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Aided Loudness Growth and Satisfaction with Everyday Loudness Perception in Compression Hearing Aid Users

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Abstract

The primary goal of this study was to examine the relationship between listeners' loudness growth and their satisfaction with loudness when wearing wide-dynamic-range compression (WDRC) hearing aids. An absolute-magnitude-estimate procedure was used to obtain listeners' unaided and aided loudness growth functions in response to a 500 and 2000 Hz warble tone. In general, listeners' unaided loudness growth functions were steeper than the average normal-hearing listeners' functions for both frequencies, and their aided loudness growth functions were shallower than their unaided functions. Loudness growth functions tended to be undercompressed for 500 Hz but overcompressed for 2000 Hz. The Profile of Aided Loudness (PAL) questionnaire was administered to determine listeners' loudness satisfaction in everyday listening situations. Most listeners were satisfied with their perception of soft, average, and loud environmental sounds, regardless of how well or not well their WDRC aids normalized their aided loudness growth.

Key Words: Compression, hearing aids, loudness growth, loudness satisfaction

Abbreviations: AME = absolute magnitude estimate; ANSI = American National Standards Institute; APHAB = Abbreviated Profile of Hearing Aid Benefit; LGOB = loudness growth in 1/2-octave bands; PAL = Profile of Aided Loudness; WDRC = wide-dynamic-range compression

Sumario

La meta primaria de este estudio fue examinar la relación entre el crecimiento de la apreciación subjetiva de la intensidad (sonoridad) en el oyente y su satisfacción con dicha sonoridad ante el uso de auxiliares auditivos con compresión de rango dinámico amplio (WDRC). Se utilizó un procedimiento de estimación absoluta de la magnitud para obtener en los sujetos las funciones de crecimiento de la sonoridad, con amplificación y sin ella, en respuesta a tonos modulados de 500 y 2000 Hz. En general, las funciones de crecimiento en la sonoridad sin amplificación mostraron una pendiente más pronunciada que dichas funciones para normo-oyentes, en ambas frecuencias, y en las mismas funciones con amplificación, las pendientes fueron menos profundas, que en aquellas sin amplificación. Las funciones de sonoridad tendieron a estar sub-comprimidas en 500 Hz pero sobre-comprimidas en 2000Hz. Se administró el cuestionario del Perfil de Sonoridad con Amplificación (PAL) para determinar la satisfacción del oyente a este incremento subjetivo de la intensidad en

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situaciones auditivas cotidianas. La mayor parte de los sujetos estuvieron satisfechos con su percepción de sonidos ambientales suaves, promedio y fuertes, independientemente de cuán bien sus auxiliares auditivos con WDRC normalizaran este crecimiento en la sonoridad.

Palabras Clave: Compresión, auxiliares auditivos, crecimiento de la apreciación subjetiva de la intensidad (sonoridad), satisfacción en cuanto a la sonoridad

Abreviaturas: AME = estimado absoluto de magnitud; ANSI = Instituto Americano Nacional de Estándares; APHAB = Perfil Abreviado de Beneficio de los Auxiliares Auditivos; LGOB = Crecimiento de la sonoridad en bandas de media octava; PAL = Perfil de Sonoridad con Amplificación; WDRC = compresión de rango dinámico amplio

Listeners with hearing loss of cochlear origin usually demonstrate some degree of loudness recruitment (Fowler, 1936). "Loudness recruitment" refers to loudness perception that grows faster than normal beyond a listener's elevated hearing threshold (e.g., Margolis, 1985; Allen et al, 1990; Neely and Allen, 1997; Hellman, 1999; Oxenham and Bacon, 2003; Moore, 2004). One purpose of nonlinear amplification, including wide-dynamic-range compression (WDRC), is to compensate for loudness recruitment by providing less gain for high-level inputs and more gain for low-level inputs (e.g., Byrne, 1996; Dillon, 1996; Kuk, 1996). Consequently, hearing aid fitting algorithms have been suggested based on average loudness growth functions for low-, mid-, and high-input levels (e.g., Killion and Fikret-Pasa, 1993; Ricketts, 1996; Valente and Van Vliet, 1997).

However, little evidence has been found indicating that loudness normalization increases satisfaction in hearing aid users (e.g., Byrne, 1996; Dillon, 1996; Kuk, 1996). In cases of severe recruitment, high compression ratios would be needed to normalize loudness growth, but such ratios could be detrimental to speech perception (e.g., Moore et al, 1992; Neuman et al, 1994; Plomp, 1994; Van Tasell and Trine, 1996; Verschuure et al, 1996). Therefore, the question is raised: Is loudness normalization necessary for listeners to be satisfied with aided loudness (Byrne, 1996)?

The purpose of the present study was to address this question by examining the relationship between listeners' loudness growth functions and their performance on the Profile of Aided Loudness (PAL) questionnaire (Palmer et al, 1999). One unique aspect of this study was to test listeners with their own hearing aids in the "as is" condition, because it is of interest for clinicians to understand how the average listener is perceiving loudness in everyday listening when wearing hearing aids that may have been modified over time. If inadequately normalized loudness growth was correlated with low satisfaction on the PAL questionnaire, we would conclude that accurate loudness normalization is important for a listener wearing a compression hearing aid. In contrast, a low correlation would suggest that loudness normalization does not play a crucial role in aided loudness satisfaction.

The primary methods used to obtain loudness growth functions include categorical measures (e.g., Allen et al, 1990; Jenstad et al, 2000), absolute magnitude estimate (AME; e.g., Collins and Gescheider, 1989; Hellman and Meiselman, 1990, 1993), and absolute magnitude production (e.g., Hellman and Meiselman, 1990, 1993). Results from categorical scales can be confounded by the range and starting point of the test stimulus (Zwislocki and Goodman, 1980) and may not be the optimal method for hearing aid fitting (Elberling, 1999). Absolute magnitude production cannot be easily performed in a typical clinic setting because it requires special test equipment. Thus, the present study employed an absolute-magnitude-estimate (AME) method to measure loudness growth.

The AME method has been widely used in listeners with normal and impaired hearing (e.g., Hellman and Zwislocki, 1968; Hellman and Meiselman, 1990, 1993; Hellman, 1994, 1999). In an AME task, the listener is asked to assign a number to the loudness of a stimulus. The results of AME may vary in listeners due to the complexity of the task and individual experience with the task (Zwislocki and Goodman, 1980); therefore, to control for these listener-specific biases, a line-length estimate task is recommended prior to the AME task (Zwislocki, 1983; Collins and Gescheider, 1989). The AME task corrected with line-length estimation has been shown to generate more accurate loudness growth functions than without (Zwislocki, 1983; Collins and Gescheider, 1989; Hellman and Meiselman, 1990, 1993).

Despite the number of studies conducted on loudness growth, relatively few studies have reported aided loudness growth functions. Jenstad et al (2000) measured a group of WDRC users' loudness growth functions using a categorical scaling technique. The hearing aids were fitted using the desired sensation level [input/output] (DSL[i/o]) fitting rationale (Cornelisse et al, 1995). The investigators found that listeners' aided loudness growth functions were more similar to those of normal-hearing listeners than their unaided functions. This finding suggests that WDRC can normalize loudness growth in listeners with hearing loss when compression is set using the DSL[i/o] algorithm.

Although loudness growth functions provide an estimate of a listener's loudness perception, they cannot directly reveal listeners' satisfaction with amplified sounds in the "real world." The PAL, a subjective outcome measure of loudness, is the only measurement currently available that is designed exclusively to assess aided loudness perception in daily life. Some outcome measures, such as the Abbreviated Profile of Hearing Aid Benefit (APHAB; Cox and Alexander, 1995), include questions on loudness in subscales, but these questions typically address a listener's perception of very loud environmental sounds (e.g., fire alarm) and do not evaluate loudness of sounds ranging more widely in level. Therefore, the PAL was used in the present study.

The PAL questionnaire consists of 12 real-world listening scenarios, which are grouped into three categories: soft, moderate, and loud. Two rating scales are used to measure the listener's loudness perception and satisfaction with loudness, respectively, for each of these 12 scenarios. This questionnaire is easy to administer and takes approximately ten minutes for the average listener to complete.

The purpose of the present study was (1) to determine how normalized listeners' aided loudness growth functions are with their WDRC hearing aids, worn at the user settings, and (2) to assess the relationship between listeners' aided loudness growth functions and the degrees of aided loudness satisfaction based on their PAL scores.

METHODS

Listeners

A total of 10 listeners with normal hearing and 12 listeners wearing WDRC hearing aids participated in this study. The normal-hearing listeners were 19 to 25 years of age and had hearing thresholds less than 20 dB HL at the octave frequencies between 250 and 8000 Hz (American National Standards Institute [ANSI], 1989). One listener's data were excluded from the analysis because this listener was unable to perform the AME task. The hearing aid users were 66 to 84 years of age and had mild-to-severe sensorineural hearing loss. Case history, middle-ear immittance, and air- and bone-conduction measures were consistent with hearing loss of cochlear origin. Table 1 lists the pure-tone hearing thresholds of the listeners with hearing loss.

Two listeners (L1 and L6) had asymmetrical hearing loss and wore one hearing aid in the ear with the worst hearing. All other listeners had symmetrical hearing loss and were fitted binaurally. The listeners in this study all wore WDRC hearing aids for at least six months and were naïve to loudness experiments. Table 2 provides a description of the specific characteristics of each listener's personal hearing aids, which were used for testing in this study. Albeit sometimes minimal, all listeners had some compression (≥1.3:1) in at least one of their personal hearing aids.

Table 1. Pure-Tone Air-Conduction Thresholds for Twelve Listeners with Hearing Impairment and Mean Soundfield Thresholds for Nine Listeners with Normal Hearing

Listener		Air-Conduction Thresholds (dB HL)								
		250 Hz	500 Hz	1000 Hz	1500 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
L1	R		40	35	45	50	65	70	75	75
L2	R	20	35	45		45	45	45	60	70
	L	20	45	55		50	45	50	60	65
L3	R	30	20	20	45	50	50	55	60	60
	L	25	25	25	50	45	55	60	65	60
L4	R	35	25	35		30	35	50	60	80
	L	25	20	25		30	35	40	50	85
L5	R	40	50	55		45	50	55	55	55
	L	40	45	60	50	45	45	55	55	60
L6	L	45	35	50		55	55	55	50	50
L7	R	30	35	50		40	45	65	80	95
	L	30	30	45		50	50	60	65	85
L8	R	45	65	65		60	60	55	60	60
	L	40	60	55		50	55	50	65	60
L9	R	15	20	35	55	70	65	65	100	110
	L	15	15	25	50	60	55	65	85	100
L10	R	30	45	40		45	60	55	60	60
	L	50	55	55		60	65	60	65	70
L11	R	45	45	50		65	55	65	75	70
	L	45	45	50		60	65	70	85	85
L12	R	30	40	40		45	50	45	60	70
	L	35	35	35		45	55	55	55	80

Throughout the AME experiment, no changes in the volume of the hearing aids were permitted. Also, no changes were made in the gain and compression parameters from the user settings. Given that the PAL was completed based on listeners' perception of loudness using their personal hearing aids in the "as is" condition, it was critical to obtain the aided loudness growth functions at the same settings.

The insertion gains for the hearing aids were obtained using the Verifit system (Audioscan, Dorchester, Ontario). Note that the purpose of this measurement was not to verify a specific target fitting but to document the in-situ gains of the hearing aids at 500 and 2000 Hz. Table 3 summarizes the insertion gains for inputs for both frequencies at 55 and 75 dB SPL, representing the soft and loud levels on the Verifit, respectively (Etymonic Design Incorporated, 2005). Data were missing for Listener L6 due to equipment problems on the day this subject was tested.

Stimuli

To obtain loudness growth functions, a GSI-16 audiometer (Grason-Stadler, Madison, Wisconsin) was used to generate a 500 and 2000 Hz warble tone. The tones were presented through a single speaker located at 0° azimuth at nine different intensity levels. The presentation levels were 4, 10, 15, 20, 30, 40, 50, 60, and 70 dB SL with regard to soundfield threshold for listeners with normal hearing and 3, 5, 8, 10, 15, 20, 25, 30, and 35 dB SL with regard to soundfield threshold for listeners with hearing impairment, in both unaided and aided listening conditions. These levels were used in previous loudness studies (Hellman and Meiselman, 1990, 1993; Hellman, 1999).

Each stimulus was presented with a duration of approximately 1 sec and with an interstimulus interval of 3–5 sec. Thus, the stimulus duration was long enough for the

Table 2. Characteristics of Listeners' Personal Hearing Aids

Listener	WDRC Model	Compression Threshold (dB HL)	Compression Ratio 500 Hz	Compression Ratio 2000 Hz	Attack Time (msec)	Release Time (msec)
L1 L2 L5 L7	Argosy Conventional WDRC	50	2.5:1 3:1 3:1 1.5:1 (R) 1:1 (L)		2	1306
L4	Argosy OnQue	40–60	1:1	1.5:1	180	400
L3 L6	Oticon DigiFocus II	50	1.2:1 (R) 1.3:1 (L) 2.1:1	1.5:1 (R) 1.6:1 (L) 1.7:1	5–20	80–640
L8	Oticon Gaia	50	1.7:1	1.6:1 (R) 1.8:1 (L)	5	640
L9	Oticon Atlas +	50	1.3:1 (R) 1.4:1 (L)	1.1:1	5	640
L10	GN ReSound Canta 250	45	1.4:1 (R) 1.5:1 (L)	2.1:1	5	70
L12	GN ReSound BZ 5	45	1.2:1 (R) 1.1:1 (L)	1.7:1	5	70
L11	Starkey Axent II*	40–50	1:1	1.1:1 (R) 1.3:1 (L)	125	300

Note: Some listeners had different compression ratios for the right (R) and left (L) hearing aids.

*Starkey Axent II hearing aids have a dual-compression system. In the stimulus range of this study, the slow-acting compression was mainly in action. Therefore, only the attack and release times of the slow-acting compression are listed.

Table 3. Insertion Gains of the Hearing Aids at 55 and 75 dB SPL, Obtained on the Audioscan Verifit System

Listener		500 Hz		2000 Hz	
		55 dB SPL	75 dB SPL	55 dB SPL	75 dB SPL
L1	R	10	7	20	15
L2	R	10	-5	22	9
	L	10	-2	23	11
L3	R	-3	-6	24	16
	L	2	-8	14	5
L4	R	4	3	22	13
	L	3	2	20	10
L5	R	10	4	19	5
	L	10	2	24	9
L6		No Data Available			
L7	R	-2	-3	7	4
	L	-16	-27	16	17
L8	R	22	14	22	16
	L	21	13	17	10
L9	R	6	1	28	33
	L	5	-1	26	26
L10	R	-4	-6	16	10
	L	7	0	17	10
L11	R	-4	-3	21	28
	L	-4	-3	16	20
L12	R	-3	-6	12	9
	L	-3	-7	12	6

listener's perception of loudness to be stable (Scharf, 1978) but not too long to cause loudness adaptation (Hellman et al, 1997). This duration also allowed for the WDRC to fully respond and stabilize. The interval time between stimuli ensured that presentation of a second stimulus would not interfere with the release of compression. The compression time constants for listeners' hearing aids are shown in Table 2.

Line-length estimates were based on seven line lengths projected onto a 1.7 m x 1.7 m white screen by a projector (Telex Caramate, Burnsville, Minnesota). The screen was set at 3.1 m from the listener and 1.83 m from the lens of the projector. A similar setup was used in the Hellman and Meiselman (1990) study. The experimenter controlled for the distance between the screen and the projector to maintain the same distance for all listeners. All participants were presented with line lengths equal to 1, 2, 3, 10, 20, 40, and 100 cm.

Procedure

Line-Length Magnitude Estimates

The line-length task was always performed before the loudness task. In the line-length task, lines of different lengths were randomly projected on the screen one at a time, and listeners were asked to assign a number to the length of each line (e.g., Collins and Gescheider, 1989). The longest and the shortest line lengths were never presented first (Zwislocki and Goodman, 1980). Listeners could use any positive numbers including decimals and fractions. They were specifically told not to estimate the physical length of the line (e.g., in inches or centimeters). Although there was no constraint on the pacing of the test, the experimenter encouraged the listeners to respond spontaneously to the stimuli.

Absolute Magnitude Estimate of Loudness

For the loudness task, listeners were placed in the sound field, and loudness growth functions were obtained at 500 and 2000 Hz. The order of presentation of the 500 and 2000 Hz conditions was randomized for all listeners. Listeners were given the same instructions as in the line-length task, but this time they were asked to assign a number to the loudness of a sound they heard instead of the length of a line. Each stimulus was randomly presented at nine different sensation levels. Listeners were presented three runs of the nine presentation levels. The first run was considered practice and not included in the final analysis. Loudness magnitude estimates were first obtained unaided and then aided in listeners with hearing impairment. The unaided ear of the two monaurally aided listeners was occluded with an earplug during all testing.

Loudness near threshold has been shown to grow faster than the rest of the dynamic range (Zwislocki, 1965; Hellman and Zwislocki, 1968; Collins and Gescheider, 1989; Moore and Glasberg, 1997; Moore, 2004). Thus, for the linear regression to best fit the loudness data, estimates of loudness at the three lowest sensation levels were excluded. As a result, only loudness data for the higher six presentation levels were analyzed in the current study. If the lower levels were included, they would have skewed the slope of the loudness growth function. This approach is consistent with other AME loudness studies that have excluded data from very low or high presentation levels (e.g., Hellman and Meiselman, 1990, 1993).

To obtain the loudness growth functions, listeners' AME data were fitted using a least-squares linear regression procedure. An example of the regression fit is provided in Figure 1. This example shows Listener L1's unaided loudness growth function using data from the six highest sensation levels. Regression fits were judged to be good as indicated by the high R^2 values for both 500 and 2000 Hz. The R^2 values for the majority of the regression fits across listeners were higher than 0.90. The slopes of these functions were obtained and then line-length magnitude estimates were used to correct the slopes in an effort to control for judgment bias (Zwislocki, 1983; Collins and Gescheider, 1989; Hellman and Meiselman, 1993). Specifically, the corrected slope (θ) of each listener's loudness growth function was calculated by dividing the slope of each listener's loudness growth function by the slope of that listener's line-length function.

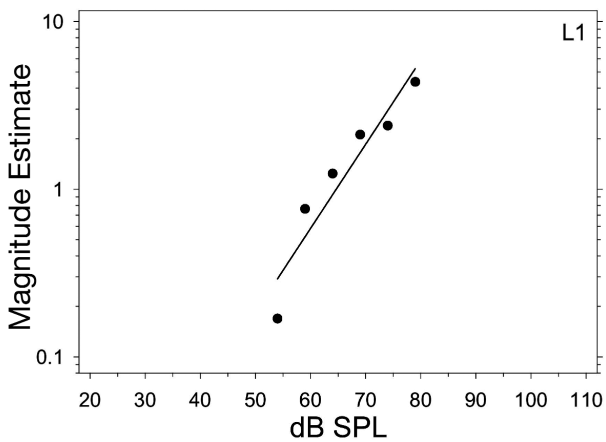

Figure 1. An example of the best-fit regression for magnitude estimate as a function of the sound pressure level of the warble tone. This example shows Listener L1's uncorrected loudness growth function at 500 Hz. The three lowest presentation levels are not included.

Profile of Aided Loudness

The PAL is comprised of two rating scales (Table 4). The loudness scale has eight levels, ranging from 0 ("do not hear") to 7 ("uncomfortably loud"). On this scale, targets for soft, average, and loud sounds are defined as 2, 4, and 6, respectively. These targets are recommended as a reference when the hearing aid needs to be clinically adjusted to optimize loudness perception. The satisfaction scale of the PAL has five levels, ranging from 5 ("just right") to 1 ("not good at all").

Both groups of listeners were given the PAL questionnaire. Listeners with normal hearing were asked to complete the loudness rating scale only. Listeners with hearing impairment were instructed to evaluate the questions in the aided condition only, because they had been consistently using amplification in everyday listening. All listeners were advised to skip any question specifying an unfamiliar environmental sound. As a result, three listeners with hearing loss skipped one question in their responses. The PAL questionnaires were scored according to the questionnaire manual (Palmer et al, 1999).

Table 4. Loudness and Satisfaction Rating Scales on the PAL

Loudness Rating	Satisfaction Rating
0 – Do not hear	5 – Just right
1 – Very soft	
2 – Soft	4 – Pretty good
3 – Comfortable, but slightly soft	
4 – Comfortable	3 – Okay
5 – Comfortable, but slightly loud	
6 – Loud, but OK	2 – Not too good
7 – Uncomfortably loud	1 – Not good at all

RESULTS

Loudness Growth Functions

The slopes of listeners' aided and unaided corrected loudness growth functions are shown in Table 5. For most listeners with hearing impairment, corrected unaided loudness growth functions were steeper than the average functions observed for listeners with normal hearing. Corrected aided loudness growth functions were generally shallower than unaided functions. In the 500 Hz condition, the decrease in the mean slope from 1.081, unaided, to 0.773, aided, was not significant (t_{11} = 1.557, p = 0.148). In the 2000 Hz condition, the decrease in the slope from 0.943, unaided, to 0.632, aided, was also not significant (t_{11} = 2.509, p = 0.064). As expected, WDRC tended to decrease the slope of the aided loudness growth functions.

Interestingly, all but two listeners (L1 and L9) had shallower aided loudness growth functions than the average normal-hearing listeners' function for 2000 Hz. Shallower functions suggest that the hearing aids were "overcompressing" the listeners' loudness growth. The opposite was observed in the 500 Hz condition, where half of the listeners' aided loudness growth functions were still steeper than the normal average. This finding implies that the hearing aids were "undercompressing" for low frequencies.

An example of under- and overcompression is illustrated in Figure 2, Plot A and B, respectively. The slopes of listeners' aided, unaided, and average normal-hearing corrected functions are recorded in the upper left corner of each figure. Note that the starting points at the lowest SPLs are intentionally overlaid for the ease of making comparisons across loudness growth functions. This plotting method has been

Table 5. Uncorrected and Corrected Slopes for Unaided, Aided, and Average Normal-Hearing Listeners' Loudness Growth Functions at 500 and 2000 Hz

Listener	Frequency	Uncorrected Slope of Loudness Function		Line Length Slope	Corrected Slope of Loudness Function	
		Unaided	Aided		Unaided	Aided
L1	500 Hz	1.721	1.160	0.791	2.176	1.466
	2000 Hz	1.313	1.190		1.660	1.504
L2	500 Hz	1.048	0.954	0.933	1.123	1.023
	2000 Hz	0.990	0.461		1.061	0.494
L3	500 Hz	0.447	0.519	0.713	0.627	0.728
	2000 Hz	0.539	0.102		0.756	0.143
L4	500 Hz	0.675	0.656	0.940	0.718	0.698
	2000 Hz	1.116	0.538		1.187	0.572
L5	500 Hz	1.491	0.455	0.438	3.404	1.039
	2000 Hz	0.856	0.260		1.954	0.594
L6	500 Hz	0.740	0.535	0.840	0.881	0.637
	2000 Hz	0.719	0.307		0.856	0.365
L7	500 Hz	0.393	0.345	0.756	0.520	0.456
	2000 Hz	0.278	0.375		0.368	0.496
L8	500 Hz	0.754	0.463	1.051	0.717	0.440
	2000 Hz	0.854	0.672		0.813	0.639
L9	500 Hz	0.663	0.687	0.551	1.203	1.247
	2000 Hz	0.360	0.814		0.653	1.477
L10	500 Hz	0.433	0.386	0.853	0.508	0.453
	2000 Hz	0.399	0.256		0.468	0.300
L11	500 Hz	0.413	0.305	0.840	0.492	0.363
	2000 Hz	0.454	0.389		0.540	0.463
L12	500 Hz	0.516	0.622	0.850	0.607	0.732
	2000 Hz	0.850	0.458		1.000	0.539
Mean NH	500 Hz	0.447		0.706	0.633	
	2000 Hz	0.508			0.720	

used in other loudness studies and is the reason why no specific SPL is labeled on the x-axis (Collins and Gescheider, 1989; Hellman and Meiselman, 1990; Hellman, 1999). In Plot A, the listener's aided loudness growth function (θ_A = 1.466) was less steep than his or her unaided function (θ_U = 2.176) but still steeper than the normal average function (θ_{NH} = 0.633), which illustrates undercompression. In Plot B, the listener's aided function (θ_A = 0.365) was less steep than both his or her unaided function (θ_U = 0.856) and the normal average function (θ_{NH} = 0.720), which illustrates overcompression.

Profile of Aided Loudness

Results from the normal-hearing listeners' performance on the PAL loudness rating scale were averaged for soft, average, and loud categories. These average ratings were 2.139 (SD = 1.098), 3.861 (SD = 1.076), and 5.806 (SD = 0.597), accordingly. These values were very close to the targets (soft: 2; average: 4; loud: 6) recommended by Palmer et al (1999).

Subjective loudness ratings from the PAL for listeners wearing WDRC hearing aids are shown in Figure 3. The recommended PAL targets are shown as cross marks in open circles. The four environmental sounds for each category of loudness (soft, average, loud) were averaged for each listener. Listeners' average ratings for loud sounds ranged from 4.75 to 6.25, close to the PAL target (6). The aided listeners' average rating (5.345) was not significantly different from the normal-hearing average (t_{19} = -0.109, p = 0.914), indicating that these listeners' aided loudness perception of loud sounds was

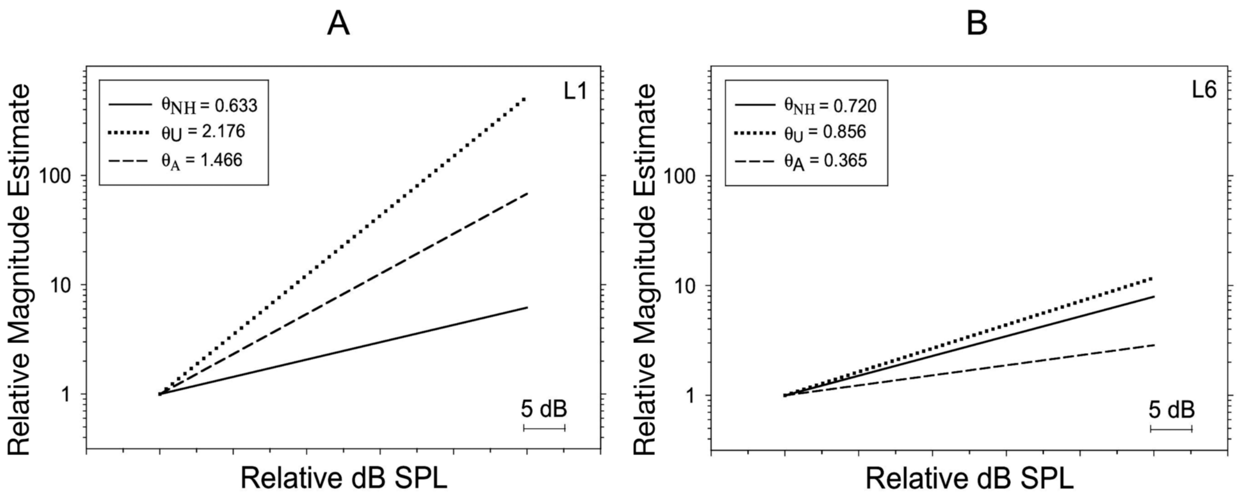

Figure 2. Examples of undercompressed *(A)* and overcompressed *(B)* aided loudness growth functions. Relative scaling of corrected loudness growth functions is used for both unaided and aided conditions at 500 Hz *(A)* and 2000 Hz *(B)*. In each panel, one listener's unaided (dotted line) and aided (dashed line) loudness growth functions are shown along with the average normal-hearing listeners' loudness function (solid line). The slope of each corrected loudness growth function is depicted by θ_{NH} (normal-hearing), θ_U (hearing-impaired, unaided), and θ_A (hearing-impaired, aided). The space between ticks on the x-axis is 5 dB SPL.

similar to normal-hearing listeners' perception. The aided listeners' average rating for average-level sounds (3.963) was close to the target (4), with the exception of two listeners (L4 and L10), who rated the average-level sounds as much higher (5.75) or lower (2.50) than the other aided listeners. However, as a group, listeners' aided loudness perception for average-level sounds was not significantly different from normal (t_{19} = 0.255, p = 0.802). All listeners rated the soft sounds higher than the PAL target (2), which suggests that soft sounds were at least audible. Similar to the other two categories, no significant difference was found between these listeners' aided perception and the normal-hearing listeners' perception of soft sounds (t_{19} = 0.740, p = 0.468).

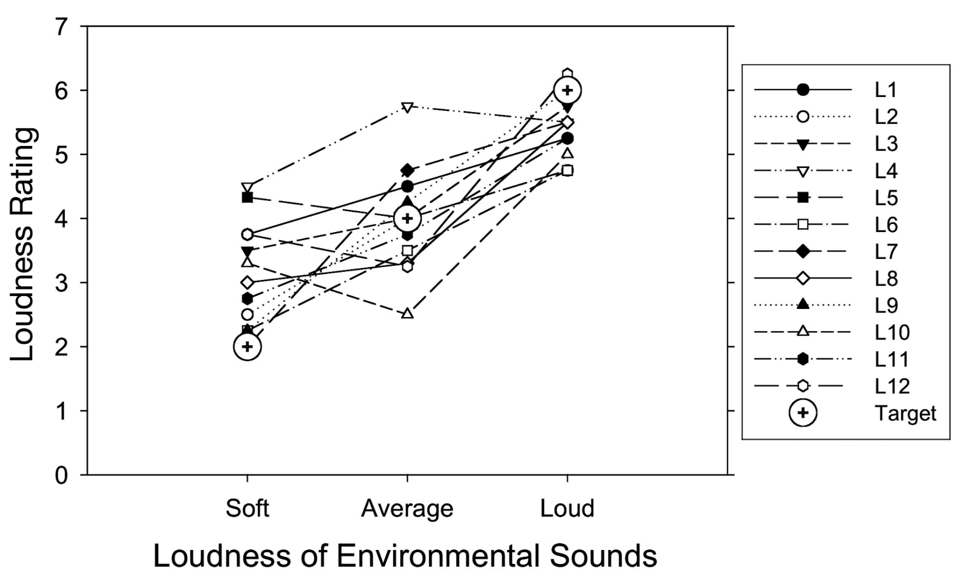

Figure 3. Individual listeners' PAL loudness ratings for soft, average, and loud sounds in everyday listening. The cross marks in open circles represent the target for aided loudness rating recommended by the PAL for soft (2), average (4), and loud (6) sounds. Other symbols represent individual listeners' ratings.

Listeners' satisfaction ratings were also averaged over the four environmental sounds for each loudness category (Figure 4). Most ratings were between 3 (i.e., "okay") and 5 (i.e., "just right"), with the exception that Listener L9's rating was below 3 for all three loudness categories. Thus, listeners were generally satisfied with their aided perception of loudness. Lower-than-okay satisfaction ratings were observed in Listeners L1 and L9, who had the steepest (most undercompressed) loudness growth functions in the group for both the 500 and 2000 Hz conditions, and for Listener L11, who had overcompressed loudness growth functions for 500 and 2000 Hz. All but one listener were satisfied with their perception of soft sounds, indicating that soft sounds were audible and comfortable for most listeners. Approximately one-third of the listeners were not satisfied with their perception of the average and loud sounds. Interestingly, most of these listeners' hearing aids had channels that were set with minimal compression (1:1–1.1:1).

Relationship between Loudness Growth Functions and PAL Satisfaction Ratings

We evaluated the relationship between listeners' loudness growth functions and their satisfaction of aided loudness by the following steps. First, we compared the slopes of the loudness growth functions to the average normal-hearing listeners' function, which provided a degree of normalization *(k)*. To compute *k,* we subtracted the slope of the average normal-hearing listeners' function from the slope of the individual's loudness function. As *k* approaches 0, the listener's loudness growth becomes more normal-like. The further the *k* value is from 0, the greater the degree of under- or overcompression (Figure 5). Undercompression ($k > 0$) was observed mainly in the 500 Hz condition, whereas overcompression ($k < 0$) occurred more frequently in the 2000 Hz condition.

Second, we took the absolute value of *k* so that under- and overcompression could be displayed together when being correlated to the PAL satisfaction ratings (Figure 6). The Spearman rank order correlation coefficient *r* between the absolute *k* value and satisfaction rating was significant for both 500 Hz (r = -0.388, p = 0.020) and 2000 Hz (r = -0.425, p = 0.010), indicating that both under- and overcompression resulted in low satisfaction of aided loudness.

Linear regression analysis of the PAL satisfaction rating as a function of the absolute *k* value was significant for both the 500 Hz ($F_{1, 34}$ = 9.657, p = 0.004) and 2000 Hz ($F_{1, 34}$ = 10.434, p = 0.003) conditions. The two

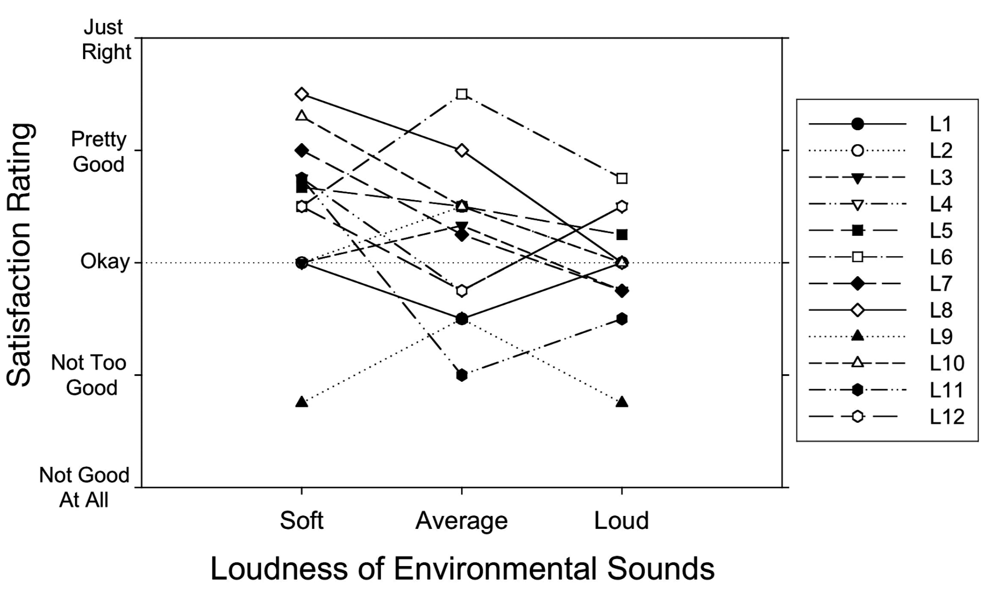

Figure 4. Individual listeners' PAL satisfaction ratings for soft, average, and loud sounds in everyday listening. The dashed line in the middle of the figure represents the rating "okay." Other symbols represent individual listeners' ratings. Ratings below the line suggest dissatisfaction with aided loudness.

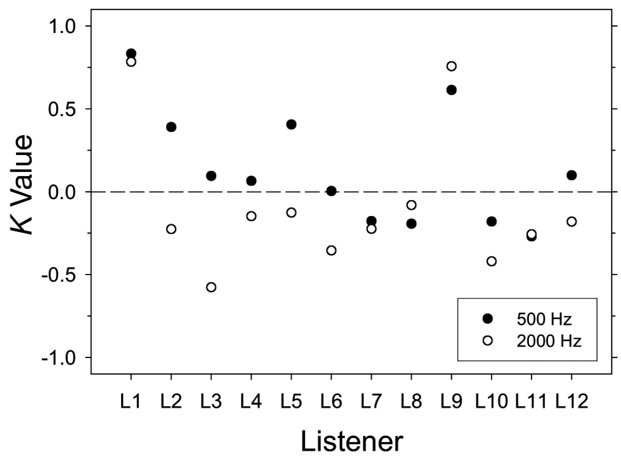

Figure 5. Degree of normalization *(k)* for 500 (filled circles) and 2000 Hz (open circles) in the AME task. The *k* value is derived from subtracting the normal average from the slope of each listener's aided loudness growth function. The dashed line in the middle of the figure represents perfect normalization ($k = 0$). Circles higher and lower than the line suggest undercompression ($k > 0$) and overcompression ($k < 0$), respectively.

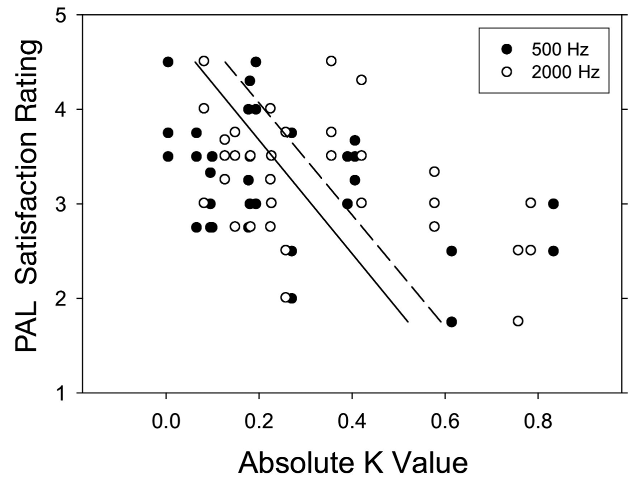

Figure 6. Correlation between the absolute values of degree of normalization *(k)* at 500 Hz (filled circles) and 2000 Hz (open circles) obtained in the AME task and listeners' satisfaction ratings on the PAL. The solid and dash lines represent the linear regression obtained for 500 and 2000 Hz, respectively.

regression lines had similar slopes, that is, -1.328 and -1.390 for the 500 and 2000 Hz conditions, respectively. These negative slopes indicate that, regardless of under- or overcompression, listeners' aided loudness satisfaction decreased as their loudness growth became less similar to the normal loudness growth ($k = 0$).

DISCUSSION

An AME task, corrected for judgment bias by magnitude estimates of line lengths, was used to measure loudness growth functions for listeners with normal and impaired hearing. For the latter group of listeners, loudness growth was tested with and without WDRC hearing aids. Normal-hearing listeners' corrected loudness growth functions were similar to those previously published (Collins and Gescheider, 1989; Hellman and Meiselman, 1990, 1993; Hellman, 1999). Specifically, Hellman and Meiselman (1990) reported the slope for normal-hearing listeners' loudness growth functions in the range of 0.40–0.70 with a mean of 0.60 for tone bursts between 500 and 4000 Hz. These values are comparable to the slopes reported for normal-hearing listeners in the present study, which were 0.633 and 0.720 for the 500 and 2000 Hz warble tone, respectively. The consistency between the studies validates the method that was used in the present study to obtain loudness growth functions.

Loudness growth functions for our listeners with impaired hearing were also consistent with those previously reported for listeners with a similar degree of hearing loss (Hellman and Meiselman, 1990, 1993; Hellman, 1999). In addition, two listeners with hearing impairment (L3 and L4) had normal hearing thresholds at 500 Hz, and their loudness growth functions for 500 Hz were similar to the average normal-hearing listeners' function. A similar finding was reported by Hellman and Meiselman (1993). However, Listener L9, who also had normal low-frequency hearing, had a steep loudness growth for 500 Hz. It is not clear why this listener had abnormal loudness growth with normal hearing in this frequency region.

As predicted, the WDRC hearing aids made listeners' aided loudness growth functions shallower than their unaided functions. However, the relationship among hearing thresholds, compression settings, and changes in the slope of loudness growth functions between the aided and unaided listening conditions was not always straightforward. For example, one listener (L8) with the greatest degree of hearing loss at 500 Hz had an unaided loudness growth function close to normal (θ_U = 0.717). His or her hearing aids were set at a compression ratio of 1.7:1, which resulted in an overcompressed aided loudness growth function (θ_A = 0.440). Another listener (L5) with similar severity of hearing loss at 500 Hz had a much steeper unaided loudness growth function (θ_U = 3.404) than normal. His or her hearing aids were set at a compression ratio of 3:1 but still resulted in an undercompressed aided loudness growth function (θ_A = 1.039). Although in both cases, compression tended to normalize listeners' loudness growth, the amount of normalization was unpredictable. Future studies should investigate aided loudness growth by systematically changing the hearing aid compression parameters.

Another factor that may have influenced the interpretation of the results is effective compression ratio, which is computed from real-ear gain measures and may not be equivalent to prescribed compression ratio. In this study, the effective compression ratios were only slightly different from the prescribed compression ratios for most of the listeners. Taking into account the listeners who had greater differences between effective and prescribed compression ratios did not change the weak relationship observed between the slope of the loudness growth functions and compression ratio settings.

An important issue to remember when interpreting the data from the present study is that the listeners were tested with their hearing aids at their user settings. It is possible that some of the hearing aids tested in this study were not fitted and/or adjusted appropriately, especially in light of the loudness-normalization results. For example, a listener with a 55 dB HL hearing loss at 2000 Hz (L3) had an unaided loudness growth function similar to that of a normal-hearing listener, suggesting that this person might need little or minimal compression from hearing aids to improve loudness perception. And in fact, this listener had an aided growth function much shallower than normal when listening through his or her hearing aids set at a compression ratio of approximately 1.5:1. Thus, the compression for this aid was likely prescribed based on "average data" for his or her degree of hearing loss but was not the optimal fit for this individual listener.

Results from the PAL satisfaction rating scale showed that only a few listeners were dissatisfied with their perception of aided loudness. Listener L9 had the lowest satisfaction rating on the PAL, and, interestingly, this listener had an aided loudness growth that was very steep compared to most listeners for both the 500 Hz (θ_A = 1.247) and 2000 Hz (θ_A = 1.477) conditions. The low satisfaction rating may be due to the fact that this listener had a severe hearing loss at 2000 Hz, but his or her hearing aid compression ratio for this frequency channel was minimal (1.1:1). Greater compression might have helped improve this listener's degree of aided loudness satisfaction.

Nonetheless, most listeners were happy with their perception of aided loudness, despite their under- or overcompressed loudness growth functions. There are several possible reasons why abnormal loudness growth functions were not strongly reflected by the PAL scores. First, we obtained loudness growth functions for only two frequencies, whereas the PAL includes environmental sounds of a broad frequency spectrum. This point is particularly relevant for users of multichannel compression aids, because loudness growth functions obtained for two frequencies may not adequately characterize a listener's overall loudness perception. Second, the AME task uses an absolute scaling technique, whereas the PAL is based on two categorical scales. A large degree of intersubject variability exists in categorical scaling measures for listeners with normal and impaired hearing (Elberling, 1999), due to the number of finite points between the endpoints (Allen et al, 1990; Hellman, 1999) and the intensity range of the signal (Ward et al, 1996). Although categorical scales have limitations, there is currently no alternative to use for an outcome measure. To develop an absolute scaling outcome measure for loudness would be interesting but is beyond the scope of the current paper. Last, the signal was more controlled in the AME task than in the real world. For example, in the AME task, signals lasted long enough to fully activate WDRC, whereas in the real world, signal length would be more variable. That is, some sounds (e.g., slamming the door) may not be long enough to fully activate and/or deactivate some compression systems.

Despite listeners' generally "okay" overall satisfaction, a relationship was observed between PAL satisfaction ratings and aided loudness growth functions. Specifically, listeners were more satisfied when their loudness growth functions were more normal-like than under- or overcompressed. The correlation between the loudness growth functions and the PAL satisfaction ratings suggests that a more normal-like loudness growth may improve a listener's satisfaction with aided loudness. Also, on the satisfaction scale, the option "just right" (the highest rating) was selected only 15% of the time across listeners, suggesting that listeners' loudness perception was less than ideal in most real-world listening situations. Thus, it may be worthwhile for clinicians to consider maximizing loudness normalization for an individual listener by using such procedures as the Loudness Growth in 1/2-Octave Band (LGOB; Allen et al, 1990) and Visual Input/Output Locator Algorithm (VIOLA; Valente and Van Vliet, 1997), which are available for clinical use. These strategies may be most helpful for listeners who have low aided loudness satisfaction, such as Listener L9 in the present study. On the other hand, some of the listeners, whose aided loudness growth functions were quite different from normal, reported "okay" for most listening scenarios on the PAL satisfaction scale. Although it would be best to obtain "just right" answers, "okay" at least suggests that the listeners are not dissatisfied with aided loudness.

In summary, a modified AME task and the PAL questionnaire were used to assess the relationship between aided loudness growth functions and aided loudness satisfaction. The loudness growth functions obtained with AME for listeners with normal and impaired hearing were consistent with those previously reported for these two populations. As expected, the WDRC hearing aids reduced the steepness of most listeners' unaided loudness growth functions. Results from the PAL showed that listeners' aided loudness satisfaction decreased as their loudness growth functions became less like those of the average normal-hearing listeners. Nonetheless, listeners' overall satisfaction with their perception of aided loudness was "okay," regardless of whether or not their hearing aids caused under- or overcompression.

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