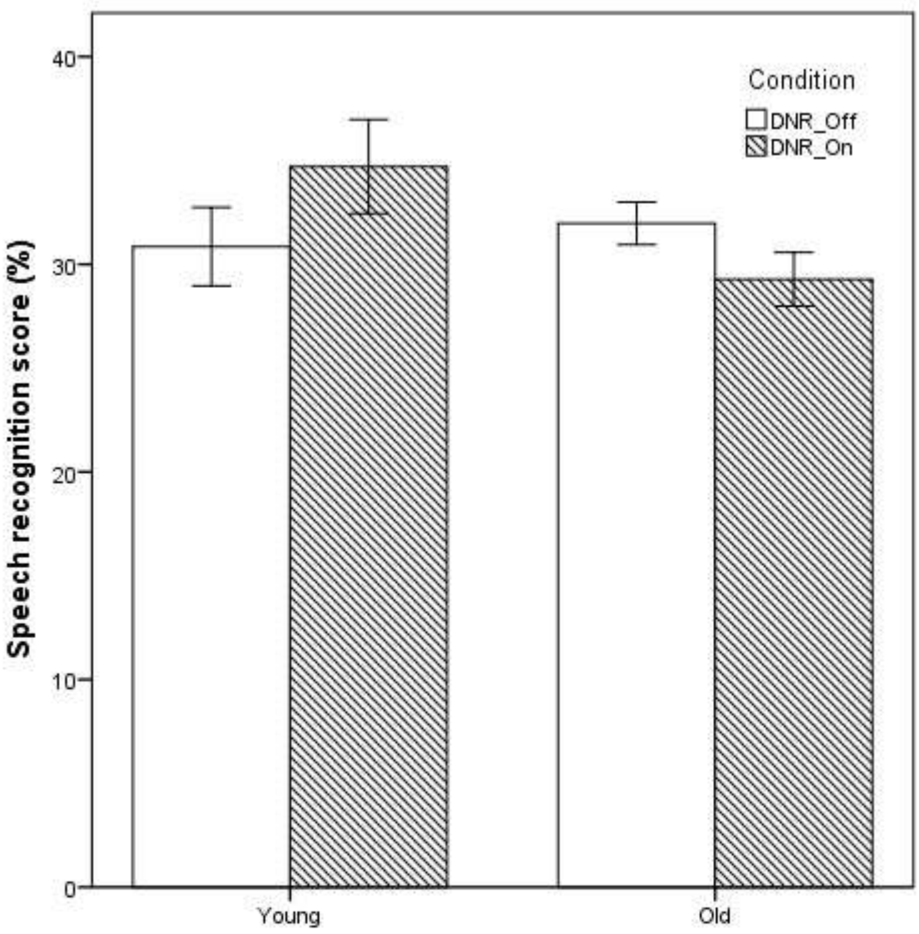

Figure 1. Speech identification scores with and without the DNR in young and older participants. Speech identification score (%) is significantly higher in DNR-on than -off in younger adults. Although speech identification scores are higher in the DNR-off than in the DNR-on condition in older adults, the difference in recognition score did not reach significance (error bars 95 % CI).

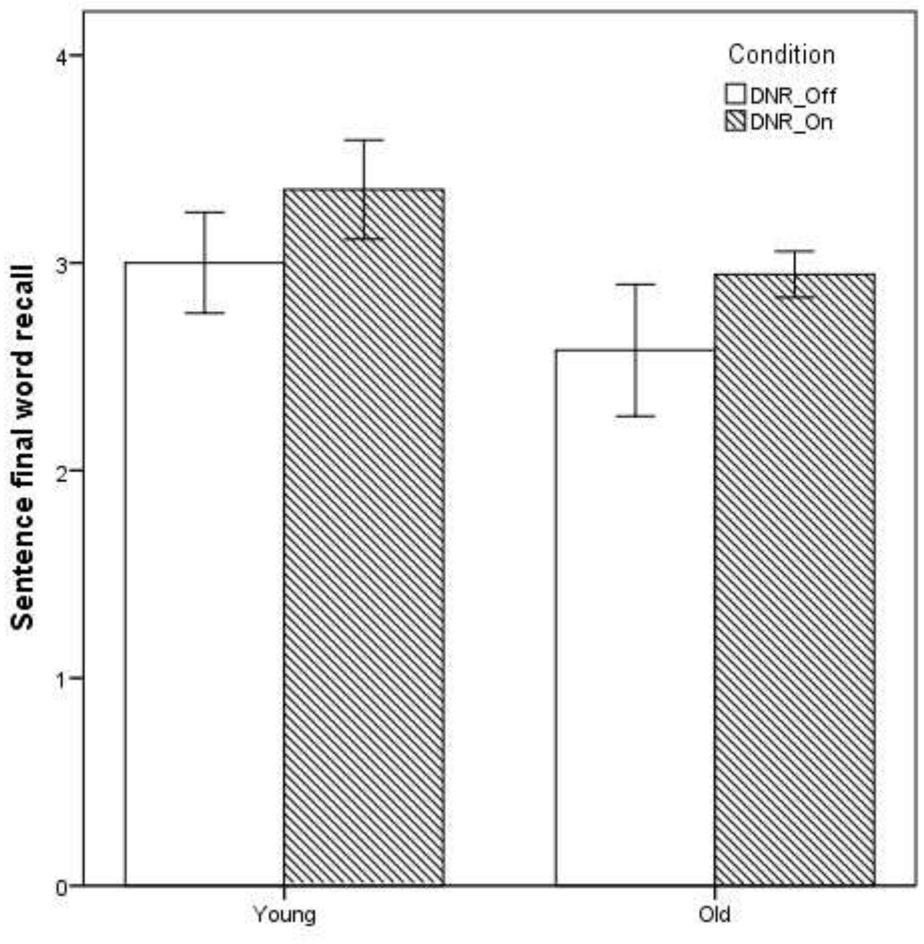

Figure 2. Sentence final-word recall with and without the digital noise reduction (DNR) in young and older participants. Listening effort is significantly lower in the DNR-on condition than in the off condition across both groups (Error bar 95 % CI).

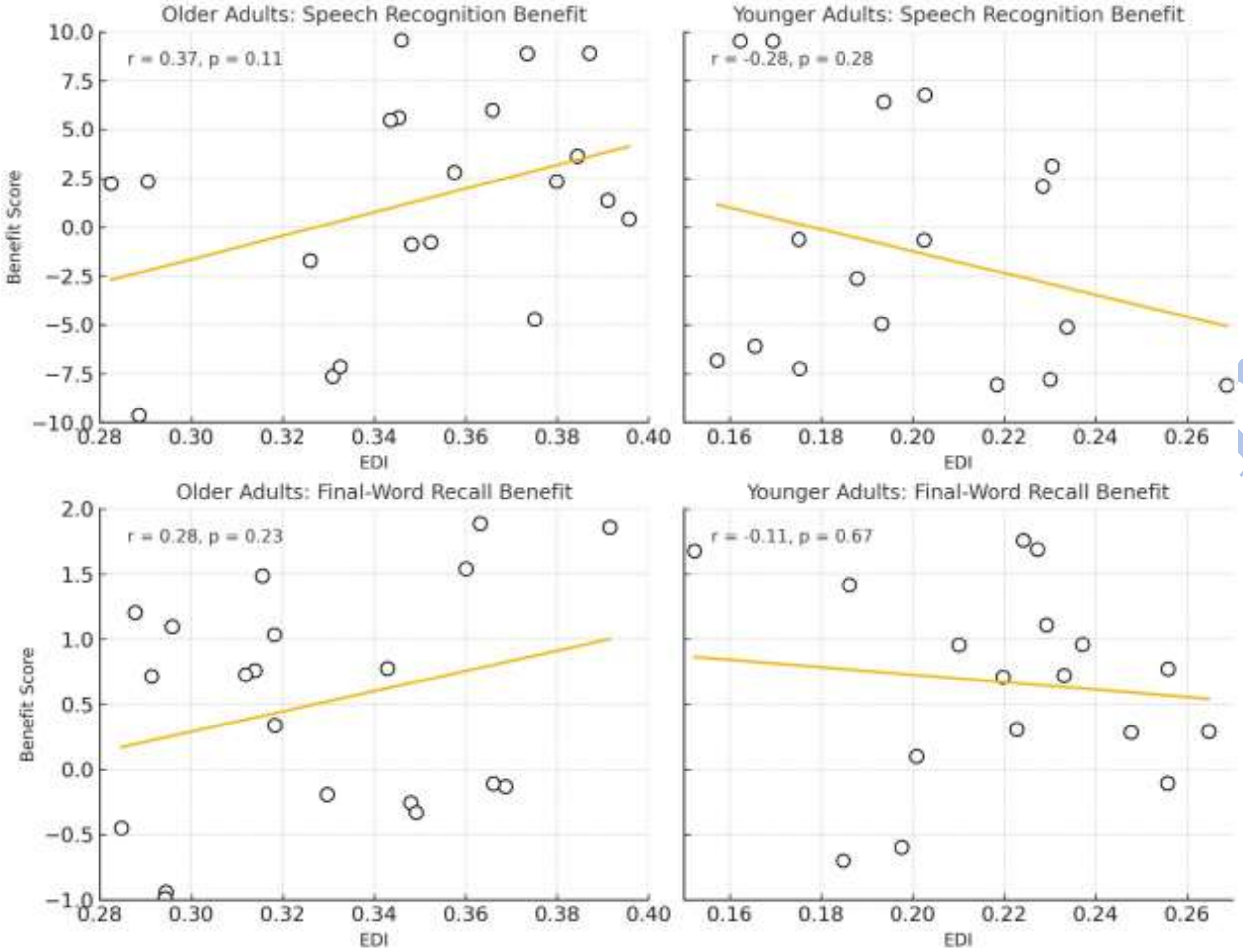

Figure 3. Scatterplot of the Envelope difference index and benefit from the Digital noise reduction (DNR) algorithm - top: Speech recognition benefit (in %) and bottom: Sentence final word recall benefit received from DNR in younger and older participants. The benefits of DNR on speech recognition score and listening effort are not correlated with the Envelope Difference Index (EDI) in each group.