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REVIEW OF THE LITERATURE ON SOUND SOURCE LOCALIZATION AND APPLICATIONS TO NOISY WORKPLACES

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ABSTRACT

In noisy workplaces, workers have to detect and localize significant sound sources. If they fail in these auditory tasks, serious accidents can occur. The present paper deals with a review of the different aspects of localization in free field and in closed spaces. Different factors such as hearing loss, hearing protectors and hearing aids have been statistically proven to worsen the ability to localize sounds in both horizontal and vertical planes. In order to emphasize the need for research in understanding the complex mechanisms involved in real life sound localization, a simulated case is presented. Arguments are given for the necessity in developing clinically relevant tests that will enable audiologists to quantify an individual's ability to localize sounds in different situations. It is important that the rationale for these tests be to improve safety in noisy workplaces and not to discriminate among job candidates.

SOMMAIRE

Dans les milieux de travail bruyants, les travailleurs doivent détecter et localiser des sources sonores importantes. S'ils échouent dans ces tâches auditives, des accidents graves peuvent survenir. Cet article porte sur une revue de la littérature des différents aspects de la localisation auditive en champ libre et en milieu réverbérant. Différents facteurs tels que les pertes auditives, les protecteurs auditifs et les aides auditives diminuent statistiquement les performances de localisation dans le plan horizontal et vertical. Un cas simulé est présenté afin de démontrer la nécessité de poursuivre la recherche d'outils cliniques qui permettront aux audiologistes de mieux quantifier les abilités d'un individu à localiser des sources sonores dans différentes situations. Ces tests devraient être faits avec l'intention d'améliorer les conditions de travail et non pas de discriminer parmi les individus qui posent leur candidature pour un emploi.

1. INTRODUCTION

Each year, serious work related accidents occur because workers claim not having identified or localized an alerting sound signal (Moll van Charente and Mulder, 1990). Much is known about sound source localization in quiet free field or closed spaces (Canévet, 1988) but very little attention has been given to sound source localization in noisy workplaces. To the author's knowledge, no detailed review of the literature or specific field studies have dealt with sound source localization in noisy workplaces where noise-induced hearing loss, the wearing of hearing aids and hearing protectors are common. This situation is particularly troublesome since existing studies do not address situations where sound sources and workers are continually in motion.

Before conducting a specific study in the field of localization in noisy workplaces, a review of the literature (Laroche, 1992) was done on localization in quiet free field and in closed spaces. Many factors such as hearing loss, hearing protectors and hearing aids have been shown to be important considerations. The present paper will summarize the effects of these factors. One simulated case will be reviewed to illustrate the application of the theoretical aspects of localization. This case will deal with the localization of a travelling crane in a closed field environment.

2. SOUND LOCALIZATION IN FREE FIELD

2.1 Horizontal plane

Canévet (1988) has summarized the actual knowledge on localization in the horizontal plane. In the free field, localization in the horizontal plane is made possible through the use of two cues: the interaural phase (or time) difference and the interaural level difference. The phase difference is valid for the low frequencies up to 1500 Hz and the level difference takes over for the high frequencies. However, between 1500 and 3000 Hz, neither cue fully helps for localization, explaining why most of the pure tone errors made by humans are centered between 1500 and 3000 Hz. Front/rear confusions are also common to all pure tones. Continuous large spectrum noises are then easier to localize than pure tones. Most of the studies have been made with no head motion allowed. Head movements seem to improve the localization of sustained sounds but the contribution of head motion to localize brief sounds is less clear. .Middlebrooks and Green (1991) propose that, for brief sounds, the duration must be long enough to allow head movements in the direction of the sound source.

2.2 Vertical plane

According to Blauert (1983), wide spectrum noises are preferred for localization in the vertical plane. In fact, the noise spectrum is the key factor. For example, 8 kHz signals will always be localized above the head, irrespective of the actual direction of the source. Narrow band sounds at 1 kHz will be perceived to originate behind the head of the subjects. Blauert (1969) has called this phenomenon the determining frequency bands. This effect is very robust and is attributed to the frequency characteristics of the hearing system. Needless to say, errors made on the same type of signal are more frequent in the vertical plane than in the horizontal plane. Head movements can improve performances but not in all subjects (Noble and Gates, 1985; Noble, 1987).

2.3 Dual plane localization

Based on two studies related to localization in both planes simultaneously (Oldfield and Parker, 1984; Makous and Middlebrooks, 1990), best performances are reached when signals are presented in front of the subject and the spectrum is wide. The smallest average errors were found to be about 2 and 3.5° in the horizontal and vertical dimensions, respectively. The size of errors increased for more peripheral stimulus locations, to maxima of about 20°.

2.4 Distance evaluation

If the auditory system is not very precise for vertical localization, its distance evaluation of sound sources is even worse. Three cues are involved in that kind of localization: level variations, the energy ratio between the direct and the reflected sounds and the spectral modifications (Canévet, 1988). Low frequency noises appear to arise from the rear regardless of their actual position and are perceived farther than high frequency noises at the same sound level. According to the few studies dealing with distance evaluation (Ashmead et al., 1990; Butler et al., 1980 Strybel and Perrott, 1984; Simpson and Stranton, 1973), the hearing mechanism is not a good rangefinder. More studies are needed to better describe the contribution of each of the three cues mentioned above.

2.5 Movement perception

Movement perception has not yet been studied in great detail despite the fact that we live in a constantly mobile environment. According to Rosenblum et al. (1987), level changes, the interaural differences and the Doppler effect seem to be crucial factors. The Doppler effect refers to the phenomenon by which sound waves' length tends to decrease at the front and increase at the rear of the source when this source is moving ahead. From the receiver's point of view, the frequency content increases as the source approaches, decreases abruptly when the source is very close and continues to decrease gradually when the source moves away.

The level changes refer to the increase or decrease of the sound level when the source is approaching or moving away from a receiver. The receiver can detect this movement but will not know exactly when he could be hurt if he can not see the source.

In their study, Rosenblum et al. (1987) have placed these three cues in a hierarchical manner: the receivers rely first on the level changes followed by the interaural time differences and lastly by the Doppler effect. As noted by the authors, their study was not done in very realistic settings. The only realistic data available on movement perception in the litterature relates to ambulance sirens. Caelli and Porter (1980) have reported that there are distance overestimations reaching twice the real distance, thereby compromising human safety. In fact, subjects did not react until the ambulance was less than 100 meters away from their car. At 60 to 80 km/hours, the ambulance siren signal would propagate as far as 33 to 44 meters, if the siren had been sounded for 2 seconds. Because subjects tend to overestimate this distance, they have very little time to react if they base their decision on auditory cues only.

2.6 Localization in noise

Localization in noise is closely related to the frequency and temporal selectivity of the auditory system (Canévet, 1988). Masking effects are predominent for the frequency range centered on the sound signal critical band. In order to optimize localization, sound levels of 10 to 15 dB over the masked threshold are proposed (Canévet, 1985; Houtgast and Plomp, 1968). Masked threshold refers to the sound level in dB necessary to just perceive the sound in a given amount of noise.

Another concept related to localization in noise is the cocktail party effect. In noisy surrondings, speech perception is possible because the receiver's attention is directed towards the speaker and he/she can then ignore interfering noise around him/her (Plomp, 1977). The dominating factor is the spatial separation of noise and speech. In this matter, the masking level difference (MLD; Hirsh, 1948) is closely related to the cocktail party effect. The MLD phenomenon refers to the improvement of masked thresholds when the phase or level interaural differences of a sound source are not identical to those of the masking noise. In real life, the MLD happens when the sound source and the noise come from different locations. Nevertheless, even if the masked thresholds are improved due to the MLD, nothing is really known about the impact of this improvement on localization abilities.

For example, if a backup alarm is heard on one side and a background noise comes from every direction, will the backup alarm be better localized due to the MLD effect which predicts an increase in the sound pressure level?

3.0 LOCALIZATION IN CLOSED SPACES

3.1 Horizontal plane

Most of the studies done in closed spaces has dealt with horizontal plane localization. Hartmann and his co-workers have investigated this problem in a series of laboratory experiments (Hartmann, 1983; Rakerd and Hartmann, 1985; Rakerd and Hartmann, 1986; Hartmann and Rakerd, 1989). According to these authors, low frequency pure tones cannot be localized inside a room. High frequency tones are easier to localize than low frequency tones but performances are still poor. A short impulse type signal (5-2000 msec) with an instantaneous rise time (< 5 msec) and a wide spectrum is the easiest sound to localize in closed spaces. Reverberation time does not seem to influence the localization of that type of signal. Unlike brief tones, continuous noises are largely disturbed by reverberation. Reflective walls can also deteriorate performances but reflections coming from the same direction as the direct sound improves performances.

More recently, Giguère and Abel (1993) confirmed that sound localization performances were lower in a reverberant room (0,6 to 1 sec.) than in an absorbent room (0.2 sec.), for one-third octave noise bands centered on 500, 1000 , 2000 and 4000 Hz. For that type of signal, they found that the benefit of a shorter rise/decay time was small and limited to low frequencies. They also found that performances depend strongly upon the array in which the speaker was embedded: localization in the lateral array led to frequency-dependent front/back confusions and response bias.

3.2 Distance perception

Mershon et al. (1989) found that short reverberation times lead to distance underestimations while longer times lead to overestimations. Background noise tended to decrease the perception of distance. In a more recent study (Hafter et al., 1994), it was shown that listeners can use echoes from a single wall reflector to improve their perception of auditory distance of single clicks and short train of clicks. However, performance was characterized by large individual differences in their subject group (N=4). Those who seemed to ignore echoes and concentrate on signal levels did better than those who did not. Several additional studies on the use of echoes in distance perception are presently underway in Hafter's laboratory. They are studying the effects of ground reflections, the most prevalent of real-world echoic surfaces. They also plan to test the importance of vision in the auditory perception of distance. Their findings will help our understanding of this complex auditory process.

4.0 EFFECTS OF HEARING LOSS

Durlach et al. (1981) have made a detailed review of the literature on the effects of hearing loss on localization performance. Based on this review, localization has been found to be more impaired in unilateral and asymetrical hearing loss cases than in bilateral cases. Localization was also statistically worse for subjects with middle ear problems and central lesions than for listeners with cochlear damage. More recently, Noble et al. (1994) confirmed this last assumption but concluded that the correlations between degree of hearing loss and localization are only moderate, suggesting that aspects of hearing impairment, in addition to simple attenuation, may also reduce auditory localization performance.

5.0 EFFECTS OF HEARING PROTECTORS

In general, localization performances are worse when protectors are worn in reverberated surroundings (quiet or noisy) than in open ear situations (Mershon and Lin, 1987). In terms of localization, Mershon and Lin (1987) concluded that hearing protectors' attenuation must be low and as uniform as possible for the entire frequency spectrum in order to minimize localization errors.

Noble et al. (1990) noticed that earmuffs induce sound source displacements to the front and earplugs induce sound source displacement to the rear. In the same line of ideas, Able and Hay (1994) found that muffs were more detrimental than plugs for front/back discrimination. In his 1981 study, Noble concluded that the removal of pinna functions through the use of earmuffs has a definite adverse effect on horizontal plane localization and a radically disruptive effect on vertical plane localization. These effects are somewhat mitigated by free head movement, but only slightly so in the vertical plane. For example, in the horizontal plane, subjects' response accuracy was 95% in the unoccluded free-head movement condition, 50% in the occluded free-head movement condition, and 24% in the occluded with head movement restriction condition. For the vertical plane, the results were 72% in the unoccluded free condition, 19% in the occluded free condition and nearly random in the restricted-head occluded condition.

Abel and Hay (1994) collected data with conventional muffs and plugs and active earmuffs worn by normal and hearing-impaired subjects. Results showed that this last group had difficulties detecting 4000 Hz one-third octave noise bands with conventional protectors but were not different from normals with active muffs. At 500 Hz, localization performances of the two groups were similar.

In an other study, Noble and Gates (1985) found that latency of localization responses were statistically longer for subjects wearing hearing protectors than for subjects in open ear conditions (5 vs 3 seconds). Noise bursts centered on 2.3 and 8.3 kHz were used as signals. In this study, subjects were free to move their head. All these studies were conducted in anechoic conditions but results seem to be similar in reverberated surroundings (Talamo, 1975; Abel and Hay, 1994). Nevertheless, as early as 1978, Wilkins and Martin stated that even if the decrease in performance due to hearing protectors varies from one study to the other, any degree of negative change can compromise workers' safety and cannot, therefore, be neglected. Coleman et al. (1984) also raised the important question of workers' safety. They suggested that if the ability to localize is important for the job at hand, then plugs are preferable to muffs. It was suggested that another option would be to develop an electronic circumaural earmuff designed to maintain the sound information as it would be perceived in the unprotected condition. There is still (ten years later) no evidence in the literature that such device exists.

6.0 EFFECTS OF HEARING AIDS

In general, localization is better with intra-aural than with other types of hearing aids, due to the minimal obstruction of the pinna (Leuuw and Dreschler, 1987; Westermann and Topholm, 1985). More recently, Noble and Byrne (1990) concluded that hearing aids in general do not restore localization ability completely. Subjects tested with in-the-canal hearing aids performed worse than with intra-aural aids. The authors could not fully explain these results. Due to the small number of subjects and a high rate of individual error they preferred to be conservative in stating that in-the-canal aids were not better than other types of hearing aids for localization.

In 1992, Byrne et al. collected new data and concluded that, when hearing level was controlled, there was no overall difference in the performance of in-the-ear and behind-the- ear aid wearers. According to these authors, the test situation they used in their experiment was more representative of real-life listening. They also demonstrated that bilateral fitting is better for moderately and severly hearing-impaired listeners. However, mildly impaired listeners fitted unilaterally performed as well, on average, as those fitted bilaterally. More data would have to be collected in order to confirm these results.

7.0 APPLICATION TO A SIMULATED CASE: LOCALIZATION OF A TRAVELLING CRANE BY A BURNER OPERATOR

The above review of the literature clearly shows that some aspects of localization must be studied in more depth in order to better understand localization in real-life situations. Wearing of hearing protectors combined with hearing loss are among the most important aspects for study. Localization in the vertical plane also needs to be clarified, especially for mobile sources. Nevertheless, based on information presented here and on a more complete review of the multiple factors involved in localization (Laroche, 1992), it is possible to relate this information to cases commonly found in noisy workplaces like the localization of a travelling crane.

7.1 Sound source

The travelling crane is used in steel plants to move scrap and metal castings. A siren is activated by a crane operator in a soundproof enclosure each time the crane circulates in the work area. Sirens found in workplaces are normally frequency-modulated sound signals between 600 and 1250 Hz. The level is not adjustable except for very few models. The sound is continuous in nature and is mobile due to the displacement of the crane.

7.2 Receptor

Mr. G. is a burner operator in a steel plant and wears earplugs and a face protector to complete his tasks. Mr G must localize the siren in a steady vertical plane and a variable horizontal plane.

7.3 Environment

The noise at the workstation varies in time, is concentrated in low frequencies (< 1000 Hz) and can reach levels as high as 100-110 dBA during the melting process. Room walls are built from concrete blocks and the roof is made of metal sheets and glass. The work area is quite limited in space.

7.4 Analysis

The localization of this siren is not done in the most favorable conditions. First of all, based on the review of the literature, it appears that sirens are difficult to localize in the vertical plane because there is no frequency content over 1250 Hz. Source localization above the head in a free field must have energy in the 8 kHz area or have a wide spectrum of up to 8 kHz. This fact can also be applied to closed spaces. This 8 kHz constraint poses a problem because a high proportion of workers have noise-induced hearing losses beginning in the 3-6 kHz range and extending to 8 kHz with age.

In order to facilitate localization in the horizontal plane, the siren should be a wide spectrum noise burst and placed in front of the workers. It is assumed that distance evaluation can be learned with practice but the fact that the siren is mobile adds to the complexity of the situation.

The siren's sound level should be 10-15 dB over the background noise in certain frequency bands in order to optimize localization. It is almost impossible to reach this target when the noise level is 100-110 dBA. Since localization in noise is closely related to frequency selectivity, workers with noise-induced hearing losses or other types of sensorineural hearing losses can experience more difficulties than normal listeners.

Secondly, Mr G may experience added difficulties with the use of earplugs. This type of hearing protector can compromise localization abilities if the attenuation is important in the high frequencies. It is also associated with front/rear confusions and leads to longer reaction times. In order to improve localization, higher signal to noise ratios would be required. This inevitably means background noises much lower than 100-110 dBA.

Thirdly, the building in which the travelling crane is installed is considered highly reverberant. The siren should therefore be pulsed and short in duration (in the order of 100-250 msec), with a 25-50 msec. rise time and a repetition rate lower than 3/sec (Patterson, 1982).

In summary, due to multiple constraints (high noise levels, long reverberation duration, presence of hearing loss and the wearing of hearing and face protectors), the localization of the siren is highly compromised. In order to improve this situation, noise reduction should be considered. This long term solution would solve two problems: it would reduce the risk of acquiring noise-induced hearing loss and allow the employee a better chance to localize sound sources. Secondly, the use of hearing protectors would then become superfluous. Aside from noise reduction per se, manufacturers must be informed of the multiple factors involved in localization and encouraged to produce safer sirens.

8.0 DISCUSSION AND CONCLUSION

The review of the literature and the simulated case demonstrate that it is difficult to generalize the results obtained in laboratories to the localization of sound in real life situations, where multiple factors interact. In fact, in the laboratory experiments reported, the number of loudspeaker positions was limited. In many studies, subjects were asked not to move their head during testing. The sound sources to localize were restricted in their spectral content, sound pressure level and duration. Most of the studies show subjects' sensitivity to one particular cue in one particular situation. We must then make this issue a research and clinical priority if we are to impact on the development of safer work environments. This can be a matter of life and death for a certain number of workers.

Presently, most of the pre-employment auditory requirements have been based on hearing thresholds within a certain range on the audiogram. With respect to the relation between auditory demands and capacities in the workplace, Hétu (1993) stated that job requirements involving auditory capacities are in fact almost always based on medico-legal definitions of hearing that were adopted in order to compensate workers affected by noise-induced hearing loss. It is now well known that if the auditory task is done in noisy surroundings, the frequency selectivity of the auditory system will be crucial. The temporal and spatial resolution (localization) are also important factors in many auditory tasks. In short, it is impossible to predict all aspects of auditory performance based on a measurement of auditory sensitivity alone.

In four recent cases of possible job disrimination filed at the Quebec and Canadian Human Rights Commission (Laroche, 1994), the audiogram was used to select candidates without considering the other auditory capacities. One exception is the case of a fireman where speech perception in silence was also considered. In all cases, localization of sound sources was part of the auditory tasks workers had to perform. Because of the lack of clinical tools, it was impossible for the present author to clearly state if these workers could safely do the jobs under analysis. It was nevertheless obvious that some adaptation of the workplace could be put in place in order to improve the safety of the workers, whatever their hearing status. With respect to the adaptation of the workplace, Hétu (1993) notes that we should explore all the facilities which might compensate for the functional limitations associated with hearing loss. For example, the workplace may be adapted by reducing the background noise or the reverberation duration and by selecting well designed warning sounds which will facilitate their localization.

In summary, no clinical tools are yet available to audiologists for the evaluation of localization abilities. The purpose of these tests should be to improve safety in noisy workplaces. Efforts should be put in the development of simple tests which will take into account the different aspects of localization such as the horizontal plane and vertical plane localization, the evaluation of distance and the movement perception, taking into consideration the wearing of hearing portectors, hearing losses and hearing aids. In the meantime, before rejecting a candidate, the auditory abilities required to perform the job should be well described and put in relation with the known auditory status (with and without hearing aids) of the candidate and all possible adapatation of the workplace should be considered. To test a candidate's real abilities in localization (or for other auditory tasks), simulations of job tasks should be performed with the candidate and his results compared to workers who are performing the same job and who are judged competent.

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INCE/USA, INCE/Japan, the Acoustical Society of America, and the Acoustical Society of Japan will join in the sponsorship of ACTIVE 95, the 1995 International Symposium on Active Control of Sound and Vibration. The conference is a continuation of the biannually–organized meetings on Recent Advances on Active Control of Sound and Vibration which were held at the Virginia Polytechnic Institute in Blacksburg, Virginia in 1991 and 1993, and the International Symposium on Active Control of Sound and Vibration which was held in 1991 in Tokyo, Japan. The format of the meeting will follow that of the Blacksburg Conferences with full–length papers in a proceedings volume available to delegates at final registration.

The Symposium will be held on 1995 July 06–08 in Newport Beach, California. The organization of the Symposium will be coordinated by INCE/USA because it immediately precedes INTER–NOISE 95, the 1995 International Congress on Noise Control Engineering which is also being held in Newport Beach on 1993 July 10–12. The venue for both meetings will be the Newport Beach Marriott hotel, an attractive resort hotel overlooking Newport Beach Harbor and the Pacific Ocean.

Professor Jiri Tichy, head of the Graduate Program in Acoustics at the Pennsylvania State University, University Park, Pennsylvania, USA will be the general chairman and Professor Hideki Tachibana of the University of Tokyo will be co–chairman for the Symposium. It is expected that approximately 150 technical papers will be presented covering all aspects of active control of noise, sound fields (including auditoria), and vibration.

CONTRIBUTIONS INVITED

Technical papers in all areas related to the active control of sound and vibration are welcome. A partial list of topics of interest is on the next page of this announcement. Abstracts of papers proposed for presentation at the symposium must be received no later than **1994 November 29.** Japanese authors should send their abstracts to Professor Tachibana. Authors from all other countries should send their abstracts to Professor Tichy. The mailing addresses are on the *abstract cover sheet* which is the third page of this announcement. All abstracts must be accompanied by the *abstract cover sheet*.

If the paper is accepted, it must be typed on special manuscript paper which will be provided by the Symposium Secretariat. The completed manuscript will be printed in the Proceedings of the symposium, and must be received no later than **1995 March 28.** Because of the specialized topic of this symposium, long (10–12 pages) manuscripts will be accepted.

SUBJECT AREAS OF INTEREST

The main subject areas to be covered at the Symposium are:

- Active noise control – theory and applications
- Active vibration control – theory and applications
- Algorithms and systems for active control
- Active control in auditoria and other listening spaces
- Transducers for active noise and vibration control

SYMPOSIUM VENUE

The site of the symposium, the Newport Beach Marriott Hotel, is approximately 1 km from the Pacific Ocean on a hill with a view to the southwest of Newport Beach Harbor, Balboa Island and, on the horizion, Catalina Island about 40 km offshore. Newport Beach is located in Orange County, California, south of Los Angeles. Orange County Airport (John Wayne Airport [SNA]) is about 15 minutes to the north of the hotel by automobile. The airport was completely rebuilt in 1990–1991, and is now an excellent final destination for delegates to INTER–NOISE 95. The Newport Beach Marriott hotel provides complimentary transportation to and from the Orange County Airport. Los Angeles International Airport (LAX) is about 60 km to the northwest. Scheduled air transportation service, scheduled bus service and frequent van service are also available from LAX to Orange County Airport.

The location of the hotel is very attractive; opportunities for recreational activities include sightseeing at *Disneyland* in Anaheim, a boat trip to Catalina Island, and the harbor and beaches in the Newport Beach and Laguna Beach areas (readily accessible without an automobile). The hotel is adjacent to one of Southern California's major shopping centers, Fashion Island, in the Newport Center, and is about 20 minutes from the well–known South Coast Plaza shopping center and the Orange County Center for the Performing Arts in Costa Mesa. Some of the best restaurants in California are within a 30–minute drive from the hotel.

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