A SPATIAL AUDITORY DISPLAY FOR THE PREVENTION OF PEDESTRIAN-MOTOR VEHICLE COLLISIONS

John G. Neuhoff *John Preston*

The College of Wooster
Wooster, OH 44691, USA
jneuhoff@wooster.edu
http://pages.wooster.edu/jneuhoff/

ABSTRACT

Pedestrian-motor vehicle collisions account for over 6% of all workplace fatalities and are the leading cause of work related traumatic injury among highway workers. Interventions to reduce these accidents have focused primarily on vision. However, given the high demands on the visual attention of both pedestrian workers and vehicle operators, auditory warning might be a fruitful avenue for the reduction of traumatic injury to pedestrians who interact with motor vehicles. Recent research on the perception of auditory looming has shown that listeners tend to underestimate the amount of time it will take for an approaching sound source to reach them. The perceptual bias effectively signals that the source is closer than actual and thus, gives the listener more time than expected to avoid collision (the margin of safety effect). Here we identified some specific acoustic conditions that maximize the perceptual bias to hear looming sound sources as closer than actual. We made binaural recordings of approaching motor vehicles that produced either tones or broadband noise as they approached. Listeners underestimated vehicle arrival time in all conditions, but exhibited a significantly larger margin of safety for vehicles that produced tones as they approached. The results suggest that making approaching vehicles produce subtle tones by introducing a temporary a pavement treatment in work zones should increase the margin of worker safety.

1. INTRODUCTION

Over two thousand pedestrian workers in the United States were fatally injured by collisions with motor vehicles in a five-year period beginning in 1995 [1]. Pedestrian-motor vehicle collisions account for over 6% of all occupational fatalities annually. Yet, they have received comparatively little attention from injury prevention researchers [2]. There have been numerous efforts to reduce pedestrian-motor vehicle collisions that focus primarily on vision. These techniques range from the modification of work zone layout to the use of illumination and high visibility apparel. Although auditory backup warnings are routinely installed on workplace vehicles and equipment, auditory methods of reducing pedestrian-motor vehicle collisions have generally received less research attention. However, given the high demands on the visual attention of both pedestrian workers and vehicle operators, warning from an auditory might be a particularly fruitful avenue for the reduction of traumatic injury.

Recent research on the perception of auditory looming has shown that listeners tend to underestimate the amount of time it will take for an approaching acoustic source to reach them (auditory time-to-arrival) [3-6]. Researchers have argued that this systematic perceptual bias has evolved to provide a "margin of safety" in the perception of looming acoustic sources [7-9]. The bias effectively signals that the source is closer than actual and thus, gives the listener more time than expected to avoid collision. The potential evolutionary origins of this perceptual bias are supported by both phylogenetic and neurophysiological evidence. First, rhesus monkeys have been shown to exhibit an analogous bias for looming tones [10]. Second, brain imaging studies in humans have identified specific brain areas that process looming tones with priority [11]. Areas of activation include those responsible for allocating auditory attention, motor planning, and the translation of sensory information into appropriate action.

However, there are two caveats to the findings on auditory looming that are important with regard to the reduction of worker fatality and traumatic injury. First, much of the pertinent research on auditory looming has been done with source velocities that are below those typically attained by motor vehicles. Second, there is emerging evidence to suggest that the perceptual margin of safety for auditory source approach is greater for tones than for the type of broadband noise that is typically emitted by a moving motor vehicle.

The objectives of this research are to identify the specific acoustic conditions that maximize the perceptual bias to hear looming sound sources as closer than actual (the margin of safety effect). This information might then be used to enhance pedestrian worker safety in a cost effective manner by taking advantage of perceptual biases. For example, if tonal sounds are found to increase the margin of safety, then measures to make approaching vehicles produce subtle tones in work zones (e.g., by the interaction of tires and a temporary pavement treatment) should produce an increased margin of safety. If workers underestimate auditory time-to-contact, they will have longer than expected to react to an approaching vehicle, thus obtaining an advanced warning of the approaching source.

1.1 Tones and Sound Source Identity

Spectral differences in estimating source approach may reflect the relative importance of harmonic tones versus broadband noise in a natural environment. In this sense, "relative importance" means the reliability with which a sound can specify source identity and the ease with which a sound can be separated or parsed from background noise. The ability to detect an approaching sound source in the presence of background noise is particularly important in roadwork environments, where workers are frequently using equipment

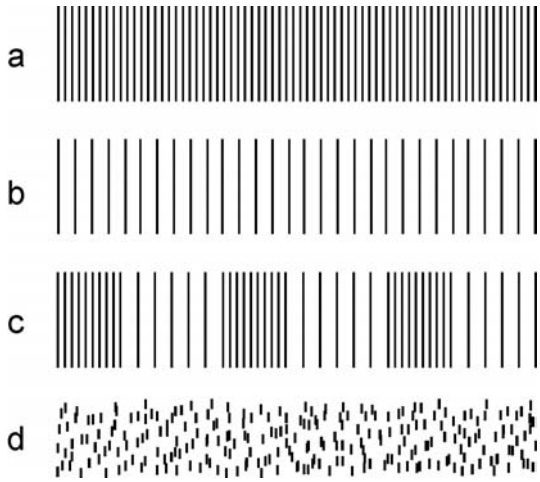

Figure 1. *A schematic of potential temporary pavement treatments that would produce* ***a.)*** *high frequency tones,* ***b).*** *lower frequency tones,* ***c).*** *frequency modulated tones, and* ***d).*** *broadband noise. Temporary pavement treatment could be much more subtle and even less expensive than traditional rumble strips because it is designed to simply produce an auditory stimulus, not the intense vibrotactile signal designed to awaken drowsy drivers.*

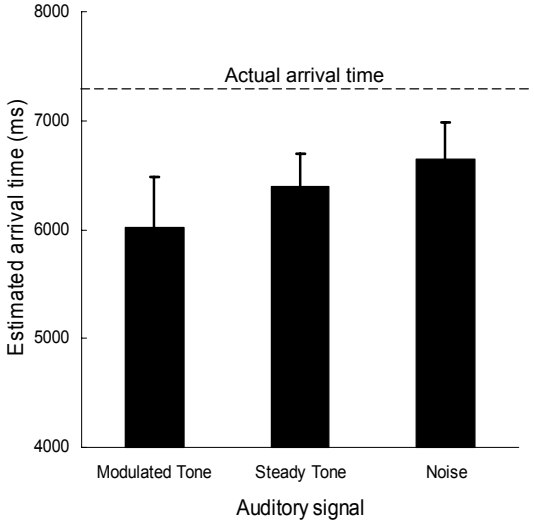

Figure 2. *Mean arrival time estimates by spectral condition. Modulated tones provide a significantly greater margin of safety for looming vehicles than broadband noise. The actual arrival time of 7300 ms is indicated by the dotted line. Error bars represent 1 SEM.*

that emits broadband noise at high levels. Tones can specify source identity more reliably than noise, in part because of the correlation between the intensity changes of their individual spectral components. Listeners can use this correlation to parse auditory scenes and identify single sources as separate from background noise [12]. In essence then, tones can specify the identity of environmentally important individual sound sources that are more easily separated from background noise.

1.2 Summary and Rationale

Listeners typically underestimate auditory arrival time and allow a margin-of-safety in judging source approach. Evidence suggests that the acoustic information acquired as a source approaches informs a categorical decision as to whether the listener has time to direct the visual system toward the source, or must initiate motor responses to avoid the approaching source. Underestimation of arrival time may be due to a perceptual asymmetry in processing rising and falling intensity change. Work with approaching and receding sound sources supports this hypothesis, showing that listeners perceive approaching sources as stopping closer than actual, and closer than receding sources with equidistant terminal positions. The effect appears to be greater for harmonic tones than for broadband noise. Despite these findings, there is relatively little research on auditory looming. The work that has shown differences between tones and noise has examined approach velocities that are below those typical of motor vehicles in a workplace environment.

The prospect of an auditory warning of approaching vehicles is attractive for several reasons. First, tones produced by the interaction of tires and a temporary pavement treatment would be an easily implemented and cost effective means of creating a high compliance warning of vehicle approach that would be unaffected by poor visibility conditions. Second, the auditory warning might have the added benefit of alerting drivers to construction zones and focusing their attention at critical junctions. Finally, the technique might also be used to reduce pedestrian-motor vehicle collisions in other critical areas where pedestrians must interact with motor vehicles (e.g., school crossings).

Here, we presented listeners with binaural recordings of approaching vehicles under three different acoustic conditions. Listeners estimated the arrival time of the looming vehicles. We hypothesized that vehicles that produced tones on approach would produced a greater margin of safety in estimating arrival time than those that produced broadband noise.

2. METHODS

2.1 Participants

We tested eight males and ten females who were all between the ages of 18 and 22 yrs. All reported normal hearing, and all were naïve to the hypothesis. Participants received course credit for their participation.

2.2 Apparatus and Stimuli

We used a Neumann KU-100 dummy head binaural microphone and a Tascam DA-P1 DAT recorder to make binaural digital recordings of an approaching automobile. The vehicle approached at 30 mph (13.4m/s) with a total travel

distance of 98.7 m from the starting point of the recording to the point where the vehicle passed the binaural microphone. A loudspeaker was mounted outside the vehicle from which acoustic stimuli were played as the vehicle approached. Three different stimuli were synthesized that simulated varying the spacing of notches in a temporary pavement treatment (see Figure 1). The three stimuli consisted of a 400 Hz tone, a tone that modulated between 200 and 700 Hz in 500 ms intervals, and white noise. The tonal stimuli were triangle waveforms. All stimuli were presented at 85 dB measured 1 m from the source, and the dummy head was placed 1 m from the path of the vehicle. Participants heard the playback from a digital audio card over headphones in a sound-attenuated booth and made their arrival time estimates by pressing the spacebar on a computer keyboard.

2.3 Design and Procedure.

Listeners were given two practice trials with each of the three stimulus types and then heard each of the 3 stimuli 3 times for a total of 9 trials in random order. Listeners indicated when the approaching source would just pass them (the point of closest approach) by pressing the spacebar on a computer keyboard. Response times were recorded by computer, and a repeated measures analysis of variance was conducted to examine difference between the mean response times in each condition.

3. RESULTS

Mean estimate of vehicle time-to-arrival are shown in Figure 2. Listeners underestimated time-to arrival in all conditions. However, a repeated measures analysis of variance showed a significant main effect for the type of auditory stimulus ($F_{2,34}$ =3.67, $p < .05$). The modulated tone provided a significantly greater degree of warning than the broadband noise signal, with the mean for the steady tone falling between the means for the noise and the modulated tone.

4. DISCUSSION

The current results suggest that approaching motor vehicles might be perceived with a greater margin of safety if they produced subtle tones as they approached. Currently, permanent inexpensive pavement modifications (rumble strips) are made to prevent run-off-road single vehicle accidents. These systems use notches in shoulder pavement up to 1.2 cm deep to produce sound and vibrations inside the vehicle to awaken drowsy drivers [13]. However, because to goal of the current proposal is a tonal warning system for workers and not a vibrotactile alarm for drivers, pavement modifications to produce tones could be employed that are temporary, more subtle, and even less costly.

4.1 Additional Benefits

4.1.1 Low Visibility

Pedestrian workers interacting with motor vehicles and equipment are at greatest risk of traumatic injury under conditions of low visibility. These conditions include work performed at night and in weather such as rain, snow, and fog. One particular advantage of incorporating auditory warnings of vehicle approach is that such a warning would be unaffected by low visibility conditions and thus, provide a safety benefit when visually based safety implements are least effective and workers are most vulnerable.

4.1.2 Cost Effectiveness

Providing acoustic warning by temporary pavement treatments should be a particularly cost effective means of reducing traumatic injury. Permanent rumble strips to prevent run-off-road single vehicle accidents can be installed for less that $ 0.30 per foot [13], and these systems are designed to produce intense vibrotactile and acoustic information that would awaken a drowsy driver. The pavement treatment in the current proposal would be temporary and would simply need to be loud enough to be heard by pedestrian workers. This type of treatment may be considerably less expensive.

4.1.3 Driver Alerts

Vehicles that produce tones when entering a construction zone may provide the added benefit of alerting drivers, focusing their attention more closely on the road and work zone, and in turn, causing a reduction in speed. Follow-up studies are proposed to examine the effects of subtle tones produced by tire-pavement interactions on driver behavior.

4.1.4 Implementation and Worker Participation

A persistent problem in implementing safety measures in the workplace is that of low worker compliance. For reasons, of convenience, productivity, or time, workers often bypass or disable important safety implements. Tonal auditory warning of vehicle approach would provide an easily implemented intervention for reducing traumatic injury. Because the intervention is an integral part of the work environment and not a measure that would need to be taken by individual workers, worker participation in the intervention would be exceptionally high.

4.1 Conclusions

The current work demonstrates a perceptual bias in estimating the time-to-arrival of a looming sound source. Tonal sounds (and particularly modulated tones) provide a greater margin of safety on approach than the broadband noise that is typically produced by approaching vehicles. Incorporating temporary pavement treatments in work zones that interact with vehicle tires to produce tones has the potential to significantly reduce traumatic injury from pedestrian motor-vehicle collisions.

5. ACKNOWLEDGEMENTS

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