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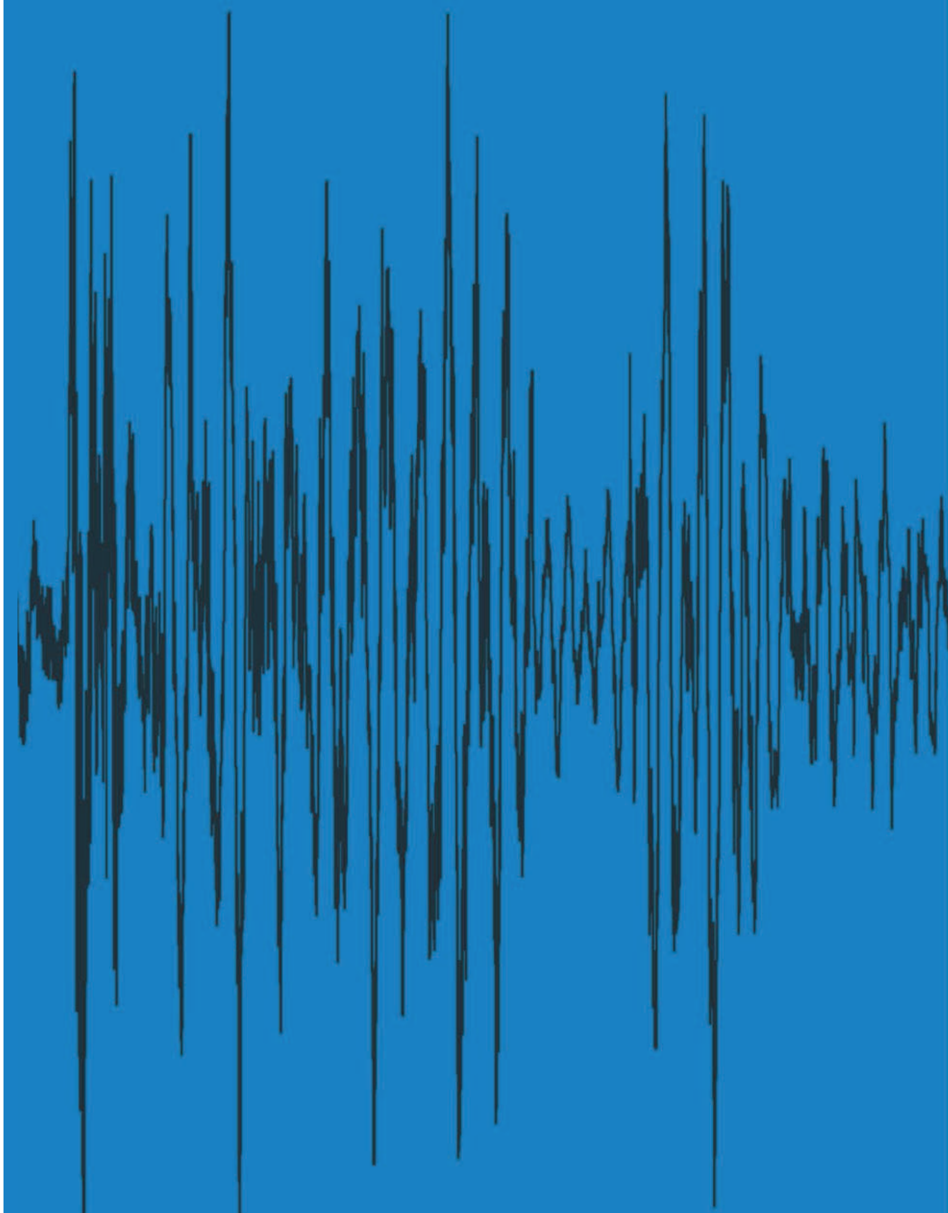

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Detection of Auditory Signals in Quiet and Noisy Backgrounds while Performing a Visuo-spatial Task

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Abstract

Context: The ability to detect important auditory signals while performing visual tasks may be further compounded by background chatter. Thus, it is important to know how task performance may interact with background chatter to hinder signal detection. **Aim:** To examine any interactive effects of speech spectrum noise and task performance on the ability to detect signals. **Settings and Design:** The setting was a sound-treated booth. A repeated measures design was used. **Materials and Methods:** Auditory thresholds of 20 normal adults were determined at 0.5, 1, 2 and 4 kHz in the following conditions presented in a random order: (1) quiet with attention; (2) quiet with a visuo-spatial task or puzzle (distraction); (3) noise with attention and (4) noise with task. **Statistical Analysis:** Multivariate analyses of variance (MANOVA) with three repeated factors (quiet versus noise, visuo-spatial task versus no task, signal frequency). **Results:** MANOVA revealed significant main effects for noise and signal frequency and significant noise–frequency and task–frequency interactions. Distraction caused by performing the task worsened the thresholds for tones presented at the beginning of the experiment and had no effect on tones presented in the middle. At the end of the experiment, thresholds (4 kHz) were better while performing the task than those obtained without performing the task. These effects were similar across the quiet and noise conditions. **Conclusion:** Detection of auditory signals is difficult at the beginning of a distracting visuo-spatial task but over time, task learning and auditory training effects can nullify the effect of distraction and may improve detection of high frequency sounds.

Keywords: Attention, auditory thresholds, distraction, noise, warning signals

Introduction

Workers are often expected to detect non-verbal acoustic signals while performing manual or visuo-spatial tasks. Such acoustic signals can indicate malfunction of machines that can pose a risk to safety. The ability to attend to important acoustic signals while performing manual tasks can prompt workers to take appropriate actions, potentially leading to more efficient machinery and safer work environments. In other work environments such as hospital settings, the ability of hospital workers to detect important signals such as beeps of physiological equipment while performing other duties is important for the safety and health of patients. Detailed user interface design guidelines for medical devices include specification of sound levels emitted by the device at a certain distance to ensure audibility of the signal.[1]

The probability of perceiving a 1 kHz tone is lowered if the individuals are involved in a relatively complex task such as performing arithmetical manipulations, especially if the signal-to-noise ratio is poor.[2] However, other factors can also affect signal detection. Rawool[3] demonstrated a significant order, signal frequency and task performance interaction in the ability to detect signals. Distraction caused by the requirement to perform a visuo-spatial task worsened auditory thresholds at the beginning of the task regardless of the test tone frequency. However, when tones of lower frequency (0.5 Hz) were presented at the end of the experiment, the thresholds under task and no-task conditions were similar and when tones of higher frequency (4 kHz) were presented at the end of the task, the thresholds were better while performing the task when compared to no-task condition.

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The ability to detect important signals while performing tasks may be compounded by ambient noise and background chatter. For this reason, consideration of environmental noise levels is recommended in designing medical devices.[1] Thus, it is important to know how task performance may interact with background chatter or babble to further hinder signal detection. Therefore, this study was designed to determine any interactive effects of speech spectrum noise and task performance on the ability to detect signals of various frequencies.

Materials and Methods

Participants

Twenty young adults in the age range of 18–30 years participated in the study. They all had auditory thresholds within 20 dB Hearing Level (HL) across the frequency range of 0.25–8 kHz to control for any effects of hearing loss on task performance. They also had normal tympanometric results showing normal middle ear function. Participants were relatively naïve to the test conditions used in the study to allow for assessment of any learning effects.

Test procedures

All testing was conducted in the sound field in a sound-treated booth. A computerized five up/five down procedure with three reversals was used to determine thresholds for warbled tones presented through a loudspeaker. Initially, the presentation levels were decreased in 10 dB steps till the occurrence of an incorrect response. After this, the levels were increased in 5 dB steps till a response was apparent and decreased in 5 dB steps till no response was apparent. Three reversals were completed to obtain the threshold. The average of three softest levels where a response was apparent was noted as the threshold for each test frequency. The presentation of test and control trials, presentation of stimulus parameters, presentation of reinforcers and calculation of thresholds were achieved via a software installed on a computer outside the test booth. Computer-generated silent control trials were interspersed among test trials, to get an estimate of false alarm rates. Thresholds were determined at 0.5, 1, 2 and 4 kHz in the following conditions presented in a random order: (1) quiet with attention; (2) quiet with task (distraction); (3) noise with attention and (4) noise with task (distraction). In noise conditions, speech spectrum noise of 60 dB Sound Pressure Level (SPL) was continuously presented through another loudspeaker in the booth. In attention conditions, participants sat quietly, listened for the warble tones and pressed a button every time they heard a tone. In task conditions, they were asked to solve a cardboard (to minimize noise) jigsaw puzzle (500 pieces) as quickly as possible, and at the same time to respond to warbled tones by turning their heads towards the loudspeaker. They were also informed that if they responded correctly, an animated toy will emerge in the darkened box in the booth and if they responded when there was no tone presented, the animated toy would not appear. Following each correct response that occurred within 9 s after stimulus onset, one of the two visual reinforcers (animated objects) was activated in a random order.

Although the four conditions were presented randomly, the test tones were always presented in the following order to control for fatigue and order[3] effects: 0.5, 1, 2 and 4 kHz [Figure 1]. Counterbalancing with other possible various orders of presentation was not attempted due to the demand for a larger pool of participants.

Analyses

Data from three of the participants were excluded from the analyses due to greater than 66% false alarm rates during the distraction task. Repeated measures Multivariate Analysis of Variance (MANOVA) [2 (noise and quiet × 2 (task, no task) × 4 (0.5, 1, 2 and 4 kHz)] was performed on the thresholds of the remaining 17 participants. Post-hoc analyses were performed with the Tukey Honest Significant Difference (HSD) test.

Results

(MANOVA) revealed a significant main effect of noise (noise versus quiet) ($P = 0.000$) showing an elevation of thresholds in the background of noise across the attention and distraction conditions [Figure 2]. There was a significant main effect of signal frequency ($P = 0.000$) on auditory thresholds. Post-hoc analyses with the Tukey HSD test revealed that the thresholds were significantly better at 4 kHz ($P = 0.000$) than at all other test frequencies; no other differences were significant. The main effect of attention versus distraction was not significant ($P = 0.099$).

There was a significant noise–frequency ($P = 0.000$) interaction [Figure 2]. The worsening of thresholds caused by noise was greater at 1 kHz compared to other frequencies. Post-hoc analyses with the Tukey HSD test revealed that there were significant differences in thresholds between all frequencies in the noise condition except for 0.5 versus 2 kHz where the thresholds did not differ significantly. In the quiet conditions, there were significant differences in thresholds at various frequencies with the exception of 0.5 versus 2 kHz and 1 versus 4 kHz where there were no significant differences. There

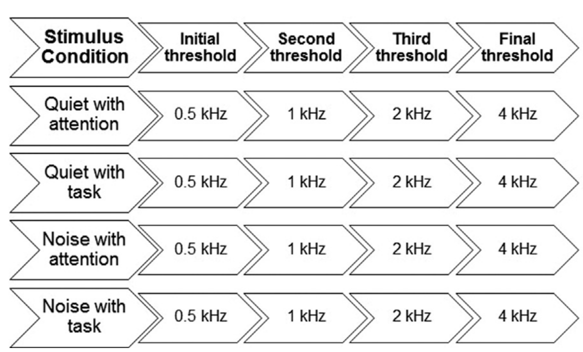

Figure 1: The four stimulus conditions presented in random order and the order of test frequency for each condition, which was the same in all four conditions

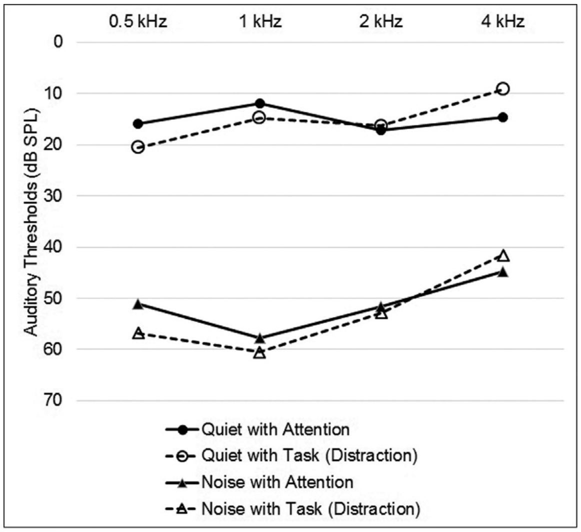

Figure 2: Mean auditory thresholds in the four conditions

was also a significant task–frequency ($P = 0.000$) interaction. Distraction caused by performing the task significantly worsened the thresholds for 0.5 kHz ($P = 0.000$) and 1 kHz ($P = 0.051$) tones presented at the beginning of each of the test conditions and had no effect on the 2 kHz ($P = 1.000$) tones presented in the middle of the test conditions. However, the thresholds obtained at the end of each condition (4 kHz) were significantly ($P = 0.0003$) better while performing the task than those obtained without performing the task.

These effects appeared to be similar across the quiet and noisy conditions as suggested by lack of significant interaction across the three factors of noise, task and frequency ($P = 0.645$). Post-hoc analyses revealed that the thresholds were significantly worse while performing the task at 0.5 kHz in both quiet and noisy ($P = 0.000$) conditions when compared to the attention or no-task condition. There were no significant differences in thresholds between the task and attention (no task) conditions at 1 ($P = 0.201$) and 2 kHz ($P > 0.997$). The thresholds were significantly better at 4 kHz while performing the task compared to the attention (no task) condition in quiet ($P = 0.000$) and noisy ($P = 0.053$) conditions.

Discussion

Effect of speech-shaped noise on auditory thresholds

As noted in the }Results} section, there was a main effect of noise and noise–stimulus frequency interaction. As expected, the speech-shaped noise worsened the thresholds as shown in Figure 2. The greatest effect of the noise was on the thresholds at 1 kHz due to the peak of the noise at this frequency.

Effect of stimulus frequency on auditory thresholds

In the quiet conditions, there were significant differences in thresholds at various frequencies with the exception of 0.5 versus 2 kHz and 1 versus 4 kHz where there were no significant differences. Such differences in quiet are expected due to the fact that average thresholds in SPL established in a sound field are usually different in normal individuals across the test frequencies. These threshold differences across frequencies were enhanced during the noise condition due to the amplitude variations in the spectrum of the speech-noise across frequencies. Thus, there were significant differences in thresholds between all frequencies in noise except for 0.5 versus 2 kHz where the thresholds did not differ significantly.

Effect of distraction caused by performing a visuo-spatial task

The current results show that in the presence of background speech noise, distraction caused by performing a visuo-spatial task (solving a 500-piece puzzle) worsens the thresholds for the 0.5 kHz tones presented at the beginning of the test conditions, has no effect on the 2 kHz tones presented in the middle of the test conditions and improves the thresholds for 4 kHz tones presented at the end of the test conditions when compared to thresholds obtained while being attentive and not performing any visual tasks. These results are similar to those reported previously without background noise[3] which showed that when 4 kHz tones are presented at the end of the test trials, auditory thresholds were better while performing the task compared to those obtained while performing no other tasks. In the current study, similar results were obtained even after the addition of a speech-shaped noise which could be considered a second distractor in addition to the puzzle solving task.

The worsening of thresholds due to distraction caused by the puzzle-solving visuo-spatial task at the beginning of the test conditions can be explained through the dual-task interference theory. If it is assumed that we have limited cognitive resources, these resources will be divided into paying attention to the tones and responding and attempting to solve the puzzle. Thus, limited cognitive resources will be available for detecting the tones causing worsening of thresholds compared to when no visual task is required. Such multisensory interference has been previously demonstrated where auditory stimuli that are easily detected when presented alone, become harder to detect in the presence of a visual stimulus. Such visual interference can be modulated by selective attention.[4]

The lack of any effect on thresholds for tones presented at the middle of the test conditions could be related to the fact that the head-turn response for tones required in the current study may become somewhat automatic or conditioned over time and thus less cognitive resources might be required allowing auditory thresholds to be similar to those obtained while performing no visual tasks.

The response automaticity mentioned above could also be partially responsible for enhancement of thresholds while performing the task at the end of the test trials. However, another factor contributing to the enhancement of thresholds while performing the visuo-spatial task may be cross-modal facilitation via multisensory integration. Previous studies have shown that irrelevant visual stimuli can enhance detection of auditory stimuli,[5] increase perceived loudness of auditory stimuli[6] and improve frequency discrimination[7] via multisensory integration.

Another factor leading to better auditory signal detection over time in background noise while performing a visual task may be related to rapid neural plasticity. Rapid adaptive changes in the spectrotemporal receptive fields of the primary auditory cortex have been noted previously. More specifically, when the signal to noise ratio is poor, the responses of cells that are away from the target tone are suppressed in an adaptive fashion, allowing easier detection of the target tone.[8]

However, a previous study has shown that the enhancement is apparent only when high frequency tones are presented at the end of the trials. More specifically, if tones of 0.5 kHz are presented at the end, the automaticity in response behaviour leads to no effect of having to perform a visual task on auditory thresholds, but it does not enhance the 0.5 kHz thresholds while performing the task.[3] The reason for lack of enhancement of thresholds for low frequency sounds may be related to the fact that these sounds are more susceptible to internal noises caused by body movements involved in attempting to solve the puzzle, compared to high frequency stimuli. They are also more susceptible to the effects of activation of the olivo-cochlear bundle due to the presence of any noise in the environment.[9]

Implications

The current results suggest that the frequency of alerting signals in multi-task, noisy environments (e.g., cockpits or intensive care units) should be around 4000 Hz for workers with normal hearing. Initial training in detecting such alerting signals while performing required or assigned tasks is recommended as such training can improve signal detection. During such training, positive reinforcement/ feedback should be provided for correct responses that occur immediately following presentation of the target stimulus. Some individuals (3/20 or 15%) in the current study showed a relatively high false alarm rate by turning their heads towards the loudspeaker in the absence of warbled tones. Such false alarm rates can decrease work efficiency in multitask environments. Different training strategies should be explored for such workers. For example, future studies may explore the effects of providing specific feedback after false alarms (e.g., visual display showing the wrong or X sign) in addition to providing feedback after correct responses.

The detection of warning signals depends on the characteristics of any background competition or noise in the work area, the auditory sensitivity of workers and acoustical properties of the work area (size, reverberation, distance between warning devices and workers).[10] Relatively low frequency sounds have been recommended for inclusion in alarms.[11,12] However, previous studies have shown that efficacy of any alarms is based on the auditory sensitivity of workers and the background noise levels. Most background noises usually have relatively high levels of low frequency noise. Thus, high frequency stimuli may be more useful in such circumstances when the workers have normal hearing in the 2000–8000 Hz range. Such high frequency alarms are obviously not suitable for those workers who have either age-related or noise-induced, high-frequency hearing loss.

When workers are required to use hearing protectors due to the presence of hazardous noise, the attenuation provided by the hearing protectors also partially determines the detection and encoding of warning signals. Warning signals should not be too soft to notice or hazardously loud, or too loud to impede any critical thought process. Very loud sounds can also provoke stress and increase cognitive load. A software tool referred to as Detectsound[13,14] has been developed which analyzes the background noise and specifies the target acoustical characteristics of warning signals for each work area. Such tools may be valuable in addressing the audibility of warning sounds in the work area but do not specifically address other important factors such as distinctiveness or urgency associated with warning sounds (e.g., in medical settings), and the cognitive load or demands associated with the workers' tasks.[15]

For workers who already have a noise-induced hearing loss which tends to be more prevalent and worse at 4 kHz, more prolonged auditory training with the use of alternative frequencies (e.g., 1 or 2 kHz) should be explored in future investigations. Future studies will also be useful in informing us about the best signals and auditory training strategies for workers who work in hazardous noise, wear hearing protection devices and have hearing loss.

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Conflicts of interest

There are no conflicts of interest.

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