

A. COVER PAGE

Project Title: Improving Communication In Noise When Wearing Hearing Protection	
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Change of Contact PD/PI: NA	
Administrative Official: PAUL HUDOBENKO University of CT Health Center Sponsored Program Services 263 Farmington Ave. MC 2806 FARMINGTON, CT 060302806 Phone number: 860 679 3951 Email: hudobenko@uchc.edu	Signing Official: TRACY M ROOT 263 Farmington Avenue Farmington, CT 060305335 Phone number: 860-679-2434 Email: troot@uchc.edu
Human Subjects: NA	Vertebrate Animals: NA
hESC: No	Inventions/Patents: Yes If yes, previously reported: Yes

B. ACCOMPLISHMENTS

B.1 WHAT ARE THE MAJOR GOALS OF THE PROJECT?

Aim 1: To develop a method for improving the intelligibility of speech in occupational noises, to permit face-to-face conversation by persons wearing electronic HPDs.

Aim 2: To develop a method for improving the audibility of alarm sounds in occupational noises, to permit warning sounds to be detected by persons wearing electronic HPDs.

Aim 3: To develop a method from those in aims 1 and 2 to improve simultaneously the understanding of speech and the audibility of warning sounds by persons wearing electronic HPDs.

B.1.a Have the major goals changed since the initial competing award or previous report?

No

B.2 WHAT WAS ACCOMPLISHED UNDER THESE GOALS?

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B.3 COMPETITIVE REVISIONS/ADMINISTRATIVE SUPPLEMENTS

For this reporting period, is there one or more Revision/Supplement associated with this award for which reporting is required?

No

B.4 WHAT OPPORTUNITIES FOR TRAINING AND PROFESSIONAL DEVELOPMENT HAS THE PROJECT PROVIDED?

NOTHING TO REPORT

B.5 HOW HAVE THE RESULTS BEEN DISSEMINATED TO COMMUNITIES OF INTEREST?

Poster papers have been presented at meetings of the Acoustical Society of America.

A journal paper was submitted and is pending acceptance.

B.6 WHAT DO YOU PLAN TO DO DURING THE NEXT REPORTING PERIOD TO ACCOMPLISH THE GOALS?

Not Applicable

It is widely recognized that many workers in noisy occupations are unwilling to wear hearing protection because they fear they will be unable to talk to co-workers or hear warning sounds. The development of specialized hearing protectors that contain electronics to adjust the amount of hearing protection in order to increase the audibility of sounds when noise levels are low aids this situation. We wanted to improve communication when noise levels are high as well as low, and in this project have been developing algorithms for this purpose that could operate in hearing protectors equipped with suitable electronics (eHPDs).

The methods developed are thus intended to enable speech and warning sounds to be heard in almost all situations, and hence reduce errors in communication between workers and the risk of injury to the user of the eHPD. The methods involve digital signal processing and were developed in MATLAB. First, band-pass filters separate sounds into parallel contiguous subbands, each with bandwidth approximately 1.5 times the effective rectangular bandwidth of the cochlea. The overall bandwidth is 200 Hz - 6 kHz and there are 16 subbands. The number of subbands and band-pass filter characteristics are chosen to enable future implementation in a stand-alone wearable device to be worn throughout a workday.

The signals in each subband are separated into the sounds from outside the hearing protector to be processed, and a control signal derived in the time domain from the envelope of these sounds. Two methods for controlling the gain applied to individual subbands have been developed: in the first, the envelope is used directly to amplitude modulate the sounds from outside the hearing protector (called here *direct modulation*); and, in the second, the control signal switches the gain applied to a given subband on or off (so-called *binary masking*), depending on whether the sounds in the subband contain mostly those desired to be heard (switch "on") or undesired noise (switch "off").

After this process, the processed sounds from all subbands are combined, and the resultant audio signal is recorded so that it can be replayed to subjects. We ask people with normal hearing to come to our laboratory to listen to the audio files. The files contain standardized groups of similar sounding words spoken in noise that are chosen to confuse the listener, who must select only one from each group (e.g., select one word from - "kit", "bit", "fit", "sit", "wit", or "hit"). This test of consonant confusion, the Modified Rhyme Test, was selected to assess the performance of our algorithms as we believe it best represents the conditions under which critical communications and warnings will need to be understood, and so represents the best listening test for maintaining occupational safety. The response of our algorithms to warning sounds, such as vehicle backup alarms, is assessed numerically by the signal-to-noise ratio (SNR) of the alarm sound to that of the environmental noise, as this is known to be related to the audibility of the warning sound.

There are a large number of control signals that could be constructed for our algorithms, some of which have been employed in other applications, such as hearing aids. We commenced our research by following the conclusions of a theoretical model for the intelligibility of speech in noise that we had previously developed. Unfortunately, this proved to generate inaccurate and overly optimistic predictions for the improvement in intelligibility to be expected. In consequence, we were forced to abandon this approach and rely solely on the results of listening tests. These require a substantial number of subjects, and therefore time, to obtain results that are statistically significant. Progress was therefore slowed by the need to obtain significant changes in word recognition to assess the performance of each modification to an algorithm, as well as by the reluctance of some individuals to come to our laboratory during the COVID-19 pandemic. For these reasons, we did not undertake listening tests to quantify changes in the audibility of warning sounds, as originally proposed, but rather calculated the warning sound to environmental noise SNR, as described above. In addition, the pandemic resulted in us being unable to evaluate the performance of algorithms in industrial noises recorded on site as originally planned.

In response to the situation, we adopted an alternative strategy for developing algorithms, namely to first quantify the maximum potential improvement in speech intelligibility of algorithms employing direct modulation, binary masking, or direct modulation and binary masking. All our algorithms increase the SNR of conventional tonal alarm sounds and so will improve the audibility of the alarm. Accordingly, this subject was not studied further.

A laboratory experiment was therefore designed in which speech and noise recordings were available separately, and could be used to produce mixtures of speech and noise with different SNRs for use in listening tests. The speech was the MRT sentences and the noise represented a low-frequency industrial noise with flat frequency response below 500 Hz, reducing by ~6 dB/octave above that frequency.

The *a priori* knowledge of speech and noise characteristics enabled us to produce mixtures which simulate a control signal with a higher SNR than that of the sounds being controlled. This was to simulate the

intended effect of our direct modulation algorithms, which are designed to improve communication by increasing the loudness of the speech compared to that of the noise in which it is embedded. We hence chose to directly modulated sounds from outside a hearing protector by linearly changing the gain when using a control signal with a higher SNR than that of the sounds being controlled. Use of linear amplitude modulation for direct modulation assumes that most information influencing intelligibility is contained in the most intense speech sounds, a conclusion reached by other researchers. In listening tests, we found that a statistically significant increase in group mean word recognition in noise compared to the unprocessed condition of up to 36% could be obtained by direct modulation.

This, then, became the target for our direct modulation algorithms that must operate under real-world conditions in which the only sounds available are those outside the hearing protector in the environment experienced by the user, where speech is already mixed with noise. This is, of course, a much greater challenge for the algorithms. Under these conditions, we have achieved a statistically significant increase in group mean word recognition of up to 12% when using direct modulation.

To establish the potential of binary masking for improving speech intelligibility in the simulated industrial noise, we developed an algorithm containing a so-called *ideal binary mask* for our laboratory experiment in which we have *a priori* knowledge of the speech and noise separately. In this experiment, the output of the ideal binary mask is used to select whether the sounds in a mixture of speech and noise contain those desired to be heard (switch "on") or not (switch "off"). Our ideal binary mask involves calculating the SNR of the envelopes of signals in each subband. In practice, the "off" value of our mask is not zero, to reduce the audibility of switching transients. By introducing a threshold value for the SNR of the envelopes above which it is deemed to contain the desired sounds, it is possible to segregate a speech and noise mixture into times when speech sounds dominate, and times when noise dominates. In this way, time segments of speech in noise in a given subband are either passed through the mask unchanged to be summed with the outputs of other subbands, or attenuated. Clearly, the binary nature of the process introduces the potential for frequency gaps in the sounds transmitted to a listener and, in situations in which noise dominates the sounds at almost all frequencies little sound would be transmitted to a listener.

An immediate question surrounds the consequences of introducing "holes" in the frequency spectrum of speech on its intelligibility. In studies conducted elsewhere, it has been demonstrated that considerable loss of frequency content in separate frequency bands produces little reduction in speech understanding. It appears the brain is capable of "filling in" the spectral gaps: in other words, there is considerable redundancy in the sounds that form speech. This observation, however, also implies that not all changes to the physical characteristics of sounds from outside the eHPD introduced by a binary mask will result in changes in speech intelligibility. Nevertheless, in listening tests we found that a statistically significant increase of group mean word recognition in noise compared to the unprocessed condition of up to 21% could be obtained by applying our ideal binary mask.

As before, this became the target for our binary masking algorithms, which, as already noted, operate under real-world conditions in that the only sounds available are those from outside the hearing protector. In listening tests, we have achieved a statistically significant increase in group mean word recognition of up to 7% when using our binary masking algorithm.

In principle, there is no reason why we cannot attempt to improve speech intelligibility in environmental noise by applying both direct modulation and binary masking at the same time. The performance of an algorithm constructed for this purpose using *a priori* knowledge of the speech and noise obtained a statistically significant increase in group mean word recognition of 22% in our listening test, while in real-world conditions the increase was up to 8%. However, this was less than the improvement in word score obtained by direct modulation alone. The reason for this disappointing result is not clear. However, it is suspected to be related to the observation, noted previously, that not all changes to the physical characteristics of sounds will result in changes to the subjective assessment of speech intelligibility. Nevertheless, the differences in word recognition between the idealized and real-world conditions lead us to believe that the performance of both direct modulation and binary masking speech enhancement algorithms can be further improved. And, even at the present state of development, speech and warning sound perception are already better than when no algorithm is used.

C. PRODUCTS**C.1 PUBLICATIONS**

Are there publications or manuscripts accepted for publication in a journal or other publication (e.g., book, one-time publication, monograph) during the reporting period resulting directly from this award?

No

C.2 WEBSITE(S) OR OTHER INTERNET SITE(S)

NOTHING TO REPORT

C.3 TECHNOLOGIES OR TECHNIQUES

NOTHING TO REPORT

C.4 INVENTIONS, PATENT APPLICATIONS, AND/OR LICENSES

Have inventions, patent applications and/or licenses resulted from the award during the reporting period? Yes

If yes, has this information been previously provided to the PHS or to the official responsible for patent matters at the grantee organization? Yes

C.5 OTHER PRODUCTS AND RESOURCE SHARING

NOTHING TO REPORT

D. PARTICIPANTS

D.1 WHAT INDIVIDUALS HAVE WORKED ON THE PROJECT?

Commons ID	S/K	Name	Degree(s)	Role	Cal	Aca	Sum	Foreign Org	Country	SS
ABRAMMER	Y	BRAMMER, ANTHONY	PHD	PD/PI	3.0	0.0	0.0			NA
INSKIM	N	Kim, Insoo	PHD	Co-Investigator	1.0	0.0	0.0			NA
HKMARQUIS	N	Marquis, Hillary K	AuD	Audiologist	1.0	0.0	0.0			NA
PEREZEC	N	Perez, Erin C	AuD	Audiologist	1.0	0.0	0.0			NA
RHSOLEYMANPOUR	N	Soleymanpout, Rahim		Graduate Student (research assistant)	12.0	0.0	0.0			NA

<p>Glossary of acronyms: S/K - Senior/Key DOB - Date of Birth Cal - Person Months (Calendar) Aca - Person Months (Academic) Sum - Person Months (Summer)</p>	<p>Foreign Org - Foreign Organization Affiliation SS - Supplement Support RE - Reentry Supplement DI - Diversity Supplement OT - Other NA - Not Applicable</p>
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D.2 PERSONNEL UPDATES

D.2.a Level of Effort
 Not Applicable

D.2.b New Senior/Key Personnel
 Not Applicable

D.2.c Changes in Other Support
 Not Applicable

D.2.d New Other Significant Contributors
 Not Applicable

D.2.e Multi-PI (MPI) Leadership Plan
 Not Applicable

E. IMPACT**E.1 WHAT IS THE IMPACT ON THE DEVELOPMENT OF HUMAN RESOURCES?**

Not Applicable

E.2 WHAT IS THE IMPACT ON PHYSICAL, INSTITUTIONAL, OR INFORMATION RESOURCES THAT FORM INFRASTRUCTURE?

NOTHING TO REPORT

E.3 WHAT IS THE IMPACT ON TECHNOLOGY TRANSFER?

Not Applicable

E.4 WHAT DOLLAR AMOUNT OF THE AWARD'S BUDGET IS BEING SPENT IN FOREIGN COUNTRY(IES)?

NOTHING TO REPORT

G. SPECIAL REPORTING REQUIREMENTS SPECIAL REPORTING REQUIREMENTS

G.1 SPECIAL NOTICE OF AWARD TERMS AND FUNDING OPPORTUNITIES ANNOUNCEMENT REPORTING REQUIREMENTS

NOTHING TO REPORT

G.2 RESPONSIBLE CONDUCT OF RESEARCH

Not Applicable

G.3 MENTOR'S REPORT OR SPONSOR COMMENTS

Not Applicable

G.4 HUMAN SUBJECTS

G.4.a Does the project involve human subjects?

Not Applicable

G.4.b Inclusion Enrollment Data

File(s) uploaded:
CumulativeInclusionEnrollmentReport.pdf

G.4.c ClinicalTrials.gov

Does this project include one or more applicable clinical trials that must be registered in ClinicalTrials.gov under FDAAA?

G.5 HUMAN SUBJECTS EDUCATION REQUIREMENT

NOT APPLICABLE

G.6 HUMAN EMBRYONIC STEM CELLS (HESCS)

Does this project involve human embryonic stem cells (only hESC lines listed as approved in the NIH Registry may be used in NIH funded research)?

No

G.7 VERTEBRATE ANIMALS

Not Applicable

G.8 PROJECT/PERFORMANCE SITES

Not Applicable

G.9 FOREIGN COMPONENT No foreign component
G.10 ESTIMATED UNOBLIGATED BALANCE Not Applicable
G.11 PROGRAM INCOME Not Applicable
G.12 F&A COSTS Not Applicable

Cumulative Inclusion Enrollment Report

This report format should NOT be used for collecting data from study participants.

Study Title:

Comments:

Racial Categories	Ethnic Categories									Total
	Not Hispanic or Latino			Hispanic or Latino			Unknown/Not Reported Ethnicity			
	Female	Male	Unknown/Not Reported	Female	Male	Unknown/Not Reported	Female	Male	Unknown/Not Reported	
American Indian/Alaska Native										
Asian										
Native Hawaiian or Other Pacific Islander										
Black or African American										
White										
More Than One Race										
Unknown or Not Reported										
Total										

I. OUTCOMES

I.1 What were the outcomes of the award?

The algorithms developed in this project are intended to enable speech and warning sounds to be heard in almost all industrial situations when wearing hearing protectors equipped with electronics for processing the sounds. They are designed to reduce errors in speech communication between workers and the risk of injury to the user. The algorithms first divide the sounds from outside the hearing protector into narrow bands of frequencies, and then either directly change the amplification of the sounds (called here direct modulation), or switch sounds at different frequencies on or off (so-called binary masking), depending on whether they contain mostly sounds desired to be heard (switch "on") or not (switch "off").

We first decided to quantify the maximum potential improvement in speech intelligibility of algorithms employing direct modulation, binary masking, or direct modulation and binary masking. This was obtained by experiments in which speech and noise were available separately. In these circumstances, the algorithms can produce idealized responses that are greater than can be obtained in the real-world where workers are talking in a noisy environment. The maximum increases in word recognition by our subjects under the idealized conditions were: 36% for direct modulation, 21% for binary masking, and 22% for direct modulation and binary masking.

For evaluating algorithms in real-world conditions, when sounds from outside a hearing protector involve speech in industrial noise, we initially used linear modulation to directly adjust the amplification of these sounds by linearly changing the gain applied to the mixture of speech and noise. In listening tests, we found that an increase in word recognition of up to 12% could be obtained by applying direct modulation.

We then used a binary mask to rapidly switch on, or off, the sounds from outside a hearing protector at different frequencies. In listening tests, we found that an increase in word recognition of up to 7% could be obtained by applying our binary mask. We finally constructed an algorithm that directly modulated the sounds from outside a hearing protector as well as switching on or off the sounds at different frequencies. In listening tests, we found that an increase in word recognition of up to 8% could be obtained by applying both linear modulation and binary masking. The reason for this disappointing result is not clear. However, it is suspected to be related to the observation that not all changes to the physical characteristics of sounds will result in changes to the subjective assessment of speech intelligibility. Nevertheless, the differences in word recognition between the idealized and real-world conditions lead us to believe that the performance of the algorithms can be further improved. As all our algorithms increase the loudness of conventional tonal alarm sounds compared to the noise, they will improve the audibility of the alarm. Hence, even at the present state of development, speech and warning sound perception are already better than when no algorithm is used.