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Original Article

Variations in voice level and fundamental frequency with changing background noise level and talker-to-listener distance while wearing hearing protectors: A pilot study

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Abstract

Objective: Speech production in noise with varying talker-to-listener distance has been well studied for the open ear condition. However, occluding the ear canal can affect the auditory feedback and cause deviations from the models presented for the open-ear condition. Communication is a main concern for people wearing hearing protection devices (HPD). Although practical, radio communication is cumbersome, as it does not distinguish designated receivers. A smarter radio communication protocol must be developed to alleviate this problem. Thus, it is necessary to model speech production in noise while wearing HPDs. Such a model opens the door to radio communication systems that distinguish receivers and offer more efficient communication between persons wearing HPDs. *Design*: This paper presents the results of a pilot study aimed to investigate the effects of occluding the ear on changes in voice level and fundamental frequency in noise and with varying talker-to-listener distance. *Study sample*: Twelve participants with a mean age of 28 participated in this study. *Results*: Compared to existing data, results show a trend similar to the open ear condition with the exception of the occluded quiet condition. *Conclusions*: This implies that a model can be developed to better understand speech production for the occluded ear.

Key Words: Speech Production, Hearing Protection, Lombard Effect, Vocal Effort, Talker-to-listener distance

Introduction

Finding the balance between good hearing protection and communication in noisy environments has been a difficult task. It is no question that workers in noisy environments must be protected to avoid noise induced hearing loss (Berger, 2003). However, communication remains a major concern for those equipped with hearing protection devices (HPD) (National Institute of Occupational Safety and Health, 2005). Understanding the changes in speech production by talkers with occluded ears in noise can provide the groundwork for better communication in noisy environments.

Using radio communication in noisy environments is a practical and affordable solution allowing communication between people with HPDs. Traditionally, one of its weaknesses lies in the lack of designating receivers: all those carrying a personal radio (e.g. walkie-talkie) are subjected to the broadcasted signal regardless of whether or not they are the intended listeners. Receiving irrelevant communication is annoying and contributes to the daily accumulated noise dose (Mazur & Voix, 2012). A new concept of a ‘radio-acoustical virtual environment’ (RAVE) is being developed (Bou Serhal et al, 2013). RAVE intends to mimic a natural acoustical environment by transmitting a radio communication signal only to people within a specific spatial range. This range is defined as the intended communication distance of the talker.

To predict the talker’s intended communication distance, speech production in the presence of noise while wearing HPDs must first be understood. Talkers with normal hearing adjust their vocal effort in the presence of noise (Junqua et al, 1999), when trying to communicate at a distance (Fux et al, 2011) and to express emotion (Schröder, 2001). These adjustments still occur when wearing HPDs, however, they are altered as a function of the effects of the HPD on the wearer’s perception of his/her own voice (Casali et al,

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Abbreviations

CIRMMT	Centre for Interdisciplinary Research in Music Media and Technology
NSERC	the Natural Sciences and Engineering Research Council of Canada
ACN	Auditory Cognitive Neuroscience
CRITIAS	Sonomax-ETS Industrial Research Chair in In-Ear Technologies (CRITIAS)
HPD	Hearing protection device
RAVE	Radio-acoustical virtual environment

1987; Tufts & Frank, 2003). The type of HPD influences the residual noise level inside the ear and the level of occlusion, which affects the perception of the wearer's own voice.

For the open ear condition, variations in the vocal effort have been well studied in the presence of noise and as a function of communication distance. Lombard speech refers to the significant changes in speech production when speech is produced in noise (Junqua et al, 1999; Zollinger & Brumm, 2011). Some of these changes include an increase in vocal level of 1–6 dB for every 10 dB of noise increase (Lane & Tranel, 1971). Shifts in fundamental frequency, F0, as well as first formant, F1, have also been observed. Studies show an increase in the fundamental frequency (Junqua, 1993; Garnier & Henrich, 2014) of anywhere between 0.6–2.5 semitones (Lu & Cooke, 2008). Summers et al. report a decrease in spectral tilt (Summers et al, 1988), while more recent studies report a shift in the spectral center of gravity (Tufts & Frank, 2003; Garnier & Henrich, 2014). Both of these findings indicate an increase in the high frequency content, which can improve speech intelligibility in noise.

In quiet conditions, in turn, talkers raise their vocal effort to reach farther distances. A doubling in the talker-to-listener distance increases the vocal level between 1.3–6 dB (Traunmüller & Eriksson, 2000; David Pelegrín-García et al, 2011; Zahorik & Kelly, 2007). A study done by Zahorik et al. (2007) showed that talkers adjust their vocal effort according to their acoustical environment as well as the communication distance (Zahorik & Kelly, 2007). The talkers' F0 as well as first formant, F1, also increase as a function of distance. As the vocal level increases, F0 increases by 5 Hz/dB while F1 increases by 3.5 Hz/dB (Liénard & Di Benedetto, 1999). The change in F0 caused by an increase in the communication distance, and thus vocal level, was determined to be unique and distinguishable from changes that occurred in Lombard speech or other factors that may raise the vocal effort (Fux et al, 2011). It is clear from previous studies that adjustments in the vocal effort as a consequence of either increase in communication distance or the presence of noise varies from talker to talker, but follows the same trend across talkers. Vocal level and changes in the talker's F0 are good indicators of increased vocal effort as a consequence of either larger communication distance or presence of background noise. It is also relevant to consider the importance and effects of auditory feedback received by a talker on speech production (Hansen & Varadarajan, 2009). On one hand, when auditory feedback is lost, talkers produce ''disorganized'' speech in noise. On the other hand, with maskers that did not affect the auditory feedback, speech intelligibility increased (Dreher & O'Neill, 1957; Ladefoged, 1972). Therefore, one's perception of one's own voice can have significant effects on changes in speech production.

Auditory feedback is received through two paths: air conduction and bone conduction (Pörschmann, 2000). Occluding the ear canal with an HPD creates a resonance of the bone-conducted vibrations originating from speech, causing talkers to hear an amplified 'boomy' version of their voice as they speak. This phenomenon is called the ''occlusion effect'' (Bernier & Voix, 2013). The occlusion effect changes the balance between the air-conduction and the bone-conduction paths, thus causing a change in speech production. A talker's perception of his/her own voice level compared to the level of noise is the driving factor in the speech production process (Tufts & Frank, 2003). Studies have shown that talkers wearing HPDs do not react to an increase in noise levels as much as talkers not wearing HPDs. Tufts et al. (2003) report that talkers wearing earplugs in noise decreased their speech level by 4–11 dB compared to their speech level in noise without HPDs. Also, overall speech level increased by only 5 dB (from 66.6 dB (SPL) to 71.9 dB (SPL)) when wearing foam HPDs, even when the noise was increased by 40 dB (Tufts & Frank, 2003). In other words, while wearing HPDs, talkers adjust their vocal effort by only 1.25 dB for every 10 dB increase in noise. In quiet, however, talkers wearing earplugs did not significantly alter their overall speech level (Navarro, 1996; Tufts & Frank, 2003) from their open-ear level, with a slight decrease of 0.6 dB. These results contradict older studies (Kryter, 1946; Casali et al, 1987) reporting that talkers increase their speech level by 4 dB while occluded in quiet. Tufts et al. (2003) attribute this contradiction to the placement of the plug in the ear and its contribution to the occlusion effect, emphasizing again the role of perception of one's own voice on speech production.

Although the effects of occluding the ear on speech production in noise have been studied, to the authors' knowledge no studies examine the effects of both background noise and changes in talker-to-listener distance. Based on the literature available, however, predictions can be made on the effects of occluding the ear while in noise for varied distances. The research hypothesis is that production changes with different distances for occluded ears should resemble those for open ears but should be smaller in magnitude.

This paper presents the results of a pilot study aimed to validate this hypothesis about the effects of occluding the ear on variations in level and F0 as a function of varied background noise and talker-to-listener distance. Conversational speech was recorded from users wearing HPDs in varying noise levels and talker-to-listener distances. Preliminary results show that variations in the vocal effort when occluded in noise follow a similar trend as the un-occluded condition. However, interesting changes are observed for the occluded quiet condition.

Method

Speech was recorded from 12 different talkers at five different distances in three different noise conditions and two quiet conditions.

Apparatus

Each participant was equipped binaurally with the intra-aural communication earpiece shown in Figure 1. This communication earpiece was chosen for several reasons:

(1) It is intra-aural, so it can be fitted into a participant's ear using different tips (roll-down foam plug, rounded flanged tips, malleable silicon wax, custom molded ear-piece) causing different levels of the occlusion effect. In this

way different tips could be used to better understand how the level of occlusion can affect speech production in noise. For the purposes of this study, foam tips (Comply™ Tx 200) were used to provide the best acoustical seal without a custom fit.

(2) It contains a microphone and miniature loudspeaker (internal receiver) inside the ear, as well as a microphone outside the ear. This allows direct assessment of how well the earpiece is worn and is further explained below.

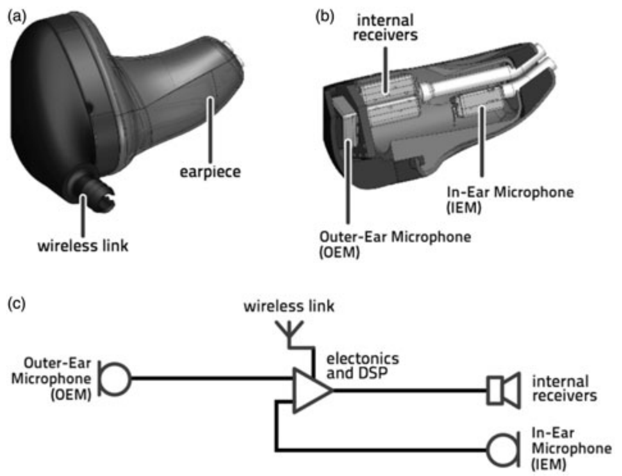

Figure 1. Intra-aural communication earpiece (a), its electroacoustical components (b), and equivalent schematic (c).

(3) It is the earpiece used for the RAVE application described in the Introduction section.

An omnidirectional studio microphone (Sennheiser® MD 211 N) was placed 0.3 m in front of each talker's mouth. The choice of a microphone placed in front of the mouth instead of a headset microphone that is fixed in front of the mouth was made to ensure that the fit of the earpiece is not altered. Although an omnidirectional microphone placed at 0.3 m from the mouth would capture some of the room acoustics, it would minimize the proximity effect and capture a more genuine speech signal. Speech was recorded using the in-ear microphones, the outer-ear microphones, and the microphone placed in front of the mouth. Recordings were made at a sampling frequency of 48 kHz using a Fireface® UCX soundcard and a Windows™ computer running MATLAB™ (MathWorks, Natick, Massachusetts, USA). Two computer loudspeakers were used to send white noise at 85 dB (SPL) to assess the acoustic seal and attenuation achieved by the earplug as well as to give talkers timing cues. The experimental set-up portraying the apparatus, the room, and the earpiece is presented in Figure 2.

Participants

For this pilot study, 12 graduate students (10 males, 2 females) were asked to participate as talkers in the study. They ranged in age from 23 to 34 with a mean age of 28. No formal audiogram was

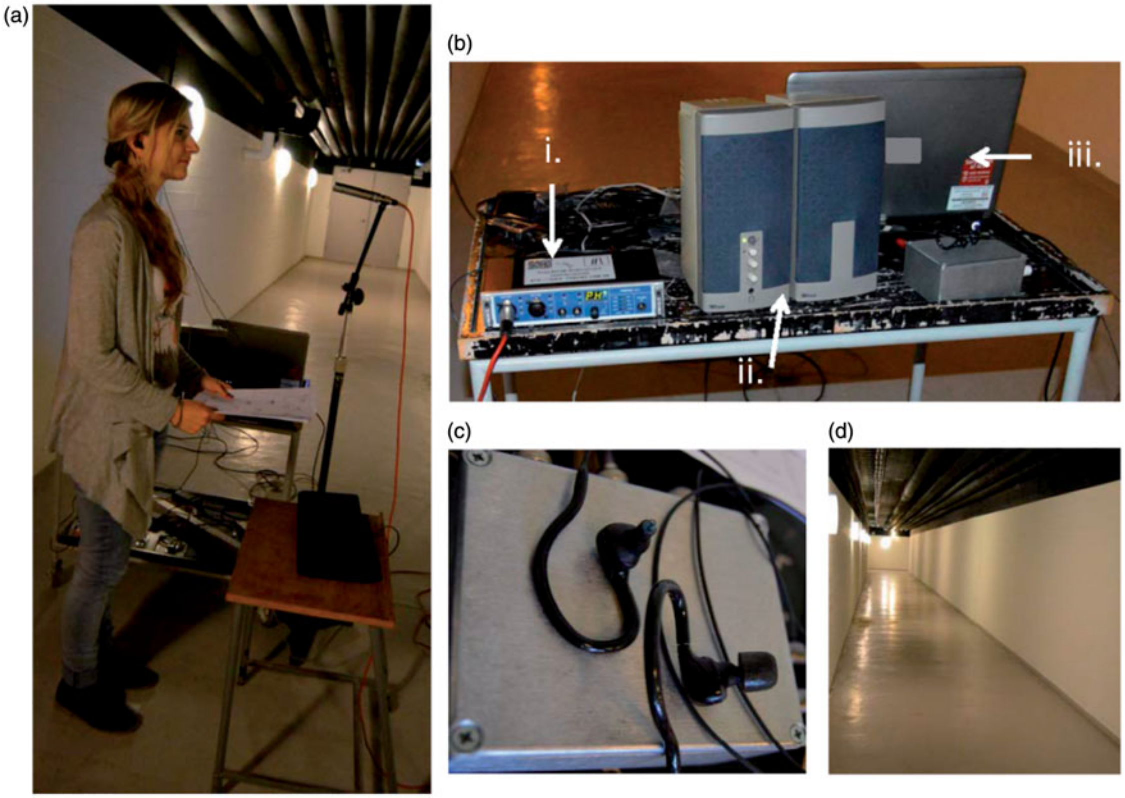

Figure 2. An example of the experimental setup with a participant (a), a close-up of the apparatus (b), including Fireface® UCX soundcard (i), the computer loudspeakers (ii), and the Windows™ computer running MATLAB™ (iii). The earpiece with and without the Comply™ tips (c), and the hallway where the experiments were held (d).

performed to measure their hearing; however, none of the participants reported any known hearing loss. One of the authors participated as the listener for all the experiments. All but one participant were involved in hearing research at the time of the study and most had basic knowledge of the Lombard effect.

Task

Each talker was given a set of geographical maps that contained landmarks, including a path that marks a start and a finish. The listener was provided the same maps with no path, but corresponding landmarks. The use of these maps has been used in the past to establish conversational speech (Anderson et al, 1991; David Pelegrín-García et al, 2011). Talkers were instructed to direct the listener from start to finish in one minute. Talkers were encouraged to use eye contact with the listener and keep a conversational flow, avoiding long pauses and maintaining continuous speech. They were asked to notice the position of the listener and speak in a manner that would be intelligible. The listener was instructed to give no auditory or visual clues of intelligibility.

Conditions

Talkers repeated the task in 25 different conditions as shown in Table 1: an un-occluded, quiet condition where talker-to-listener distance varied from 1 to 30 m (1, 5, 10, 20, and 30 m), four occluded conditions, in quiet and in three different simulated levels of noise (70, 80, 90 dB (SPL)). Factory noise from the NOISEX-92 database (Varga & Steeneken, 1993) was only played inside the ear through the internal receiver depicted in Figure 1, leaving the outer-ear microphones, as well as the microphone placed in front of the mouth, free of noise. Noise played inside the ear depended on the transfer function of each participant's earpiece. The measurement of the individual earpiece is further explained in section 2.5. The experiments were conducted in a 45-m long corridor, in a basement connecting two buildings. Talkers were positioned on a reflective surface (concrete) at a distance of 2 m from the closest wall. Even though it is believed that the room gain is considerably low, since all the experiments were conducted in the same room, with talkers at the same position, any effects from the room gain affected all conditions similarly. Furthermore, since most of the conditions were occluded and the auditory feedback restricted to bone conduction, the effect of the room acoustics was assumed to be of minor concern. Any effects on speech production caused by reverberation may be mainly attributed to the characteristics of the simulated residual noise and the visual feedback of the hallway.

Procedure

After instructions on the nature of the experiment were given, each talker was equipped with the communication headset from Figure 1.

Table 1. Experimental conditions with changing talker-to-listener distance for the quiet un-occluded ear and occluded ear in noise and in quiet.

Ear condition	*Noise (dB (SPL))*	*Distances (m)*
Un-occluded	Quiet	1, 5, 10, 20, 30
Occluded	Quiet	1, 5, 10, 20, 30
Occluded	70, 80, 90	1, 5, 10, 20, 30

After the earpiece was inserted, three main steps, explained below, were taken to ensure a well-fitted earplug and proper residual noise under the HPD. Prior to recording, the microphone in front of the mouth was adjusted and measured to be 0.3 m away from the center of the mouth. The talker was instructed not to touch the earpiece and to remain in one position at one end of the room. The listener gradually changed distances from closest (1 m) to farthest (30 m) at each condition. The choice of increasing the distance consecutively was made to mimic the experimental conditions of Pelegrín-García et al. (2011) and to be able to later compare their open-ear speech production model to the occluded-ear model (Pelegrín-García et al, 2011). Once the occluded conditions were completed, the talker was then asked to remove the earpiece and perform the quiet open-ear task.

Measurement of individual earplug transfer function

To ensure a good acoustical seal, the transfer function of the earpiece was measured for each talker. This was done by playing white noise over the loudspeakers while the talker's head is placed in front of them for two seconds and recording simultaneously using the in-ear and outer-ear microphones, and calculating the transfer function using MATLAB™.

Assessment of well-fitted earplug

A good acoustical seal was defined as a transfer function with no amplifications in the low frequencies; an example is given in Figure 3. A leakage in a closed volume behaves like a vent in an acoustical volume, acting like a Helmholtz resonator, and would show up as an amplification of the low frequencies in the transfer function (Voix & Laville, 2004). The fit was adjusted by giving more detailed direction on proper earplug insertion, followed by asking the participant to reinsert the earpiece until a good acoustical seal was reached.

Adjustment of the background noise level

If the fit was acceptable, the transfer function of the fit for each ear was recorded and stored. The transfer function of each of the participant's ears was used to calculate the residual noise in each ear for each noise condition. Prior to the experiments, 70, 80, and 90 dB (SPL) noise was recorded in an audiometric booth using the outer-

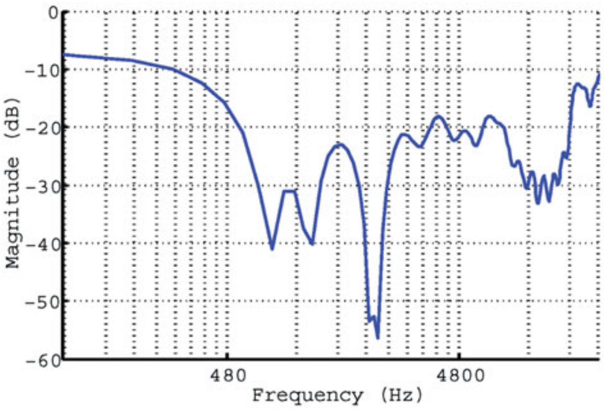

Figure 3. An example of a transfer function of a well fitted earplug.

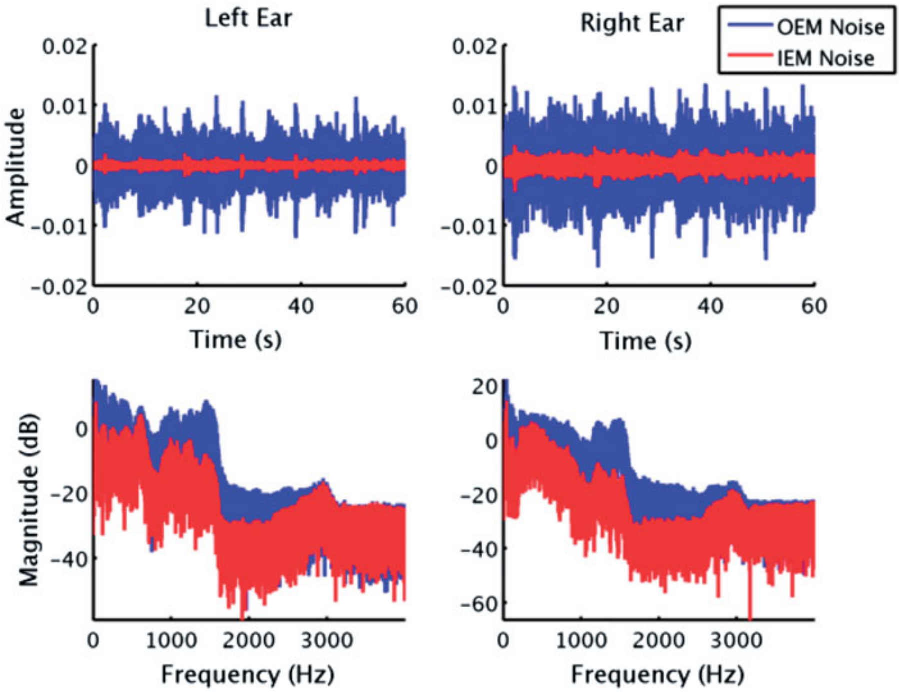

Figure 4. The spectral and temporal differences between the simulated residual noise inside the ear (IEM noise) and the noise as it would have been outside the ear (OEM noise).

Table 2. The mean (μ) and standard deviation (σ) of absolute level values across speakers for all conditions and distances in dB(A).

	Level (dB(A))				
Distance (m) Conditions	*1*	*5*	*10*	*20*	*30*
Un-occluded (Quiet)					
μ	55.93	58.04	58.86	60.45	61.85
σ	3.86	3.57	3.34	3.18	2.91
Occluded (Quiet)					
μ	63.06	65.65	66.99	68.86	70.36
σ	3.69	3.53	3.62	3.13	3.19
Occluded (70 dB (SPL))					
μ	65.79	67.33	68.17	69.41	70.23
σ	3.38	2.71	2.77	2.66	2.81
Occluded (80 dB (SPL)))					
μ	66.20	67.99	69.35	70.45	71.86
σ	3.39	2.48	2.62	2.41	2.40
Occluded (90 dB (SPL))					
μ	68.43	70.11	71.27	72.36	73.69
σ	3.40	2.43	3.03	2.62	2.66

Table 3. The mean (μ) and standard deviation (σ) absolute F0 values (in Hz) across speakers for all conditions and distances.

	F0 (Hz)				
Distance (m) Conditions	*1*	*5*	*10*	*20*	*30*
Un-occluded (Quiet)					
μ	136.72	136.03	137.75	141.79	146.41
σ	25.80	26.74	28.69	28.93	28.46
Occluded (Quiet)					
μ	136.94	139.07	142.41	146.42	152.89
σ	26.60	30.28	29.71	30.32	32.56
Occluded (70 dB (SPL))					
μ	140.94	142.29	144.45	148.53	153.49
σ	31.15	30.70	34.73	32.74	33.38
Occluded (80 dB (SPL))					
μ	139.68	144.65	149.28	153.78	158.60
σ	28.77	31.79	33.92	35.06	34.00
Occluded (90 dB (SPL))					
μ	146.61	149.95	156.41	162.72	169.34
σ	31.08	33.47	32.47	36.04	34.69

ear microphones equipped by one of the authors. For each talker and for each ear, the three levels of noise were then passed through the individual's earplug transfer function before they were played directly inside the respective ear canal using the internal receivers, simulating the residual noise. A randomly selected example of the simulated noise in each ear showing the spectral and temporal differences from the OEM noise and the binaural differences as a function of each earplug's transfer function is shown in Figure 4.

Analysis

All speech recordings were run through an A-weighted filter. A-weighted SPL value was chosen over an overall SPL value, to better match the analysis bandwidth to the speech communication bandwidth and to apply less weight to any extraneous low-frequency parasitic noise that could have been picked up by the microphones, given the ambient background noise (HVAC). While some of the energy present in the voice at F0 frequencies, may be affected by the roll-off of the A-weighting filter and while this effect may be slightly changed as F0s shift towards higher

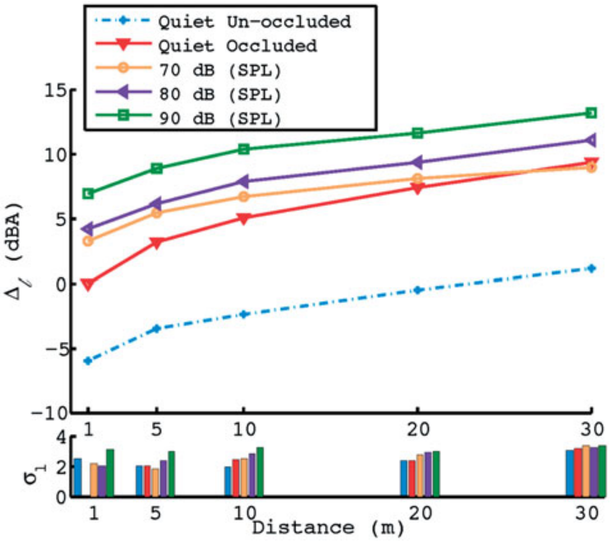

Figure 5. Average increase in speech level, Δl from the occluded quiet condition over increasing distance and noise levels. The level at 1 m distance for the quiet occluded condition is used as reference for all the curves. The variance, σl, in Δl across talkers over different noise conditions and distance.

Table 4. Overall change in linear level from 1 to 30 m for different noise conditions.

Condition	*Overall change (dBA)*
Un-occluded quiet	7.5
Occluded Quiet	9.3
70 dB (SPL)	5.7
80 dB (SPL)	6.9
90 dB (SPL)	6.23

Table 5. Overall change in F0 as well as the overall rate of change of F0 per dB increase for each condition.

Condition	*Overall change (cents)*	*Rate (cents/dB)*
Un-occluded quiet	81.1	10.8
Occluded Quiet	128.9	13.9
70 dB (SPL)	102.2	17.9
80 dB (SPL)	150.1	21.8
90 dB (SPL)	173.2	27.8

frequencies, equivalent patterns were also observed with overall unweighted sound pressure levels. For these reasons, and for convenience, the RMS value of the A-weighted signal was then calculated throughout the whole analysis. The fundamental frequency, F0, was extracted using the speech processing toolbox, (Brookes 1997).

Results

Excluding the quiet occluded condition, the changes in vocal level and F0 were as expected: as the noise level and distance increased, so did the speech level and the fundamental frequency, F0. The average speech level and F0 for all conditions across speakers are presented in Table 2 and Table 3, respectively.

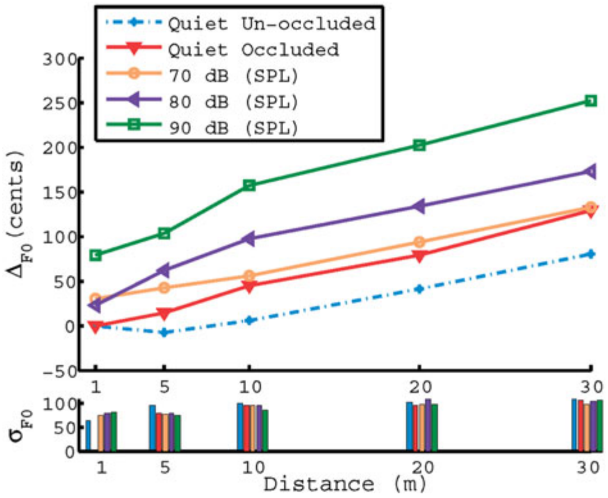

Figure 6. Average increase in F0 level, $\triangle_{F0}$, from the occluded quiet condition over increasing distance and noise levels. F0 at 1 m distance for the quiet occluded condition is used as reference for all the curves. The variance, σ_{F0}, in $\triangle_{F0}$ across talkers over different noise conditions and increasing distance.

Since the occluded quiet condition would be used as a baseline for applications such as RAVE, changes in the speech level and F0 were thus normalized to the occluded quiet condition. The trend in vocal level changes, as well as the standard deviation across talkers, as the distance and noise increase are presented in Figure 5. Contradictory to the findings of Tufts et al. (2003) and Navarro (1996) a decrease of 6 dB in level is observed in the un-occluded quiet condition compared to the occluded quiet condition. It is also interesting to note that as the distance increased, particularly from 20 to 30 m, talkers adjusted more in the occluded quiet condition than in the 70 dB noise condition. On average, for every 10 dB (SPL) increase in noise, the voice level increased by 1.8 dBA. A maximum standard deviation of 3.4 dBA is observed for the 90 dB (SPL) noise condition at the farthest distance of 30 m. Table 4 shows the overall change in the level from 1 to 30 m for different noise conditions. Using Greenhouse-Geisser correction, a significant main effect was found for both noise condition ($F(2.38,44) = 223.127$, $\varrho < 0.001$) and distance ($F(1.28,44) = 87.902$, $\varrho < 0.001$), as well as a significant interaction ($F(16,176) = 4.519$, $\varrho < 0.001$). Multiple pairwise t-test comparisons with Bonferroni correction confirmed that all noise conditions and distances were significantly different from each other (all $\varrho < 0.03$). Two follow-up repeated measures ANOVAs were conducted. In the first, only the data from the two quiet conditions were examined. Again, the main effects of condition ($F(1,11) = 192.297$, $\varrho < 0.001$) and distance ($F(1.67,44) = 97.758$, $\varrho < 0.001$), as well as the interaction ($F(1.69,44) = 3.920$, $\varrho < 0.05$) were all significant. In the second, only the data from the three simulated noise conditions were examined. While the main effects of noise condition ($F(1.22,44) = 67.091$, $\varrho < 0.001$) and distance ($F(1.39,22) = 81.841$, $\varrho < 0.001$) were significant, the interaction was not ($F(8,88) = 1.245$, $\varrho = 0.28$).

Many studies have shown that, when un-occluded, a talker's F0 increases as the vocal level increases (Titze & Sundberg, 1992; Sundberg & Nordenberg, 2006; Garnier & Henrich, 2014). Figure 5 shows the average changes in F0, as well as the standard deviation across talkers, as talker-to-listener distance increases for the varying noise conditions. As can be seen, F0 increases at the onset of noise and as the distance increases. However, at 1 m, changes in F0 between the quiet, 70 dB (SPL), and 80 dB (SPL) are relatively small; a maximum of 30.3 cents (note 100 cents = 1 semitone) is observed between the quiet occluded and the 70-dB noise condition. At 90 dB of noise, on average, F0 increased by 79 cents at the 1-m position. Again, the largest variability is observed at the 90-dB (SPL) noise condition at the farthest distance of 30 m. Table 5 shows the overall change in F0 from the closest to the farthest position for each noise condition as well as the rate of change in F0 with the increase in level. A maximum overall change in F0 of 173 cents is observed for the 90 dB (SPL) condition. Using Greenhouse-Geisser correction, a significant main effect was found for both noise condition ($F(4,44) = 48.041$, $\varrho < 0.001$) and distance ($F(1.70,44) = 39.990$, $\varrho < 0.001$) as well as a significant interaction ($F(16,176) = 2.413$, $\varrho = 0.003$). Multiple pairwise t-test comparisons with Bonferroni correction confirmed that, with the exception of unoccluded quiet vs. occluded quiet and occluded quiet vs. 70 dB, all conditions were significantly different from each other (all $\varrho < 0.02$). Similarly, with the exception of 1 vs. 10 m and 1 vs. 5 m, all distances were significantly different from each other (all $\varrho < 0.03$).

Discussion

It is clear that the trend of increased vocal level and fundamental frequency as distance and noise increase is still present when wearing HPDs. Similarly to Tufts et al. (2003) who found an average of 1.25 dBA increase in level for every 10-dB increase of noise when occluded, this study showed a 1.8-dBA increase. However, in contrast to Tufts et al. (2003) and Navarro (1996), in this study, speech level decreased in the un-occluded condition in quiet with a talker-to-listener distance of 1 m. One explanation for this is that the open-ear condition was the last one to be performed and occurred immediately after the 90-dB (SPL) occluded condition. The drastic change between the two feedback conditions could have caused the talkers to dramatically decrease their vocal level from a natural level. Another explanation could be the room acoustics of the hallway. Since the un-occluded condition was the only condition where the room acoustics could affect speech production the small changes in level as the distance increased and the overall decrease in level could be attributed to the effects of the room on the talker's perception of his/her own voice (Pelegrín-García et al, 2011). The elevated rate of change in the level as the distance increased for the occluded quiet condition is unclear. Once noise was introduced, the rate decreased, causing a crossover between the 70 dB (SPL) noise condition and the occluded quiet condition at 30 m. The variability across talkers is relatively large when considering the small variations that occurred as the noise and distance changed. However, other studies observed similar levels of variability across talkers (Lu & Cooke, 2008; Garnier & Henrich, 2014). An important thing to note about this study is that, since the noise introduced inside the ear canal under the HPD was based on each talker's personal earplug attenuation, the level of noise inside the ear was not the same across talkers. For example, a participant with a really good fit may have had less noise exposure than a participant with a fit that is not as good. It would be of interest to examine the relationship between the type of fit and the magnitude of differences produced by each talker. For the application of RAVE, it is crucial to look at the trends in the changes of level and F0 as recorded by the in-ear microphone, since in practice the in-ear microphone would be a more reliable source of information in high noise environments. So far, studies have only included normal-hearing listeners. It would be of great relevance to conduct a similar study to include hearing-impaired talkers to create a speech production model better tailored to hearing-impaired users.

Conclusions

Overall, this pilot study demonstrated that tracking the differences in F0 and level for each talker could be used to determine a talker's intended communication distance. With access to level of background noise and the level of residual noise even the unexpected changes caused by occluding the ear in quiet can be accounted for. A study involving more participants and access to each participants earplug transfer function could open up a door to a unified model of speech production in noise as a function of talker-to-listener distance and background noise level for the occluded ear. Such a model could be used for applications such as RAVE to enhance the communication experience of occluded persons in noisy environments, thus promoting the use of hearing protection devices and reducing the risk of noise-induced hearing loss.

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