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The Effects of Nonlinear Frequency Compression and Digital Noise Reduction on Word Recognition and Satisfaction Ratings in Noise in Adult Hearing Aid Users

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Abstract

Background: Nonlinear frequency compression (NLFC) and digital noise reduction (DNR) are hearing aid features often used simultaneously in the adult population with hearing loss. Although each feature has been studied extensively in isolation, the effects of using them in combination are unclear.

Purpose: The effects of NLFC and DNR in noise on word recognition and satisfaction ratings in noise in adult hearing aid users were evaluated.

Research Design: A repeated measures design was used.

Study Sample: Two females and 13 males between the ages of 55 and 83 yr who were experienced hearing aid users participated. Thirteen were experienced with NLFC and all were experienced with DNR. Each participant was fit with Phonak Bolero Q90-P hearing instruments using their specific audiometric data and the Desired Sensation Level v5.0 (adult) fitting strategy. Fittings were verified with probe microphone measurements using speech at 65-dB sound pressure level (SPL). NLFC verification was performed using the Protocol for the Provision of Amplification, Version 2014.01.

Data Collection and Analysis: All testing was conducted in a double-walled sound booth. Four hearing aid conditions were used for all testing: Baseline (NLFC off, DNR off), NLFC only, DNR only, and Combination (NLFC on, DNR on). A modified version of the Pascoe's High-Frequency Word List was presented at 65-dB SPL with speech spectrum noise at 6-dB signal-to-noise ratio (SNR) and 1-dB SNR for each hearing aid condition. Listener satisfaction ratings were obtained after each listening condition in terms of word comfort, word clarity, and average satisfaction. Two-way repeated measures analyses of variance were conducted to assess listener performance. Pairwise comparisons were then completed for significant main effects.

Results: Word recognition results indicated a significant SNR effect only (6 dB SNR $>$ 1 dB SNR). Satisfaction ratings results indicated a significant SNR and hearing aid condition effect for clarity, comfort, and average satisfaction. Clarity ratings were significantly higher for DNR and Combination than NLFC. Comfort ratings were significantly higher for DNR than NLFC. Average satisfaction was significantly higher for DNR and Combination than for NLFC. Also, average ratings were significantly higher for Combination than Baseline.

Conclusions: Activating NLFC or DNR in isolation or in combination did not significantly impact word recognition in noise. Activating NLFC in isolation reduced satisfaction ratings relative to the DNR or Combination conditions. The isolated use of DNR significantly improved all satisfaction ratings when compared with the isolated use of NLFC. These findings suggest NLFC should not be used in isolation and should be coupled with DNR for best results. Future research should include a field trial as this was a limitation of the study.

Key Words: digital noise reduction, hearing aid, nonlinear frequency compression

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Abbreviations: ANOVA = analysis of variance; DNR = digital noise reduction; HFWL = High-Frequency Word List; NLFC = nonlinear frequency compression; SNR = signal-to-noise ratio; SPL = sound pressure level

INTRODUCTION

Nonlinear frequency compression (NLFC) and digital noise reduction (DNR) are hearing aid features often used for the adult population. NLFC moves high-frequency energy into lower frequency regions where hearing is less impaired (Parsa et al, 2013). NLFC compresses frequencies greater than a predetermined cutoff frequency and shifts them to a lower frequency range according to the frequency compression ratio. Frequencies less than the compression cutoff frequency are amplified without NLFC. NLFC attempts to improve the audibility of high-frequency speech cues otherwise unaidable because of poor hearing sensitivity in high-frequency regions (Bohnert et al, 2010). DNR attempts to improve the signal-to-noise ratio (SNR) at the output of the hearing aid by amplifying speech signals and reducing gain for certain competing background noises. The hearing aid analyzes incoming signals and alters the gain and output according to rules which determine SNRs on the basis that speech is a highly modulated signal whereas background noise is less modulated (Alcántara et al, 2003). Thus, the goal of DNR is to improve speech perception and listening comfort in background noise (Bentler et al, 2008).

Previous studies have evaluated frequency compression in adults using various outcome measures: sound detection, consonant recognition, monosyllabic word recognition, plural recognition, speech recognition in noise, and self-report. Results indicated performance and preference with NLFC varied in quiet and noise. In quiet, NLFC significantly improved consonant recognition tasks (Glista et al, 2009; Ellis and Munro, 2015), plural recognition tasks (Glista et al, 2009), monosyllabic word recognition (Simpson et al, 2005), speech recognition thresholds (Bohnert et al, 2010), and vowel–consonant stimuli processed with NLFC (Alexander et al, 2014). Conversely, other studies did not find a significant difference when using NLFC on consonant recognition tasks (McDermott and Henshall, 2010; Perreau et al, 2013; Picou et al, 2015), dual-task cognitively loaded tests of speech intelligibility (Kokx-Ryan et al, 2015), consonant discrimination, or monosyllabic word recognition in listeners with more severe hearing loss (Simpson et al, 2006).

The effects of NLFC on performance in noise tasks also indicated varying results. Research indicated an increase in sentence recognition in noise with NLFC for one of five participants (Simpson et al, 2006) and for 7 of 11 participants (Bohnert et al, 2010). Ellis and Munro (2015) reported a statistically significant increase in sentence recognition in noise when using NLFC (Ellis and Munro, 2015). In addition, Hopkins et al (2014) and Ellis and Munro (2015) indicated consonant recognition performance in noise was significantly improved when using NLFC. Conversely, other studies did not find a significant sentence recognition performance differences (Hopkins et al, 2014; Picou et al, 2015; Miller et al, 2016) or speech recognition performance differences when using NLFC (McDermott and Henshall, 2010; Perreau et al, 2013). Furthermore, performance on the QuickSIN, Modified Rhyme Test, or dual-task cognitively loaded tests of speech intelligibility was not improved when using NLFC (Kokx-Ryan et al, 2015).

Studies evaluating adults' self-reported preference for NLFC in quiet and/or noise indicated no significant preference for NLFC on or off (Simpson et al, 2006; Glista et al, 2009; Parsa et al, 2013; Perreau et al, 2013; Ellis and Munro, 2015; Picou et al, 2015; Miller et al, 2016); however, one study suggested satisfaction improved after two months of NLFC use (Bohnert et al, 2010). Research also suggested benefit from NLFC may be related to the degree and configuration of the hearing loss and the age of the hearing aid user. For example, Glista et al (2009) and Bohnert et al (2010) suggested listeners with more high-frequency hearing loss receive more benefit from NLFC than listeners with less high-frequency hearing loss whereas Simpson et al (2006) noted individuals with similar degrees and configurations of hearing loss did not show significant benefit with NLFC. Kokx-Ryan et al (2015) suggested hearing aid users above the age of 65 received more benefit from NLFC. In summary, research suggests benefit with NLFC in quiet and in noise varies significantly. Benefit variability with NLFC may be related to factors such as the type of outcome measures used, variability in NLFC fitting protocols, degree of hearing loss, configuration of hearing loss, and the age of the hearing aid user.

DNR was designed to increase speech intelligibility and comfort in the presence of background noise; however, DNR may also reduce the audibility of noise-like speech sounds such as fricative and affricates. As with NLFC, multiple studies have evaluated DNR. For example, Alcántara et al (2003) evaluated DNR in adults and noted no significant improvements in speech intelligibility or satisfaction with DNR activated in noise. Other studies indicated DNR improved listening comfort and preference but did not significantly improve speech understanding in noise (Walden et al, 2000; Ricketts and Hornsby, 2005). Bentler et al (2008) evaluated a DNR algorithm without directional microphone involvement to assess the effectiveness of the DNR algorithm alone with three different DNR onset times

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(4, 8, 16 sec). Speech perception measures and sound quality ratings showed no significant effect of DNR on versus off; however, differences were seen among DNR onset times for ratings of listening comfort with the four-sec onset time being rated poorer than the eight-sec onset or the DNR-off condition. Overall, speech recognition in noise did not significantly change with DNR, but there was a decrease in self-reported listening effort in challenging listening environments (Desjardins and Doherty, 2014) and increased acceptance of noise (Mueller et al, 2006; Lowery and Plyler, 2013), which may suggest improved listening comfort with DNR.

In summary, studies evaluating NLFC indicated varied results on consonant improvement, speech recognition, and overall preference in quiet and in noise. Similarly, studies evaluating DNR suggested the feature did not impact speech recognition in noise but did improve listening comfort. It should be noted that previous NLFC and DNR research evaluated each feature in isolation; however, NLFC and DNR are commonly used simultaneously in adult hearing aid fittings. Therefore, what remains unclear is if the simultaneous use of NLFC and DNR affects listener performance in noise with the devices.

One hypothesis holds the combined use of DNR with NLFC may improve listener performance and perception in noise. For example, NLFC may improve the audibility of high-frequency speech sounds whereas DNR may decrease background noise, thereby resulting in improved speech intelligibility and improved listening clarity and comfort in noise. Conversely, an alternative hypothesis holds the combined use of DNR with NLFC may degrade listener performance in noise. For example, many of the speech sounds NLFC targets, such as fricatives, affricates, and sibilants (e.g., /f/, /t͡ʃ/, and /ʃ/), have modulation patterns consistent with noise. As a result, the increased high-frequency audibility from NLFC could be offset by gain reduction from DNR, thereby reducing speech intelligibility and sound quality in noise. Thus, the purpose of this study was to evaluate the effects of NLFC and DNR on listener performance in noise in adults. The following research questions were addressed:

- Does the isolated or combined use of NLFC and DNR improve word recognition in noise?
- Does the isolated or combined use of NLFC and DNR improve satisfaction ratings in noise?

METHODS

Participants

Fifteen adults (13 males and 2 females) participated in this experiment. The participants had sloping audiometric configurations (Figure 1), the degree of high-frequency hearing loss ranged from 48 to 100 dB HL, and the average age of the participants was 73 yr (range = 55–83 yr). The criteria for inclusion included (a) sensorineural hearing impairment consistent with the available fitting range of the test hearing instruments, (b) current Phonak Bolero hearing aid user, and (c) native English speaker with no known neurological, cognitive, or learning deficits as reported by the participants. A power analysis using a repeated measures 2 × 4 analysis of variance (ANOVA) design and assuming large effect sizes (0.40) for each factor showed that 15 participants yielded a statistical power value of 0.99 for SNR and 0.96 for hearing aid condition. A large effect size was assumed because small effects may not be relevant clinically. Thus, the sample size in the present study was likely sufficiently large to find a significant effect of SNR and/or hearing aid condition, if a large difference between the variables actually existed. Thirteen participants were experienced with NLFC and all were experienced with DNR. All qualification and experimental testing was conducted in a sound-treated examination room (Industrial Acoustic) with ambient noise levels suitable for testing with ears uncovered (ANSI, 1999). Participants were not compensated and the total duration of each experimental session was <90 min. This study was approved by the Institutional Review Board at the University of Tennessee Health Science Center, and all participants signed an informed consent form before participation in the study.

Hearing Instruments and Fittings

The test hearing instruments used were Phonak Bolero Q-90P devices. The same two hearing aids were used for each participant. The fitting range of these devices is from mild to profound hearing loss. The slim tube and dome coupling used during experimental testing mimicked the tube and dome type used with each

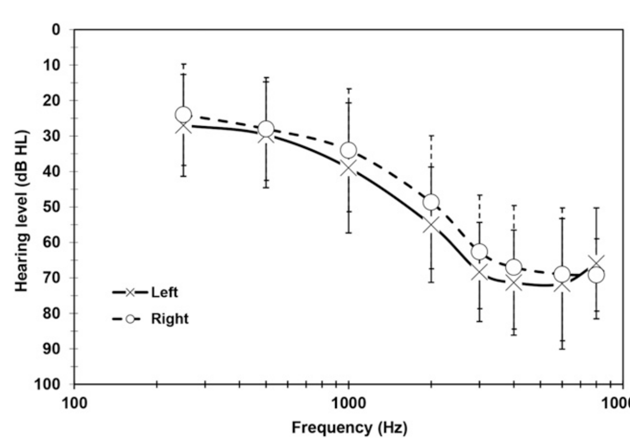

Figure 1. Mean right and left air conduction thresholds of the participants. Standard deviation bars are shown.

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participant's current hearing aid fitting; therefore, the coupling varied across participants but was controlled within participants for each listening condition. Adaptive feedback cancellation was deactivated to maximize high-frequency amplification; however, feedback required activation of the feature for 2 of the 30 fittings. Both devices were set to omnidirectional microphone mode to assess the effects of DNR without influence from a directional microphone. Each experience level was set to 100% to provide consistency with their current fittings; however, two participants' experience levels were set to 90% because of overall loudness complaints. DNR was activated at the maximum setting for each device. Each hearing aid was programmed with the following four conditions for each participant in random order and the participants were unaware of which condition they were using at all times:

- Baseline: NLFC Off, DNR Off
- NLFC: NLFC On, DNR Off
- DNR: NLFC Off, DNR On
- Combined: NLFC On, DNR On

Each participant was fit binaurally. Otoscopy was completed before each fitting to ensure ear canals were clear of cerumen. Participant-specific audiometric data were used to program each hearing aid using the Desired Sensation Level v5.0 (adult) fitting strategy. This prescription was selected to maximize high-frequency audibility. To verify target matches, probe microphone measures were performed using the Audioscan Verifit Open fittings with speech presented at 65-dB sound pressure level (SPL) (SpeechMap, carrot passage). NLFC and DNR were deactivated initially. Adjustments were made as needed to match targets using a criteria of ±6 dB from 500 to 4000 Hz. NLFC was then verified and adjusted for each ear using the Protocol for the Provision of Amplification, Version 2014.01 (Bagatto et al, 2016). Calibrated /s/ and /ʃ/ stimuli of 65-dB SPL served as the input signals. DNR was deactivated in each hearing instrument to prevent interaction with the /s/ or /ʃ/ stimuli. Probe microphone measures were made to assess the audibility and spectral separation of the /s/ and /ʃ/ stimuli. Frequency compression parameters were adjusted (crossover frequency ratio) to the weakest possible settings that provided audibility and spectral separation to allow for discrimination between the two sounds (Brennan et al, 2014). Following NLFC verification, DNR was activated in each hearing aid in the memory assigned to the DNR and Combined conditions.

Stimuli

A modified version of the Pascoe's High-Frequency Word List (HFWL) (Pickett et al, 1970) served as the test stimuli. Pascoe's HFWL consists of four lists of 50 monosyllabic words that emphasize phonemes that are difficult for listeners with impaired hearing to identify (Pickett et al, 1970). Three vocalic nuclei are used and voiceless fricatives and voiceless plosives form 63% of the number of consonant sounds. The remaining consonant sounds are nasals, laterals, and voiced plosives. For the present study, speech recognition was assessed using 25 monosyllabic words from Pascoe's HFWL containing affricates, fricatives, and/or sibilants (Appendix). It was hypothesized words containing high-frequency information with noise-like modulation patterns would be more sensitive to the effects of NLFC and DNR with the hearing instruments under test than other stimuli. The same 25 words were randomized into four lists.

Speech spectrum noise served as the background noise as previous research indicated DNR was more effective for steady-state noise than noise containing speech (Mueller and Ricketts, 2005). Speech spectrum noise was produced by an audiometer (GSI-61) and did not have the same long-term spectrum as the speech stimuli. The speech spectrum noise consisted of equal energy per frequency to 1000 Hz with a 12 dB/octave roll-off from 1000 to 6000 Hz (ANSI, 2010). Pilot testing with a Knowles Electronics Manikin for Acoustic Research confirmed that DNR engaged after 16 sec of speech spectrum noise; therefore, 30 sec of speech spectrum noise preceded the presentation of the speech stimuli to ensure DNR had sufficient time to activate. Speech spectrum noise was presented constantly during testing. Pilot testing also confirmed the selected speech stimuli presented after 30 sec of speech spectrum noise effectively engaged the NLFC and DNR of the test hearing instruments.

Protocol

All speech stimuli were produced by a compact disc player and speech spectrum noise was produced by an audiometer (GSI-61). Speech and noise stimuli were routed through the two-channel diagnostic audiometer (GSI-61) to a loudspeaker located at zero degrees azimuth in the sound-treated examination room located 1 m from the participant. The output levels of the speech stimuli and background noise were calibrated at the vertex of the listener. Speech stimuli were consistently presented at 65-dB SPL and background noise was presented at either 64-dB SPL or 59-dB SPL, resulting in a 1- or 6-dB SNR. These SNRs were chosen so that findings could be directly compared with previous DNR research (Ricketts and Hornsby, 2005).

Word recognition was evaluated for each participant using the test hearing aids in each listening condition (Baseline, NLFC, DNR, and Combined) at each SNR (1 and 6 dB). The order of hearing aid condition, noise level, and word list were randomly assigned for each

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participant. The participants' task was to verbally repeat the words presented into a lapel microphone placed near their mouth. Responses were recorded and scoring was completed posttesting by the examiner (second author).

Once word recognition testing was completed for a given condition, the participant was asked to rate their satisfaction in terms of word clarity and word comfort for that test condition. The following 5-point Likert scale was posted on the interior wall of the sound booth in front of the participants.

Word Clarity	Word Comfort
5 Very clear	5 Very comfortable
4 Somewhat clear	4 Somewhat comfortable
3 Clear	3 Comfortable
2 Unclear	2 Uncomfortable
1 Very unclear	1 Very uncomfortable

Each participant read the following instructions before each test condition: "At the end of the 25 word list, you will be asked to rate how satisfied you were with the clarity and the comfort of the words using the scales posted on the wall in front of you." Half ratings between intervals were allowed (e.g., 1.5 or 3.5). An average listener satisfaction was calculated by averaging the individual participants' word clarity and word comfort ratings. Participants were given the opportunity to take breaks throughout the test session as needed.

RESULTS

Data Analysis

For word recognition data, individual percent-correct scores were converted to rationalized arcsine transform units before statistical analyses to stabilize error variance (Studebaker, 1985). For satisfaction ratings data, some have argued that individual questionnaire items resulting in ordinal data cannot be accurately evaluated using parametric statistical methods. However, many statistician-scientists disagree with this viewpoint (Velleman and Wilkinson, 1993). Consequently, we have followed the opinion of Nunnally and Bernstein (1994) and used parametric analyses for the satisfaction ratings data.

Four, two-way ANOVAs were conducted to evaluate the effects of hearing aid program and SNR on listener performance. The dependent variables were the Pascoe HFWL score and the satisfaction ratings for word clarity, word comfort, and the average rating. For each ANOVA, the within-subject factors were hearing aid program with four levels (Baseline, NLFC, DNR, and Combined) and SNR with two levels (1 and 6 dB). Pairwise comparisons were conducted to further investigate any hearing aid program main effects whereas family-wise error rate was controlled across the tests at the 0.05 level using the Holm's sequential Bonferroni procedure.

Word Recognition

Results on the Pascoe HFWL were averaged across participants for each hearing aid program and SNR (Figure 2). The ANOVA revealed a significant main effect for SNR; however, the main effect for hearing aid program and the hearing aid program by SNR interaction were not significant (Table 1). These results indicated word recognition was significantly greater for the 6-dB SNR condition than the 1-dB SNR condition; however, word recognition was not significantly different between any of the hearing aid conditions.

Word Clarity Satisfaction Ratings

Results on the word clarity satisfaction ratings were averaged across participants for each hearing aid program and SNR (Figure 3). The ANOVA revealed a significant main effect for hearing aid program and for SNR; however, the hearing aid program by SNR interaction was not significant (Table 2). Pairwise comparisons indicated that word clarity satisfaction ratings were significantly lower for the NLFC program than the DNR and the Combined programs. Word clarity satisfaction ratings for the Baseline program were not significantly different than the ratings for the NLFC, DNR, or Combined programs (Table 3). These results indicated that satisfaction with word clarity was significantly higher at +6-dB SNR than +1-dB SNR. In addition, satisfaction with word clarity was significantly higher for the DNR and Combined programs than the NLFC program.

Word Comfort Satisfaction Ratings

Results on the word comfort satisfaction ratings were averaged across participants for each hearing aid program and SNR (Figure 4). The ANOVA revealed a significant main effect for hearing aid program and for

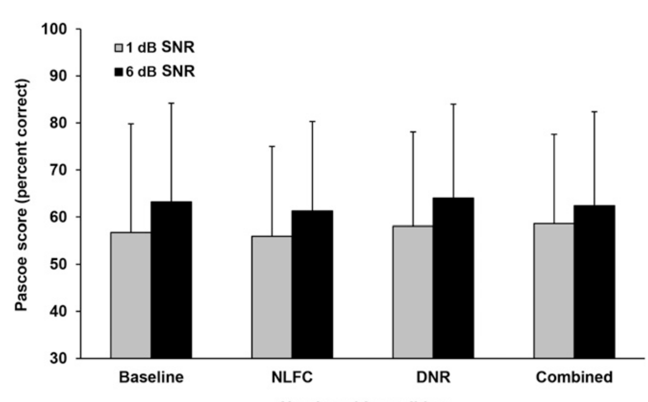

Figure 2. Mean Pascoe's HFWL scores and standard deviations for each hearing aid condition at each SNR.

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Table 1. ANOVA Results for the Pascoe's HFWL Data

	F	df	p	η_p^2	Ω
Hearing aid program	0.469	3, 42	0.706	0.032	0.136
SNR	21.695	1, 14	***< 0.000***	0.608	0.991
Hearing aid program × SNR	0.212	3, 42	0.888	0.015	0.086

Note: The values in bold italics indicate statistical significance was met.

SNR; however, the hearing aid program by SNR interaction was not significant (Table 2). Pairwise comparisons indicated that word comfort satisfaction ratings were significantly lower for the NLFC program than the DNR program. Word comfort satisfaction ratings for the Baseline program were not significantly different than the ratings for the NLFC, DNR, or Combined programs. These results indicated that satisfaction with word comfort was significantly higher at 6-dB SNR than 1-dB SNR. In addition, satisfaction with word comfort was significantly higher for the DNR than the NLFC program.

Average Satisfaction Ratings

An average satisfaction rating was calculated for each listener by averaging the individual participants' word clarity and word comfort ratings. Results on the average satisfaction ratings were averaged across participants for each hearing aid program and SNR (Figure 5). The ANOVA revealed a significant main effect for hearing aid program and for SNR; however, the hearing aid program by SNR interaction was not significant (Table 2). Pairwise comparisons indicated that average satisfaction ratings were significantly lower for the NLFC program than the DNR and the Combined programs. Average satisfaction ratings for the Baseline program were also significantly lower than the ratings for the Combined program. These results indicated that average satisfaction was significantly higher at 6-dB SNR than 1-dB SNR. In addition, average satisfaction was significantly higher for the DNR and Combined programs

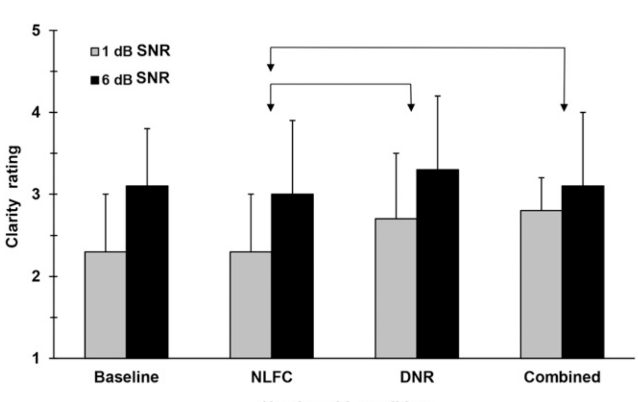

Figure 3. Mean word clarity satisfaction ratings and standard deviations for each hearing aid condition at each SNR.

Table 2. ANOVA Results for the Satisfaction Data

Word Clarity	F	df	p	η_p^2	Ω
Hearing aid program	4.607	3, 42	***0.007***	0.248	0.859
SNR	11.233	1, 14	***0.005***	0.445	0.876
Hearing aid program × SNR	1.078	3, 42	0.369	0.072	0.270
Word Comfort	**F**	**df**	**p**	**η_p^2**	**Ω**
Hearing aid program	4.911	3, 42	***0.005***	0.260	14.732
SNR	14.253	1, 14	***0.002***	0.504	14.253
Hearing aid program × SNR	2.215	3, 42	0.100	0.137	6.646
Average	**F**	**df**	**p**	**η_p^2**	**Ω**
Hearing aid program	7.770	3, 42	***< 0.000***	0.357	23.309
SNR	14.159	1, 14	***0.002***	0.503	14.159
Hearing aid program × SNR	1.616	3, 42	0.200	0.104	4.849

Note: The values in bold italics indicate statistical significance was met.

than the NLFC program. Average satisfaction was also significantly higher for the Combined program than the Baseline program.

Age and Degree of Hearing Loss

Correlations were conducted to determine if a relationship existed between the age and/or degree of high-frequency hearing loss of the listener and benefit on the word recognition and satisfaction measures when using NLFC and/or DNR. The degree of high-frequency hearing loss was calculated for each listener by averaging pure-tone threshold values at 3000, 4000, and 6000 Hz across ears (mean = 68 dB HL, standard deviation = 14.8 dB HL, and range = 48–100 dB HL). Benefit was calculated by subtracting performance in the Baseline condition from performance in the NLFC, DNR, and Combination conditions (NLFC—Baseline, DNR—Baseline, Combination—Baseline); therefore, a positive benefit score indicated that the listener performed better in the NLFC, DNR, or Combination condition than the Baseline condition and vice versa.

Age was not correlated with benefit from any hearing aid condition for the Pascoe HFWL or any satisfaction ratings. High-frequency hearing loss was positively correlated with benefit from the DNR [$r_{(15)} = 0.761$, $p < 0.01$] and Combination [$r_{(15)} = 0.534$, $p < 0.05$] conditions for average satisfaction ratings; however, high-frequency hearing loss was negatively correlated with benefit from the NLFC condition for word comfort [$r_{(15)} = -0.575$, $p < 0.05$]. High-frequency hearing loss was not correlated with benefit from any hearing aid condition for the Pascoe HFWL. These results indicated that benefit with NLFC and/or DNR was not related to the age of the listener; however, average satisfaction increased as the degree of high-frequency hearing loss increased when noise reduction was used (DNR and

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Table 3. Pairwise Comparison Results for the Satisfaction Data

		Mean Difference		
Word Clarity	Mean	6 dB		
1 dB	2.57	***−0.57***		
6 dB	3.15			
		NLFC	DNR	Combined
Baseline	2.75	0.07	−0.27	−0.25
NLFC	2.68		***−0.34***	***−0.32***
DNR	3.02			0.02
Combined	3.00			
		Mean Difference		
Word Comfort	Mean	6 dB		
1 dB	2.57	***−0.65***		
6 dB	3.22			
		NLFC	DNR	Combined
Baseline	2.75	0.05	−0.33	−0.28
NLFC	2.70		***−0.38***	−0.33
DNR	3.08			0.05
Combined	3.03			
		Mean Difference		
Average Rating	Mean	6 dB		
1 dB	2.57	***−0.61***		
6 dB	3.18			
		NLFC	DNR	Combined
Baseline	2.75	0.06	−0.30	***−0.27***
NLFC	2.69		***−0.36***	***−0.33***
DNR	3.05			0.03
Combined	3.02			

Note: Mean and mean difference values are shown with significant comparisons indicated in bold and italics.

Combination). Results also indicated that word comfort satisfaction decreased as high-frequency hearing loss increased when NLFC was used.

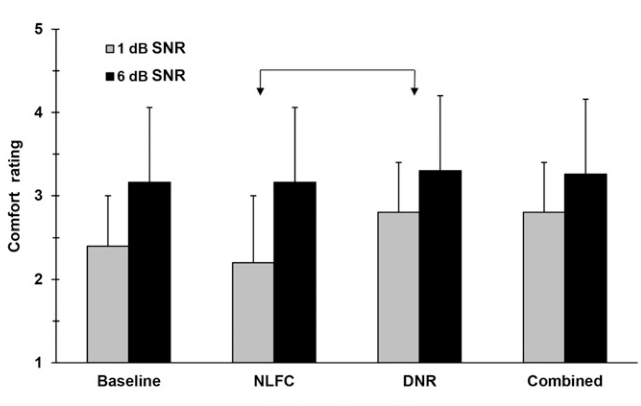

Figure 4. Mean word comfort satisfaction ratings and standard deviations for each hearing aid condition at each SNR.

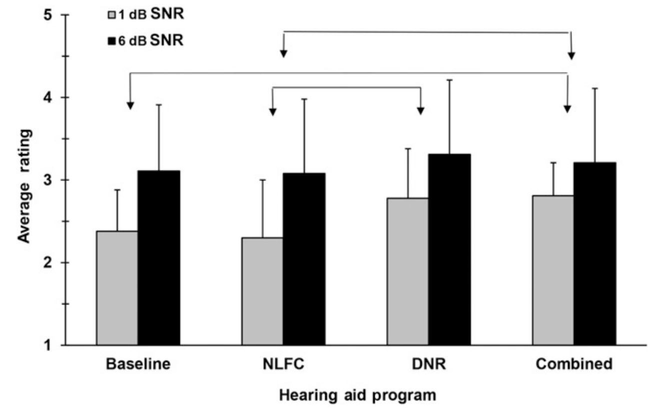

Figure 5. Mean average satisfaction ratings and standard deviations for each hearing aid condition at each SNR.

Post Hoc Analyses

In the present study, two participants were below the age of 65 yr (#2 and #6), two participants were not current users of NLFC (#11 and #14), and two participants required the hearing aids to be set at 90% experience levels because of overall loudness complaints (#9 and #13). Therefore, post hoc analyses were conducted to determine if age, experience with NLFC, or the experience level used in the fitting may have impacted the results. For each issue (age, NLFC experience, and experience level in the fitting), benefit measures detailed in the previous paragraphs were averaged for the two participants in question and for the remaining 13 participants. Average benefit scores for the larger sample were subtracted from the average benefit scores for the smaller sample (Table 4). A positive value indicated the smaller sample in question received more benefit from the hearing aid feature than the larger sample and vice versa. Lastly, values were averaged across hearing aid conditions for each issue and task.

Although most values in Table 4 indicate minimal differences in benefit, it should be noted that word recognition data revealed the two participants below age 65 received 13.46% less benefit from NLFC than the older participants. However, word recognition data also indicated the two participants fit at 90% experience levels received 13.08% more benefit than participants set to 100% experience levels. Overall, the values in Table 4 suggest the two participants below the age of 65 yr, the two participants who were not current users of NLFC, and the two participants who required the hearing aids to be set at 90% experience levels because of overall loudness complaints had minimal impact on the results.

DISCUSSION

Previous research suggested performance with NLFC or DNR varied significantly. Performance

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Table 4. Values Reflect the Average Benefit Scores for the Larger Sample Subtracted from the Average Benefit Scores for the Smaller Samples in Question (Two Participants below the Age of 65 Yr, the Two Participants Who Were Not Current Users of NLFC, and the Two Participants Who Required the Hearing Aids to Be Set at 90% Experience Levels)

Task	Condition	Age	NLFC Experience	Experience Level
Word recognition	NLFC	−13.46	−0.77	13.08
	DNR	−10.46	3.38	2.23
	Combined	−7.54	4.00	5.15
	Mean	−10.49	2.21	6.82
Word clarity	NLFC	−0.36	−0.07	−0.07
	DNR	−0.31	0.13	−0.45
	Combined	−0.58	0.14	−0.14
	Mean	−0.41	0.07	−0.22
Word comfort	NLFC	−0.23	0.35	−0.81
	DNR	0.48	0.19	−0.82
	Combined	0.54	0.54	−0.47
	Mean	0.26	0.36	−0.70
Average rating	NLFC	−0.02	−0.45	0.20
	DNR	−0.17	−0.61	0.48
	Combined	−0.42	−0.28	0.08
	Mean	−0.21	−0.45	0.25

Note: Positive values indicate the smaller sample in question received more benefit from the hearing aid feature than the larger sample and vice versa.

variability was attributed to factors such as the type of outcome measures used, variability in fitting protocols, degree of hearing loss, configuration of hearing loss, and the age of the hearing aid user. The research design used in the present study attempted to control for these factors. The speech stimuli contained high-frequency information with noise-like modulation patterns that were sensitive to the effects of NLFC and DNR with the hearing instruments under test. Pilot testing confirmed the selected speech stimuli presented after 30 sec of speech spectrum noise effectively engaged the NLFC and DNR of the test hearing instruments. Probe microphone measures were performed to match targets using a criterion of ±6 dB from 500 to 4000 Hz, and NLFC was verified and adjusted for each ear (Bagatto et al, 2016). The participants had sloping audiometric configurations, the degree of high-frequency hearing loss ranged from 48- to 100-dB HL, and the average age of the participants was 73 yr (range = 55–83 yr). Therefore, it is unlikely that the results obtained in the present research were confounded by these factors noted in previous studies.

Word Recognition

The first purpose of this study was to determine if the isolated or combined use of NLFC and DNR improved word recognition in noise. Word recognition was significantly better for the 6-dB SNR condition than the more difficult 1-dB SNR condition; however, word recognition was not significantly different between any of the hearing aid conditions. These results indicated the isolated or combined use of NLFC and/or DNR did not improve nor degrade word recognition in noise relative to not using the features.

Word recognition results were consistent with previous research that suggested the isolated use of NLFC (McDermott and Henshall, 2010; Perreau et al, 2013; Hopkins et al, 2014; Kokx-Ryan et al, 2015; Picou et al, 2015; Miller et al, 2016) or DNR (Walden et al, 2000; Alcántara et al, 2003; Ricketts and Hornsby, 2005; Bentler et al, 2008; Desjardins and Doherty, 2014) did not positively or negatively affect listener performance in noise. For NLFC, this result was somewhat surprising, given the fact NLFC was adjusted and verified in each hearing aid to attempt to maximize the audibility of the high-frequency speech cues necessary for identification. It is possible the use of NLFC improved access to the high-frequency information but did not significantly affect intelligibility. For DNR, this result was expected and was consistent with the findings of Ricketts and Hornsby (2005) who reported sentence recognition was significantly better for the 6-dB SNR condition than the 1-dB SNR condition; however, sentence recognition was not significantly affected by the use of DNR.

Similarly, the combined use of NLFC and DNR did not significantly improve or degrade word recognition at either SNR tested. It was hypothesized that the combined use of NLFC and DNR could improve speech intelligibility in noise if NLFC increased the audibility of high-frequency speech sounds whereas DNR decreased background noise. It was also hypothesized that the combined use of NLFC and DNR could degrade speech intelligibility in noise if increased high-frequency audibility from NLFC was offset by gain reduction from DNR. Results of the present study did not support either hypothesis. One possible explanation for this finding could be that the NLFC and DNR effects were not large enough to be detected by the listener; however, results from subjective testing do not support this explanation. It is also possible that listeners with less hearing loss received no benefit from the features whereas listeners with more hearing loss received significant benefit from the features thus cancelling out the effects; however, degree of hearing loss was not correlated with benefit from NLFC, DNR, or the combined use for word recognition in noise.

A more plausible explanation may be that the results obtained with simultaneous use of NLFC and DNR were consistent with their use in isolation. For example, results obtained with each feature in isolation revealed no effect on word recognition. Consequently, this would suggest that NLFC did not significantly improve access to high-frequency speech information and DNR did not

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significantly reduce speech spectrum noise (to improve word recognition) or reduce speech sounds with noise-like modulation patterns (to degrade word recognition). Taken together, these findings suggest the isolated and simultaneous use of NLFC and DNR did not positively or negatively impact word recognition in noise.

Satisfaction Ratings

The second purpose of this study was to determine if the isolated or combined use of NLFC and DNR improved listener satisfaction in noise. Satisfaction with word clarity, word comfort, and average satisfaction was significantly higher at 6-dB SNR than 1-dB SNR. In addition, listener satisfaction was significantly different between the hearing aid conditions for word clarity, word comfort, and average satisfaction. Word clarity ratings were significantly higher for DNR and combination than NLFC, word comfort ratings were significantly higher for DNR than NLFC, and average satisfaction was significantly higher for DNR and combination than for NLFC. Average satisfaction was also significantly higher for combination than baseline. These results suggested the use of NLFC in isolation significantly reduced listener satisfaction relative to the isolated use of DNR or the combined use of NLFC and DNR.

Satisfaction ratings results were consistent with previous research that suggested the isolated use of NLFC or DNR did not positively or negatively affect subjective performance when compared with the Baseline condition. For NLFC, these findings were in agreement with research evaluating adults' self-reported preference for NLFC in quiet and/or noise that indicated no significant preference for NLFC on or off (Simpson et al, 2006; Glista et al, 2009; Parsa et al, 2013; Perreau et al, 2013; Ellis and Munro, 2015; Picou et al, 2015; Miller et al, 2016). For DNR, these results were in agreement with research evaluating DNR in adults who noted no significant improvements in satisfaction with DNR activated in noise (Alcántara et al, 2003). Therefore, these results were expected and were consistent with previous comparisons.

Interestingly, the isolated use of DNR significantly improved all satisfaction ratings when compared with the isolated use of NLFC. These results were somewhat surprising given the fact neither feature was significantly different in isolation from the Baseline condition. Moreover, the combined use of NLFC and DNR significantly improved satisfaction ratings for word clarity and average satisfaction when compared with the isolated use of NFLC. It should also be noted that average satisfaction for the Combined condition was the only experimental condition that resulted in a significant difference from the Baseline condition. Given the fact the isolated use of DNR was not significantly different from the Baseline or Combined conditions on any satisfaction measure, it is reasonable to postulate that the positive effects observed during the combined use of the features were due more to DNR than to NLFC. Stated differently, it appears the positive attributes of DNR outweighed any negative effects produced by NLFC. Consequently, these findings were in agreement with previous studies suggesting

DNR improved listening comfort (Walden et al, 2000; Ricketts and Hornsby, 2005) and noise acceptance (Mueller et al, 2006; Lowery and Plyler, 2013) whereas decreasing listening effort in challenging listening environments (Desjardins and Doherty, 2014).

Previous research also suggested benefit from NLFC may be related to the degree and configuration of the hearing loss and the age of the hearing aid user. In the present study, age was not correlated with benefit from any hearing aid condition for word recognition or any of the satisfaction ratings. High-frequency hearing loss was positively correlated with benefit from the DNR and Combination conditions for average satisfaction ratings; however, high-frequency hearing loss was negatively correlated with benefit from the NLFC condition for word comfort. These results indicated that average satisfaction increased as the degree of high-frequency hearing loss increased when noise reduction was used (DNR and Combination). Results also indicated that word comfort satisfaction decreased as high-frequency hearing loss increased when NLFC was used.

It was hypothesized that the combined use of NLFC and DNR could improve listener satisfaction in noise if NLFC increased the audibility of high-frequency speech sounds whereas DNR decreased background noise. Results of the present study seem to support the DNR portion of this hypothesis. Results of the present study also highlight the importance of subjective measures when assessing hearing aid features. For example, word recognition results did not indicate a significant difference across hearing aid conditions; however, satisfaction ratings results indicated significant differences between NLFC and conditions when DNR was used. One possible explanation for this finding could be that the effects were more qualitative than quantitative. Stated differently, the hearing aid conditions used resulted in significant changes to the hearing aid output that did not impact the quantity of speech sounds identified correctly or the categorization of phonemes but did significantly alter the sound quality of the speech. Consequently, the satisfaction ratings may have been more sensitive to the effects being studied. Taken together, these findings suggest the isolated use of DNR and simultaneous use of NLFC and DNR positively impacted listener satisfaction in noise.

Limitations and Future Studies

The present study attempted to control for confounding factors noted in previous studies; however, several

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limitations should be mentioned. The present study equally weighted the word clarity and word comfort satisfaction ratings when calculating the average satisfaction rating; however, it is possible some listeners placed greater weight on word comfort over word clarity (and vice versa) when rating their satisfaction. In addition, a measure of overall preference was not included, so it remains unclear if conditions resulting in improved satisfaction were preferred by the participants. A field trial to measure performance in real-world conditions was not included; therefore, it is unclear if the findings observed would generalize beyond the laboratory setting. Lastly, all findings are limited to the hearing aids and test conditions used. As hearing aid technology evolves, the results of this study will only generalize to the specific hearing aids and features under test. For example, the form of NLFC used in the test hearing aids (SoundRecover) has been changed (SoundRecover2). Thus, it is unclear if findings reported in this study regarding NLFC will generalize to updated versions of the technology for this manufacturer.

Future research should examine the effects of combining NLFC and DNR in the pediatric population. Under distorted conditions or with degraded input, the stream of phonological information is incomplete, and it is more difficult for the receiver to match the information with stored representations from long-term memory. Postlingually deafened adults have a built mental lexicon and can process and interpret the rapid flow of information by "filling in the blanks." Children do not have a developed language lexicon to use. Consequently, degradation of a speech signal may have more of an effect on the pediatric population when listening in noise. Therefore, future research should investigate the effects of the simultaneous use NLFC and DNR on outcomes in the pediatric population.

CONCLUSIONS

The purpose of this study was to evaluate the effects of NLFC and DNR on word recognition and listener satisfaction in noise in adults. Activating NLFC or DNR in isolation or in combination did not significantly impact word recognition in noise. Activating NLFC in isolation reduced satisfaction ratings relative to the DNR or Combination conditions. These findings suggest NLFC should not be used in isolation and should be coupled with DNR for best results. Future research should include a field trial and extend the research to the pediatric population.

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APPENDIX

Pascoe's HFWL. Words in bold font were used in the present study.

1. Robe
2. Grime
3. **Sift**
4. Mime
5. **Thick**
6. Hope
7. Nine
8. Poke
9. **Ship**
10. Grind
11. **Sis**
12. **Hick**
13. Row
14. Rhyme
15. **Sipped**
16. Mine
17. **Oak**
18. **Hits**
19. **Sip**
20. **Coke**
21. Load
22. **Hip**
23. **Sick**
24. Pope
25. Line
26. **Oat**
27. **Chick**
28. **Pit**
29. **Skit**
30. Lime
31. Coat
32. Wine
33. Road
34. **Soap**
35. Boat
36. **Hit**
37. **Sit**
38. **Soak**
39. Rhine
40. Goat
41. Low
42. **Chip**
43. **Pip**
44. **Hiss**
45. **Skip**
46. **Tip**
47. Goad
48. Folk
49. Wrote
50. Rope

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