Improving Mobile Phone Speech Recognition by Personalized Amplification: Application in People with Normal Hearing and Mild-to-Moderate Hearing Loss

Anna Chi Shan Kam,[1,2,3] John Ka Keung Sung,[3] Tan Lee,[4] Terence Ka Cheong Wong,[3] and Andrew van Hasselt[3]

Purpose: In this study, the authors evaluated the effect of personalized amplification on mobile phone speech recognition in people with and without hearing loss.

Methods: This prospective study used double-blind, within-subjects, repeated measures, controlled trials to evaluate the effectiveness of applying personalized amplification based on the hearing level captured on the mobile device. The personalized amplification settings were created using modified one-third gain targets. The participants in this study included 100 adults of age between 20 and 78 years (60 with age-adjusted normal hearing and 40 with hearing loss). The performance of the participants with personalized amplification and standard settings was compared using both subjective and speech-perception measures. Speech recognition was measured in quiet and in noise using Cantonese disyllabic words. Subjective ratings on the quality, clarity, and comfortableness of the mobile signals were measured with an 11-point visual analog scale. Subjective preferences of the settings were also obtained by a paired-comparison procedure.

Results: The personalized amplification application provided better speech recognition via the mobile phone both in quiet and in noise for people with hearing impairment (improved 8 to 10%) and people with normal hearing (improved 1 to 4%). The improvement in speech recognition was significantly better for people with hearing impairment. When the average device output level was matched, more participants preferred to have the individualized gain than not to have it.

Conclusions: The personalized amplification application has the potential to improve speech recognition for people with mild-to-moderate hearing loss, as well as people with normal hearing, in particular when listening in noisy environments.

Key words: Hearing loss, Mobile phone, Personalized amplification, Speech recognition.

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INTRODUCTION

Mobile phones are indispensable in modern daily life. According to the International Telecommunication Union, the number of global mobile-broadband plus mobile-cellular subscriptions will reach 10.3 billion by the end of 2015 (International Telecommunication Union 2015). Despite the high popularity of mobile devices, the quality and intelligibility of the speech signal in mobile communications are still far from perfect. Without the adoption of wideband speech transmission, mobile telephone signals can be affected by the same limited bandwidth as landline telephone signals (Laaksonen et al. 2009; Roup et al. 2011). Important high-frequency acoustic cues are removed by the limited telephone bandwidth (300 to 3300 Hz) thus reducing both speech quality and intelligibility (Rodman 2003). The presence of environmental noise, either at the sending or receiving end of the communication channel, also deteriorates the intelligibility of mobile telephone signals (Jokinen et al. 2012a). Together with the lack of visual cues, daily mobile telephone listening is challenging and especially so for people who have hearing loss.

Some post processing methods have been suggested to improve the intelligibility of mobile telephone signals. One approach is to implement a noise cancellation method in which the noise is estimated and subtracted from the corrupted signal (Tavares Reyes et al. 2012). Another approach is to increase the high-frequency information, such as by artificial bandwidth extension, which refers to widening of the signal bandwidth of the telephone speech at the receiving end of the transmission chain by adding new, artificially generated spectral content to the high-frequency band (4000 to 8000 Hz; Laaksonen et al. 2009) or by energy reallocation to transfer energy from the first formant to higher frequencies (Jokinen et al. 2012b). Although these studies (e.g., Jokinen et al. 2012b; Tavares Reyes et al. 2012) have provided evidence for the efficacy of some post processing methods in improving the intelligibility of mobile telephone signals in people with normal hearing, none of these methods have been tested in people with hearing impairment.

Apart from post processing, speech intelligibility of mobile phone signals may also be improved by preprocessing. Preprocessing of a telephone signal for listeners with hearing impairment has been investigated in a few studies (e.g., Terry et al. 1992). Frequency shaping of the telephone signal has been proven to be effective in enhancing intelligibility for people with mild hearing loss (Terry et al. 1992). A recent study, which applied a telephone speech-enhancement algorithm based on an average hearing profile that was compiled from 100 elderly people, showed that preprocessing of the acoustic signal was a viable method of improving speech recognition via the telephone (Roup et al. 2011). The telephone speech-enhancement algorithm, which was based on a hearing aid compression processing algorithm, was a multichannel compression algorithm aimed at preserving spectral contrast within the speech signal. The justification for the use of an average hearing profile was that the preprocessing would be done by the telephone service provider, who should have no prior knowledge of the individual's profile. This obviously limits the application of the preprocessing as each individual's hearing profile is unique, and even people with the same hearing loss may respond to the same

[1]Department of Special Education and Counselling, [2]Centre for Brain and Education, The Education University of Hong Kong, Tai Po, Hong Kong; [3]Department of Otorhinolaryngology, Head and Neck Surgery, and [4]Department of Electronic Engineering, The Chinese University of Hong Kong, Tai Po, Hong Kong.

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signal modification differently due to intersubject variability (Johnson & Dillon 2011).

The benefit of individualized amplification on cellular phone signal has been demonstrated in a study that evaluated different cellular phone speech-encoding strategies in a group of 14 elderly people with sensorineural hearing loss (Mackersie et al. 2009). At similar overall loudness levels, phoneme scores and subjective ratings were significantly higher for the individualized amplification setting, which were based on the NAL-NL1 (Byrne et al. 2001) prescription formula, than for the standard setting. As suggested by the authors, a system which combines the hearing threshold measurement and frequency response adjustment would be needed to realize practical implementation of individualized amplification of mobile phone signal for speech intelligibility enhancement (Mackersie et al. 2009).

Our research group has developed and tested a hearing test protocol delivered on a smartphone platform that we have shown to be a reliable and valid measure of an individual's unique hearing profile (Kam et al. 2012). If individuals' hearing profiles can be obtained and stored in the smartphone, personalized amplification of the mobile signal according to each individual user's hearing profile becomes possible. This study thus aimed to evaluate the effect of this personalized amplification application (PAA) on user perception of mobile phone speech signals in terms of speech intelligibility and signal quality.

MATERIALS AND METHODS

Participants

The study involved 100 adult participants, of which 60 had ages ranging from 20 to 74 (average = 47.8, SD = 16.8) years and age-adjusted normal hearing, and 40 had ages ranging from 23 to 78 (average = 56.7, SD = 9.9) years and mild-to-moderate hearing loss. Age-adjusted normal hearing levels were obtained by adding an age-correction factor and gender effect to the normal hearing levels according to the US Occupational Safety and Health Administration guide (Peterson & Cohen 1996). There were 10 men with normal hearing and 16 men with hearing loss. Demographic data on the participants are shown in Table 1. The participants with normal hearing were recruited from the surrounding community, and those with hearing loss were recruited from the audiology clinic of the Prince of Wales Hospital, Hong Kong.

Ethical Considerations

This study abided by the Declaration of Helsinki. Research ethics approval for this study was granted by the Joint Chinese University of Hong Kong – New Territories East Cluster Research Ethics Committee.

Procedures

All potential subjects first completed a routine audiological assessment in a soundproof booth at the Audiology Clinic of the Prince of Wales Hospital, where standard pure-tone audiometry and an otoscopic examination were performed. The audiometry thresholds were measured according to the procedures recommended by the British Society of Audiology (2004). Air-conduction thresholds were obtained at 250, 500, 1000, 2000, 4000, and 8000 Hz, with a GSI 61 clinical audiometer with Telephonics TDH-50 headphones. Bone-conduction thresholds at 500, 1000, 2000, and 4000 Hz were also obtained with the audiometer with a B71 bone vibrator (calibrated in accordance with ANSI S3.6-1996 [American National Standard Institute 1996]). Subjects were invited to participate in the study when all the inclusion criteria were met. Inclusion criteria for the normal group were (1) age over 18 years; (2) air-conduction thresholds at all octave frequencies tested (250 to 8000 Hz) within age-adjusted normal levels (Peterson & Cohen 1996); (3) native Cantonese-speaking; and (4) ability to understand and give informed consent. The same inclusion criteria applied to the group with hearing loss except that their air-conduction thresholds at one or more octave frequencies tested (250 to 8000 Hz) were higher than the age-adjusted normal level (Peterson & Cohen 1996). Current hearing aid users were also excluded as it was assumed that they would have more severe hearing loss and would need to wear hearing aids for telephone listening. The participants were then seen once during a 90-min session in a soundproof booth after obtaining their informed consent. This prospective study used double-blind, within-subjects, repeated measures, controlled trials to evaluate the effectiveness of PAA based on the hearing profile of the user captured on the mobile device. The participants' performance in the personalized and standard settings was compared using both subjective and speech-perception measures. All comparisons were done monaurally and the subject-preferred ear for telephone listening was selected as the test ear.

Capturing of Hearing Profile

Hearing profile of the subject was obtained via a validated computerized self-administered hearing test for mobile devices. Previous research carried out in sound booth setting found that there were no significant differences between self-administered hearing test thresholds and standard pure-tone audiometric thresholds (Kam et al. 2012). A participant's hearing profile was obtained using the validated hearing test protocol on a mobile phone (Apple iPhone 4 with iOS5) via standard earbuds which come with the basic model of an Apple iPhone. There is no standard for calibrating the output of earphones used with audio devices. The earphone was plugged into a KEMAR pinna that attached to a Zwislocki coupler. The other side of the coupler was connected to a Bruel & Kjær Sound Level Analyser (Type 2260 Investigator), which measured the output of the system via the earphone. The right and left earphone was measured separately. At each frequency tested, the signal amplitude was adjusted according to the readings from the sound level meter so as to ensure that all output levels (in 5-dB steps) measured in dB SPL were equivalent to the dB HL values set in the system when the conversions from the Zwislocki coupler to 2-cc (HA-1) SPL (Wilber et al. 1988) were applied. Six test frequencies were used (250, 500, 1000, 2000, 4000, and 8000 Hz).

Pulsed pure tones of all test frequencies were presented on the right side first. The sequence of test frequency followed that of conventional pure-tone audiometry. The subject was required to press the "–" sign if the test tones could be heard, and, when the test tones disappeared, the subject had to press the "+" sign once. By pressing the "+" or "–" sign, the test signal would be increased or decreased by 5 dB. The subject could repeat the steps as many times as they needed until the test signal could just be heard. This level of volume would be set as the threshold

TABLE 1. Participants' demographic data

	N (%)
Normal group (N = 60)	
Age range (yrs)	
20–40	20 (33.3)
41–60	20 (33.3)
>60	20 (33.3)
Sex	
Male	10 (16.7)
Female	50 (83.3)
Hearing-impaired group (N = 40)	
Age range (yrs)	
20–40	3 (7.5)
41–60	21 (52.5)
>60	16 (40.0)
Sex	
Male	16 (40.0)
Female	24 (60.0)
Average hearing level (dB HL)	
≤25	10 (25.0)
26–40	19 (47.5)
41–55	11 (27.5)

Average hearing level refers to average hearing thresholds across all tested frequencies (250 to 8000 Hz).

and be saved by the program once the subject pressed the "OK" button on the touch screen of the smartphone. Figure 1 shows the average hearing profiles of the test ears obtained in the normal hearing and hearing-impaired groups. Hearing level measured was within plus or minus 5 dB of the threshold obtained via the standard pure-tone audiometry at all tested frequencies in all of the participants.

Personalized Amplification Application

For the purpose of this article, PAA refers to frequency response shaping of the phone signals based on a modified One-Third Gain rule (Libby 1986). It has been suggested that people with mild-to-moderate hearing loss, that is, our target hearing-impaired subject group need gain more closely approximating a one-third gain rule as a target insertion gain (Libby 1986). The modifications were based on the participants' performance and feedback observed in a pilot study of a group of 20 Chinese adults who have mild-to-moderate hearing loss. Specifically, no gain is applied for hearing threshold better than or equal to 15 dB HL and more high-frequency gain (plus 3 dB at 2000 Hz and above) on top of the one-third of the hearing threshold gain is applied for preserving cues for tone identification (Yuan et al. 2009), which are crucial for speech intelligibility in tonal languages such as Cantonese.

For the purpose of this study, the PAA was written as a mobile app. Every time the app was activated, the PAA ON and PAA OFF settings would be randomly assigned as Program 1 or Program 2. Subjective and speech-perception measures were then carried out with both programs. The program number instead of the PAA setting would be displayed on the mobile screen. Both the subject and the tester had no information about the corresponding PAA setting during the test to ensure double-blinding. The tester would switch between Program 1 and 2 and adjust the device volume to the predetermined ones for each test condition, and the subjects had no control of the device. The tester was required to decode the program setting after each test had been completed.

To avoid any effect of mobile signal transmission stability and interference, speech test materials were saved in the mobile phone as audio files and played for testing. All speech test materials for both objective and subjective tests were processed by applying a low-pass filter with a cutoff frequency at 3300 Hz so as to imitate telephone quality. All of the hearing profiles were recorded as were the volume settings for each test condition. All tests were performed without using the earbuds, that is, the participants had to listen to the output signals directly from the mobile phone's speaker. The mobile phone was mounted on a tripod phone holder with the phone's speaker positioned at the ear canal opening of the subject's test ear. The subject was asked to sit still and keep the pinna touching the phone throughout the test. Medical tape was adhered on the subject's face and head to mark the handset position for monitoring purpose during the test and across test conditions.

Speech-Perception Measures

Speech-perception measures included speech recognition in quiet and in noise. Eight lists of 50 disyllabic Cantonese words were used, and the speech recognition scores both in quiet and in noise were determined in both the PAA ON and PAA OFF conditions. The test items were recorded by a female native Cantonese speaker in a sound booth with a Bruel & Kjær Type 2669 condenser microphone that was connected via an acoustic interface preamplifier to a Cool Edit Pro 2.1 software. Equalization was performed, after low-pass filtered at 4000 Hz, to ensure similar root mean square amplitude of each item. Street noise and restaurant noise were recorded, by the same set of equipment, on a typical busy street and in a Chinese restaurant during lunch time, respectively. Four 5-min continuous sound samples were recorded in each location. The four recordings, after removal of silent gaps and normalization of sound waves, were mixed to form a continuous noise. A 1-min 1000 Hz pure tone was added before the noises for calibration purpose. In the speech recognition test, the word lists were played

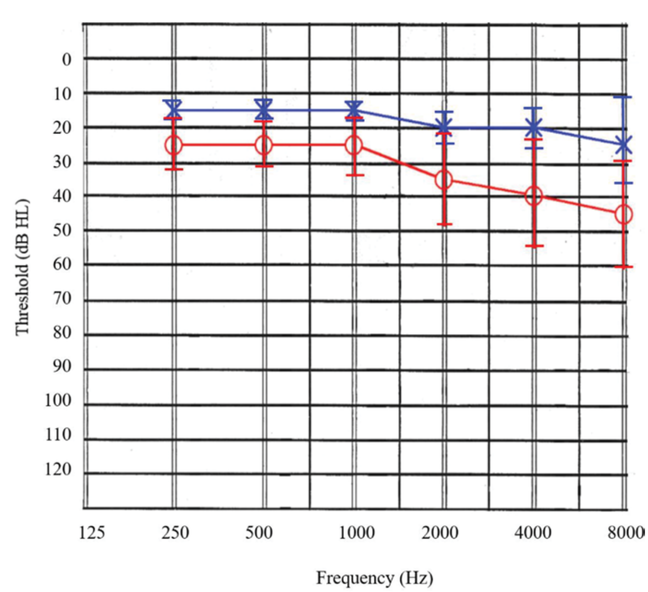

Fig. 1. Average hearing profile of the test ears of the participants with age-adjusted normal hearing (X) and hearing impairment (O) (I = ±1 SD).

randomly via the mobile phone, and the participants were asked to repeat what was heard. Words instead of sentences were used as test stimuli to increase the task difficulty. Sentences, which carry more contextual cues, can be recognized with less auditory information (Boothroyd & Nittrouer 1988) and reduce the importance of high frequencies above 3000 Hz for speech recognition (Stelmachowicz et al. 2001).

There were 3 listening conditions: (1) in quiet, (2) in street noise, and (3) in restaurant noise. In the 2 noise conditions, noise was played at 70 dB SPL in the sound field via a loudspeaker, which was located 1 m away from the participant at 0° azimuth. Before testing in quiet, the participants were asked to adjust the volume button of the mobile phone until the most comfortable loudness providing good clarity was reached both with PAA ON and PAA OFF while listening to a prerecorded news report via the phone. The volume settings were marked as VQON and VQOFF as the test volumes to be used in quiet with PAA ON and PAA OFF, respectively. The same procedures were repeated with the presentation of street noise before testing in noise. The volume settings selected were marked as VNON and VNOFF as the test volumes to be used in noise with PAA ON and PAA OFF, respectively. No further adjustment of the volume was allowed during the test.

Subjective Rating and Preference Measures

A prerecorded news report in a male voice was used for the rating of sound quality. Street noise was played at 70 dB SPL from the audiometer via a loudspeaker, which was located 1 m away from the participant at 0° azimuth for testing in noise. Subjective ratings of PAA ON and PAA OFF were measured using an 11-point scale (0 = very dissatisfied to 10 = very satisfied) under the following five conditions: "speech sound quality," "speech sound clarity in quiet," "speech sound clarity in noise," "comfort with speech perception," and "overall satisfaction with speech perception."

The same materials were used for the subjective preference measure. A paired-comparison procedure was used to obtain the participants' preferences for programs 1 or 2 (the PAA ON and PAA OFF setting had to be decoded after the test by the experimenter). The same speech material was presented in a listening condition, while the program was switched to 1 and 2 by the tester. In each listening condition, the participant was allowed to switch back and forth between presentations with program 1 and 2 as many times as was necessary before a preference decision was made. The participants and the tester were blinded to the PAA setting in use to minimize any bias. The sequence of listening conditions and the order of PAA settings being evaluated were randomized to counter any task order effect.

Device Output Level Measurement

The sound output level at each test condition was measured with the Knowles Electronics Manikin for Acoustic Research (KEMAR) in the absence of the participants for further analysis. There were four measurements (volume at VQON with PAA ON; volume at VQOFF with PAA OFF; volume at VNON with PAA ON; and volume at VNOFF with PAA OFF) for each subject. Device output level was measured with the mobile phone speaker (earpiece) placed next to the ear canal opening of the KEMAR pinna, which attached to an ear simulator (Zwislocki coupler) that has been designed to have the same impedance characteristics as the average human ear. The other side of the coupler was connected to a Bruel and Kjær Sound Level Analyzer (Type 2260 Investigator), which measured the output level of the system via the earpiece. Figure 2 shows the setup of the device output level measurement. Measurement of device sound output level (dB SPL) was taken at 7 frequencies: 250, 500, 1000, 2000, 4000, 6300, and 8000 Hz. The output equivalent continuous sound pressure level (Lleq) was also measured for comparison.

RESULTS

Speech-Perception Measures

Means and SDs of the speech recognition scores obtained under all test conditions are summarized in Table 2. A three-way mixed analysis of variance (ANOVA) with repeated measures on two within-subject factors (PAA setting and test condition) and one between-subject factor (presence of hearing loss) was performed. The "PAA setting" factor was significant ($F = 45.77$, $p < 0.01$, partial $\eta^2 = 0.32$), indicating that in general the speech recognition scores obtained with PAA ON were significantly higher. The "test condition" factor was significant ($F = 25.85$, $p < 0.01$, partial $\eta^2 = 0.21$), indicating that the subjects performed significantly different in different test conditions. Specifically, the speech scores obtained in quiet were significantly higher than those obtained in street noise ($p < 0.01$) and restaurant noise ($p < 0.01$). There were no significant differences in performances between noise types for PAA ON, and no significant differences in performances between noise types for PAA OFF. The interaction between "PAA setting" and "presence of hearing loss" was significant ($F = 10.87$, $p < 0.01$, partial $\eta^2 = 0.10$), indicating that the improvement in speech recognition scores obtained with PAA ON was significantly higher in the hearing-impaired group than in the normal group. To further investigate the significant main effect, post hoc analysis using paired-sample *t* tests was carried out and revealed that the speech recognition scores obtained with PAA ON were significantly better than with PAA OFF in the hearing-impaired group in all test conditions (df = 39, $t = -4.24$ to -3.08, $p = 0.000$ to 0.004) with Bonferroni correction applied. The speech recognition scores obtained with PAA ON were significantly better than with PAA OFF in the normal group only in street noise (df = 39, $t = -3.17$, $p = 0.002$).

Subjective Rating and Preference Measures

Subjective rating of PAA ON and PAA OFF was measured using the 11-point scale described earlier. The Wilcoxon signed-rank test revealed no significant difference in subjective rating between PAA ON and PAA OFF under all conditions measured in the normal group. Similar findings were observed in the hearing-impaired group. In a forced-choice format, the participants were required to show their preference for PAA use for the aforementioned five items. Chi-square test revealed no significant preference for either PAA ON or PAA OFF.

Device Output Level Measurement

The averages of the device's gain with PAA ON (i.e., output level with PAA ON minus output level with PAA OFF) at the seven frequencies are displayed in Figure 3 for the normal hearing group. In general, the average sound output level measured

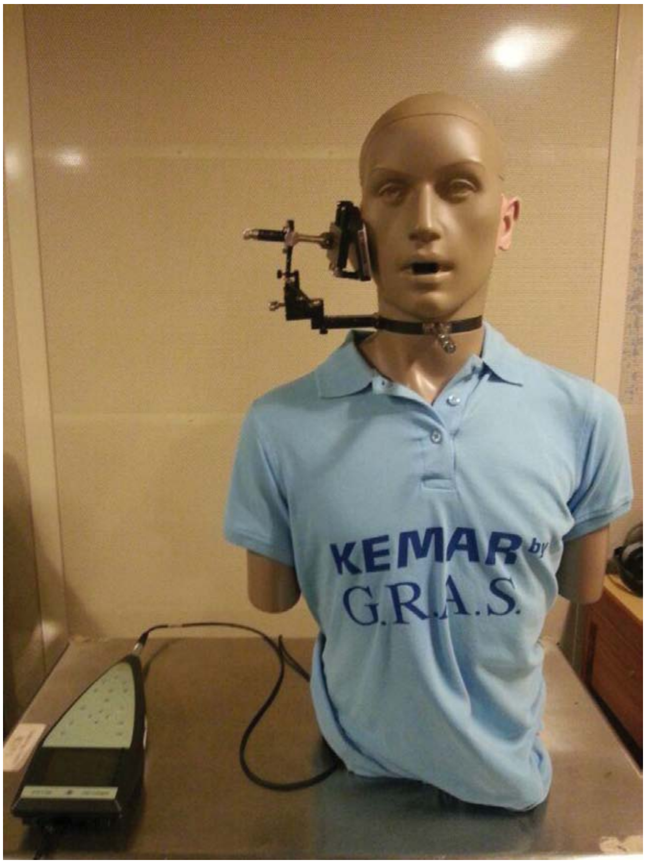

Fig. 2. Setup of the device output level measurement.

at all frequencies was higher with PAA ON than with PAA OFF both in quiet and in noise in the normal hearing group. Paired-sample t test revealed significantly higher average sound output level at all measured frequencies with PAA ON than with PAA OFF in quiet (df = 59, $t = -4.43$ to -2.24, $p < 0.05$). The average output levels at all measured frequencies except 500 Hz were significantly higher (df = 59, $t = -4.77$ to -1.69, $p < 0.05$) with PAA ON than with PAA OFF in noise. The average increase in output level was 2.1 to 3.3 dB SPL across the frequency range in quiet and 1.3 to 3.6 dB SPL across the frequency range in noise. The mean Lleq with PAA ON and PAA OFF were 80.8 and 79.2 dB SPL in quiet and 87.9 and 86.0 dB SPL in noise, respectively. The mean Lleq was significantly higher (df = 59, $t = -3.34$, $p < 0.05$) with PAA ON than with PAA OFF both in quiet and in noise.

The averages of the device's gain with PAA ON at the seven frequencies are displayed in Figure 4 for the hearing-impaired group. The average sound output level measured at all frequencies was higher with PAA ON than with PAA OFF both in quiet and in noise in the hearing-impaired group. Paired-sample t test revealed significantly higher average output level at all measured frequencies with PAA ON than with PAA OFF in both quiet and in noise (df = 39, $t = -11.91$ to -1.89, $p < 0.01$). There was more increment in output level at higher frequencies than at lower frequencies. The average increase in output level was 2.1 to 7.0 dB SPL across the frequency range in quiet and 5.0 to 9.0 dB SPL across the frequency range in noise. The mean Lleq with PAA ON and PAA OFF were 91.6 and 85.5 dB SPL in quiet and 95.7 and 88.0 dB SPL in noise, respectively. The mean Lleq was significantly higher (df = 39, $t = -13.1$ to -7.94, $p < 0.01$) with PAA ON than with PAA OFF both in quiet and in noise.

Performance Comparison With the Same Device Output Equivalent Continuous Sound Pressure Levels (Lleq)

Further analysis was carried out to determine if there would be any difference in performance when data recorded for PAA ON and PAA OFF gave the same Lleq. It is possible to have the same Lleq with PAA ON and PAA OFF as Lleq is a measure of average sound pressure level over a period of time. For example, in a case where the VQOFF with PAA OFF offered a relatively flat frequency response while VQON with PAA ON provided a frequency response with less low frequencies and more high frequencies, then the Lleq measured in these two settings may be the same. When tested in quiet, the settings of 27 (20 in the normal hearing group and 7 in the hearing-impaired group) participants were included in the analysis because the Lleq measured were equal with PAA ON and PAA OFF. The average device output levels at different frequencies are shown in Table 3. Paired-sample t test revealed that the Lleq were not significantly different between PAA ON and OFF, but the frequency-specific device output level was significantly higher with PAA ON at 4000 and 6300 Hz with Bonferroni correction applied. A two-way mixed ANOVA with repeated measures on one within-subject factor (PAA setting) and one between-subject factor (presence of hearing loss) was performed to evaluate the speech recognition scores. The "PAA setting" factor was significant ($F = 21.01$, $p = 0.000$, partial $\eta^2 = 0.46$), indicating that the speech recognition scores obtained with PAA ON were significantly greater than with PAA OFF. The interaction between "PAA setting" and "presence of hearing loss"

TABLE 2. Mean and SD of speech recognition scores in percent correct obtained in all test conditions with PAA ON and PAA OFF

		PAA Setting	
		OFF	ON
Participant Group	Test Condition	Mean (SD)	Mean (SD)
Normal	Quiet	97.86 (3.28)	98.81 (1.09)
	Street noise	91.45 (12.49)	94.79 (8.84)
	Restaurant noise	92.54 (9.35)	95.18 (5.17)
Hearing impaired	Quiet	85.15 (20.56)	91.74 (11.83)
	Street noise	73.80 (33.18)	81.18 (27.40)
	Restaurant noise	75.36 (30.94)	81.78 (28.26)

PAA, personalized amplification application.

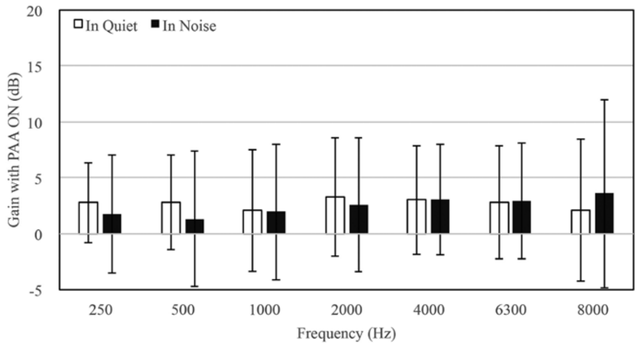

Fig. 3. Average device gain (output with PAA ON minus output with PAA OFF) measured in different test conditions for the normal hearing group. PAA indicates personalized amplification application.

was significant ($F = 15.54$, $p = 0.001$, partial $\eta^2 = 0.38$). Thus post hoc analysis using paired-sample *t* tests was carried out and revealed that the speech recognition scores were significantly higher with PAA ON than with PAA OFF in the subjects with hearing impairment (df = 6, $t = 3.25$, $p = 0.17$) with Bonferroni correction applied.

When tested in noise, the settings of 21 (all with normal hearing) participants were included in the further analysis because the Lleq were the same with PAA ON and PAA OFF. The average device output levels at different frequencies are shown in Table 4. Paired-sample *t* test revealed that the Lleq were not significantly different between PAA ON and OFF, but the frequency-specific device output level was significantly higher with PAA ON at 6300 Hz with Bonferroni correction applied. A two-way ANOVA with repeated measures on two within-subject factor (PAA setting and noise type) was performed to evaluate the speech recognition scores. The "noise type" factor and the interaction between "PAA setting" and "noise type" was insignificant. The "PAA setting" factor was significant ($F = 7.25$, $p = 0.14$, partial $\eta^2 = 0.27$), indicating that the speech recognition scores obtained with PAA ON were significantly greater than with PAA OFF.

The subjective rating of PAA ON and PAA OFF was compared within the Lleq-matched participants. Wilcoxon signed-ranks test revealed no significant difference in subjective rating between PAA ON and PAA OFF in the five measured items. In a forced-choice format, the participants were required to show their preference for PAA use for the five items. Chi-square test revealed significant preference for PAA ON in terms of speech clarity in quiet ($p < 0.05$).

DISCUSSION

The results from the study show that the PAA provided better speech recognition via the mobile phone both in quiet and in noise for people with mild-to-moderate hearing loss and people with normal hearing. One may argue that the improvement in performance with PAA ON was caused by the overall increase in device output level, which may simply achieved by adjusting the mobile phone volume control. This may be the case if the user's hearing profile is flat. However in reality, people do not usually have equal hearing sensitivity at different frequencies (Lee et al. 2012) and with increasing age, a drop in hearing levels at high frequency is expected, which is indeed what our data showed. The range of adjustment is limited to a few broad categories in mobile phone volume control and does not allow appropriate frequency shaping for people with hearing loss (Mackersie et al. 2009). With PAA applied, the device output level is increased in an algorithmic proportion according to the hearing profile captured. Proportional compensation is then provided for people with different degrees of hearing loss at different frequencies. Because most of the participants in the study (from either the hearing-impaired or normal hearing group) have poorer hearing at high frequencies, there is a larger increment in the device output level predictably observed at high frequencies. The enhancement provided at high frequencies is especially useful for listening in noise (Turner & Henry 2002; Plyler & Fleck 2006).

When people find the mobile signal too soft, they will increase the device volume. This works in quiet listening situations, but in noisy environments, the signal may not be audible even at the maximum volume of the device, and there is a possible risk of noise exposure from the device. This risk may be reduced with PAA as shown in the further analysis of the device output sound pressure level. When measured at the same Lleq, there was a significantly higher sound pressure level only at the high frequencies with PAA ON rather than with PAA OFF. This resulted in significantly better speech recognition in noise. This means that while being exposed to the same sound pressure levels (Lleq), the participants could hear better in noise with PAA ON. In general, when the average device output level was matched, more participants preferred to have PAA ON than PAA OFF in a forced-choice manner. Thus, the application of PAA has not degraded the sound quality or comfort of the signal but has enhanced the speech clarity.

Previous research (Byrne 1996) has shown that frequency shaping based on NAL-R (Byrne & Cotton 1988) enhanced speech intelligibility compared with a flatter frequency response offered by increasing overall volume. A recent study (Mackersie et al. 2009) also showed that individualized amplification implemented in simulated telephone signals improved speech recognition in subjects with hearing impairment. However, for practical implementation, there should be a convenient way to measure an individual's hearing levels and apply the individualized frequency response shaping accordingly. The present study investigated the feasibility and effectiveness to do both in the form of a mobile app. The findings suggest that it is feasible to measure an individual's hearing levels and applied personalized

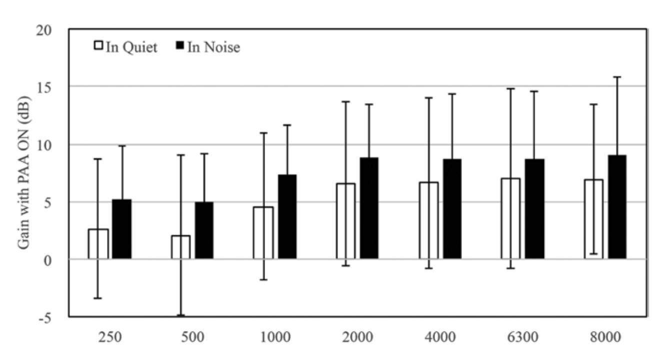

Fig. 4. Average device gain (output with PAA ON minus output with PAA OFF) measured in different test conditions for the hearing-impaired group. PAA indicates personalized amplification application.

TABLE 3. Paired-sample *t* test results for device output measured at different frequencies with PAA OFF and PAA ON in quiet with the same device output equivalent continuous sound pressure levels (Lleq) (N = 27)

			Device Output Level (dB SPL) (Mean)						
			Frequency (Hz)						
PAA Setting	Device Volume (Mean)	Lleq	250	500	1000	2000	4000	6300	8000
OFF	8.52	79.09	64.11	67.09	63.89	74.93	65.03	61.11	62.14
ON	7.26	79.48	63.18	66.31	64.70	76.71	67.22	64.12	64.40
t	3.29*	−2.01	1.66	1.33	−1.05	−2.19*	−2.43†	−3.11†	−1.66

**p* < 0.05.
†*p* < 0.01.
PAA, personalized amplification application.

amplification instantly to enhance speech recognition. As shown by the ANOVA results, the improvement in speech recognition was significant for both people with and without hearing loss, while the hearing-impaired subjects gained more benefit with PAA.

According to the National Institute on Deafness and Other Communication Disorders of the U.S., 36 million Americans (17% of the adult population) have a hearing loss (National Institute on Deafness and Other Communication Disorders 2010). Only 20% of these people actually seek help, and most tend to delay treatment until their communication is severely affected. Some individuals may take 10 years to recognize that they have a hearing problem (Davis et al. 2007). Being unaided, and with the absence of visual cues and probably the presence of background noise, these people may encounter problems while listening to a mobile phone. With the ever increasing popularity, connectivity, community penetration, and diverse functions provided by mobile devices, assistance should be provided to this disadvantaged community. The results from this study suggested that the PAA may be a possible solution.

Our study showed that PAA could improve speech intelligibility but not sound quality of the speech signals as judged by the subjects. This could be due to a number of factors, including the use of a simple sound quality measure, which may not be sensitive enough, in this study. Another possible reason is that our tested algorithm provides more high-frequency gain and less low-frequency gain, while the listeners may prefer more low-frequency gain. Similar findings have been observed in a study on judgments of aided speech quality with different low-frequency responses programmed in a linear hearing aid (Punch & Beck 1980). In that study, subjects preferred more low-frequency gain while more high-frequency gain provided better speech intelligibility (Punch & Beck 1980). Previous research has also shown that listeners did not necessarily prefer a frequency response that provides better speech intelligibility (Souza 2002) and there may be little correspondence between intelligibility measures and sound quality measures (Gabrielsson at el. 1988). Further studies of the interaction between speech intelligibility and sound quality judgements with different algorithms and measurement tools are needed.

Most of the participants in this study had normal or mild hearing loss. The application of PAA in a population with more severe hearing loss needs to be evaluated. It is important to note that the present study only examined one signal modification algorithm, a modified one-third gain rule, which is believed to be more suitable for prescribing gain for mild hearing loss. It is possible that other algorithms may yield better speech intelligibility, especially for greater hearing losses. Hence, comparison for different algorithms should be performed. As PAA manipulates the output level of the mobile device, some output limiting should be prescribed to safeguard the users as in the case of hearing aid fitting. Output limiting features should be explored and investigated in future research. In this study, speech recognition was measured with prerecorded speech material only. Future evaluation of the performance of PAA on real-time mobile phone signals is warranted. Possible areas of concern may include processing delay and discourse intelligibility.

This study only applies to Cantonese which may limit the generalization of the findings. Cantonese is one of the world's many tonal languages that use pitch variations to distinguish one word from another (Bauer & Benedict 1997). Tone changes correspond to variations in fundamental frequencies (F0) which

TABLE 4. Paired-sample *t* test results for device output measured at different frequencies with PAA OFF and PAA ON in noise with the same device output equivalent continuous sound pressure levels (Lleq) (N = 21)

			Device Output Level (dB SPL) (Mean)						
			Frequency (Hz)						
	Device Volume (Mean)	Lleq	250	500	1000	2000	4000	6300	8000
OFF	15.00	85.88	71.91	75.67	74.06	84.91	75.90	70.86	69.36
ON	13.76	86.31	71.17	75.16	72.89	85.76	78.43	73.89	72.06
t	3.53*	−1.35	1.06	0.67	1.83	−1.20	−2.40*	−2.74†	−1.65

**p* < 0.05.
†*p* < 0.01.
PAA, personalized amplification application.

are typically below 300 Hz (Gandour 1981), and these low-frequency cues would help speech recognition in Cantonese. It would be interesting to see how PAA affects speech recognition in non tonal languages in which such low-frequency cues are unavailable.

CONCLUSION

PAA has the potential to benefit people with mild-to-moderate hearing loss and people with normal hearing, especially when listening to mobile phones in noisy environments.

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All authors contributed equally to this study.

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Address for correspondence: Anna Chi Shan Kam, Department of Special Education and Counselling, The Education University of Hong Kong, 10 Lo Ping Road, Tai Po, N.T., Hong Kong. E-mail: annakam@eduhk.hk

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