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A Technical Note

Audible pedestrian traffic signals: Part 3. Detectability

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Abstract—This project (10) evaluated audible pedestrian traffic signals (APTS) from three perspectives: 1) the patterns of use and the impact of these signals on pedestrian travel; 2) the physical characteristics of the sound emitted by the Nagoya/Traconex APTS; and, 3) the detectability of the sounds emitted by this brand of APTS. This paper, the last of three companion articles (13,14), describes the detectability of the sounds emitted by the Nagoya/Traconex audible traffic signal, the unit most commonly found in the western United States and almost exclusively in California. To determine detectability, three groups of subjects with normal hearing—young sighted adults (controls), elderly sighted adults, and elderly blind adults—participated in an audiological study. Auditory stimuli, which consisted of APTS sounds embedded in various levels of interfering traffic noise, were presented to subjects seated inside a double-walled sound-treated chamber. The subjects were instructed to press down on a response button as soon as they heard the audible pedestrian traffic signal. The percentage of correct detections determined the absolute detectability of APTS under various S/N ratios. The subjects' speed of response indicated how quickly a pedestrian might begin to cross the intersection upon hearing the APTS.

Key words: *audible pedestrian traffic signals, audiological tests, detectability, elderly, signal to noise ratio, speed of response, traffic noise, visually impaired.*

BACKGROUND

In order for audible pedestrian traffic signals to be effective, the sounds they produce must be easily heard so that an appropriate response can be elicited. A review of the literature examined several issues that bear on this stimulus-response behavior. These issues include auditory sensitivity, effects of masking due to traffic noise, signal type and duration, effects of age, and the implications of signal detection theory with respect to the desired response.

Auditory sensitivity and traffic noise interference

Auditory threshold for the range of frequencies heard by the human ear (20 to 20,000 Hz) is best between 2000 to 5000 Hz. This means that audible traffic signals will be the most readily heard if their sounds contain frequency components within this range, even if there is low frequency interference such as that from traffic noise. In their spectral analysis of traffic noise, Welsh and Blasch (16) found 78 dB of sound pressure level (SPL) at 125 Hz and only 45 dB SPL at 12,500 Hz when the overall traffic level was 84 dB SPL.

Although most of the sound energy in traffic noise occurs in frequencies below 2000 Hz, low frequency sounds can nevertheless effectively mask signals in the 2000 to 5000 Hz region if the intensity of the masker is sufficiently strong (80 to 100 dB SPL) (6). Recorded traffic noise samples at intersections studied in this project ranged from 55 dB to 85 dB SPL. Therefore, low frequency masking of the audible pedestrian signal is possible.

Signal type

Besides the level of background noise, spectral complexity of the signal also affects its detectability in noise. Signals that are complex (i.e., ones containing a variety of frequencies at different intensities) are easier to detect

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than a pure tone (3,8). This finding implies that maximally detectable audible traffic signals should emit multiple frequencies.

Signal frequency and duration

Both the frequency and duration of the signal also affect its detectability. Detectability of signals in noise steadily worsens with signal durations shorter than 500 ms (7). Furthermore, low frequencies (< 1000 Hz) require more intensity or longer durations than high frequencies (> 3000 Hz) to be equivalently detectable (9). Therefore, audible traffic signals should be at least 500 ms in duration and contain frequency components above 3000 Hz.

Effects of age

Audible traffic signals are intended to help blind and sight impaired pedestrians, many of whom are elderly. Smith and Sethi (11) found a slowing of brain wave activity in their healthy elderly subjects and a delay in central reaction times based on their longer time for recognition and slower response speeds. The Committee on Hearing Bioacoustics and Biomechanics reported that a slowdown of both sensory motor and mental processes occurred with aging even in normal hearing older subjects (4). Blackington (1) found that elderly subjects with normal hearing were also more susceptible than their young normal hearing counterparts to the effects of masking noise when that noise precedes (forward masking) the target signal. The groups, however, performed similarly when the signal and the masker were presented simultaneously. Both simultaneous and forward masking conditions due to traffic noise exist for the older pedestrian trying to detect the audible traffic signal at a typical intersection.

Theory of signal detection

Detectability of signals depends not only on the relative intensities of the traffic noise and signal, but also on how different the signal is from the noise and on the costs associated with making an *incorrect* decision. The theory of signal detection (TSD) directly addresses this issue. TSD makes the distinction between what the subject actually hears (auditory sensitivity) and the manner in which he/she responds. The response reflects not only a subject's auditory sensitivity, but also the bias and response criteria assumed by the subject (12).

TSD states that a subject's criteria for making a response to a signal imbedded in noise are based on three factors: 1) the probability of there being a signal plus noise versus noise alone; 2) the amount of overlap between conditions of signal plus noise and noise alone; and, 3) the values and costs associated with the outcome of either a walk or don't walk decision. In short, a subject's response to an audible traffic signal is strongly dependent on auditory sensitivity, the separation between the noise alone and signal plus noise probability distributions, the ability of the auditory system to make use of this separation, and the subject's relative value criteria for correct and incorrect responses.

Response time has also been examined in the context of TSD (7). It was observed that as signal to noise (S/N) ratios became more negative (difficult) and fell below the decision criterion, "no" decisions (i.e., signal was not heard) would become more rapid, while less negative (easier) S/N ratios above the decision criterion resulted in more rapid "yes" decisions (i.e., signal was heard). Emmerich, Gray, Watson, and Tanis (5) found that a listener's response latency shortened as he/she became more confident that a signal in noise was heard. Similarly, as the listener became more confident that there was not a signal (noise only), his/her response speed for a "no" response increased. These findings are relevant to the blind pedestrian who needs to be highly confident that the audible traffic signal was present before he/she would begin crossing the street. Thus, decision time or response latency would be expected to lengthen under conditions of poorer S/N ratios.

With the above as background, an audiological study (2) was conducted to: 1) determine the relative detectability of the north-south (cuckoo) and east-west (chirp) APTS in the presence of various levels of background traffic noise (S/N ratios of −5 to −30 dB); and, 2) compare the response times to these signals from three subject groups: young normal-sighted normal-hearing, elderly normal-sighted normal-hearing, and elderly normal-hearing blind subjects. Audible pedestrian traffic signals made by Nagoya/Traconex (15) were chosen for this audiological study because they are almost exclusively used in California and because the manufacturer made them available for extended use by the research team.

METHODOLOGY

Seven young normal-sighted adults ages 22 to 35 years (mean of 29.1 years), seven elderly normal-sighted adults ages 61-78 years (mean of 67.6 years), and five legally blind adults ages 62 to 84 years (mean of 73 years) participated in this study. "Normal sighted" meant the ability to readily see the WALK/DON'T WALK traffic signal from across the street. "Normal hearing" meant pure tone air conduction thresholds of 25 dB HL or better for frequencies between 500 and 4000 Hz (ANS, 1969). All subjects had unremarkable medical histories.

Stimulus parameters

Field recordings of the sound pressure levels of the audible traffic signals and traffic noise levels were made at three busy intersections that had audible pedestrian traffic signals in place (14). The decibel (dB) sound pressure levels (SPLs) for the signals were 105 to 110 dB SPL (A weighted) measured 3 cm in front of the device. The traffic noise ranged from 55 dBA to 85 dBA peak impulse, measured at 9:30 to 11:00 a.m. and during the evening rush hours of 4:00 to 6:00 p.m.

The north-south cuckoo signal contained major frequency peaks at approximately 950, 1950, 2875, 3825, and 4725 Hz. The sound pattern lasted about 400 ms, repeated once every 1.5 s, and had a characteristic sound of an electronic "cuckoo" produced by incrementally changing from one primary frequency to another (1250 Hz to 950 Hz). In contract, the east-west chirp signal contained major frequency peaks at approximately 2100 and 6300 Hz. The electronic chirp was produced by a continuous variation in frequency fundamentals from 2600 to 1500 Hz with harmonics up to 7000 Hz. This sound pattern lasted about 140 ms and repeated at 1-second intervals. Spectral analysis of the traffic noise revealed wide-band noise with frequency components from 6 Hz to 7000 Hz. Most of the acoustic energy, however, was below 1000 Hz (14).

Stimulus generation

Special tape recordings of the traffic signals and traffic noise were made for the audiological study. To obtain a clear recording of the signals without background noise, the sounds emitted by north-south and east-west Nagoya/Traconex audible pedestrian traffic signals were tape-recorded in a double-walled sound treated test chamber using a Sharp tape recorder. To obtain a somewhat constant source of traffic noise, a continuous loop of tape (10 s) was made by retaping on automatic gain the earlier field recordings of the wide-band traffic noise.

The continuous loop traffic noise tape, played back on a Sharp tape recorder, was channeled into a Lafayette Instrument module. The tape recorder's output was fed directly into the shaped rise/fall audio switch (ANL-913), and then onto the 600 ohm attenuator (ANL-917). The traffic noise was shaped with a rise/fall time of 10 ms, attenuated, and fed into the audio amplifier/mixer (ANL-914). The traffic signal tapes were played back on a high fidelity Marantz tape recorder (Model PMD 221), channeled into a second attenuator (ANL-917), and then fed to the audio amplifier/mixer (ANL-914) where the traffic noise and signals were mixed (**Figure 1**).

After mixing, the signal and noise stimuli were fed into a Madsen clinical audiometer (OB822). The audiometer was set at a fixed output intensity level of 65 dB HL, and the sounds were presented binaurally via standard TDH-39 earphones. The traffic signal attenuator (ANL-917) was adjusted to achieve presentations at the following S/N ratios: −5, −10, −15, −20, −25, −30, −35 dB.

Custom designed software for an Apple II Plus computer started each presentation by turning on the traffic noise; controlled the length of the traffic noise presentation (10 s); generated a random time element before starting the APTS signal during the traffic noise presentation; and recorded the subjects' response times to the traffic signals.

Calibration of the Bruel and Kjaer sound level meter (Type 2226) was verified using a Quest CA22 sound calibrator. The level of the traffic noise and signals were calibrated into dB SPL values through a Madsen clinical audiometer (OB822) at the earphone using a Bruel and Kjaer sound level meter (Type 2203). At the onset of testing, intensity levels for both the signals and noise were adjusted to peak at zero dB on the V.U. meter of the audiometer.

Test procedures

All testing was performed with the subjects comfortably seated inside a double-walled sound treated test chamber. The auditory stimulus was presented binaurally via TDH-39 earphones housed in MX/AR cushions. The subjects were instructed to press down on a hand-held response button as soon as they heard the audible pedestrian traffic signal. For each trial, a "get ready" warning light illuminated, and then 10 s of traffic noise began. Following a random delay, the cuckoo or chirp signal began to sound. The traffic noise sound level was set at 65 dB HL while the traffic signal presentation level varied in intensity to achieve the desired S/N ratios. For each stimulus trial, a series of 3 cuckoos or 4 chirps were present during the 10 s of traffic noise.

All seven signal to noise ratios were presented to each subject during every 2-hour test session. The entire procedure consisted of two trials of five presentations each, heard at each of the seven S/N ratios. To familiarize

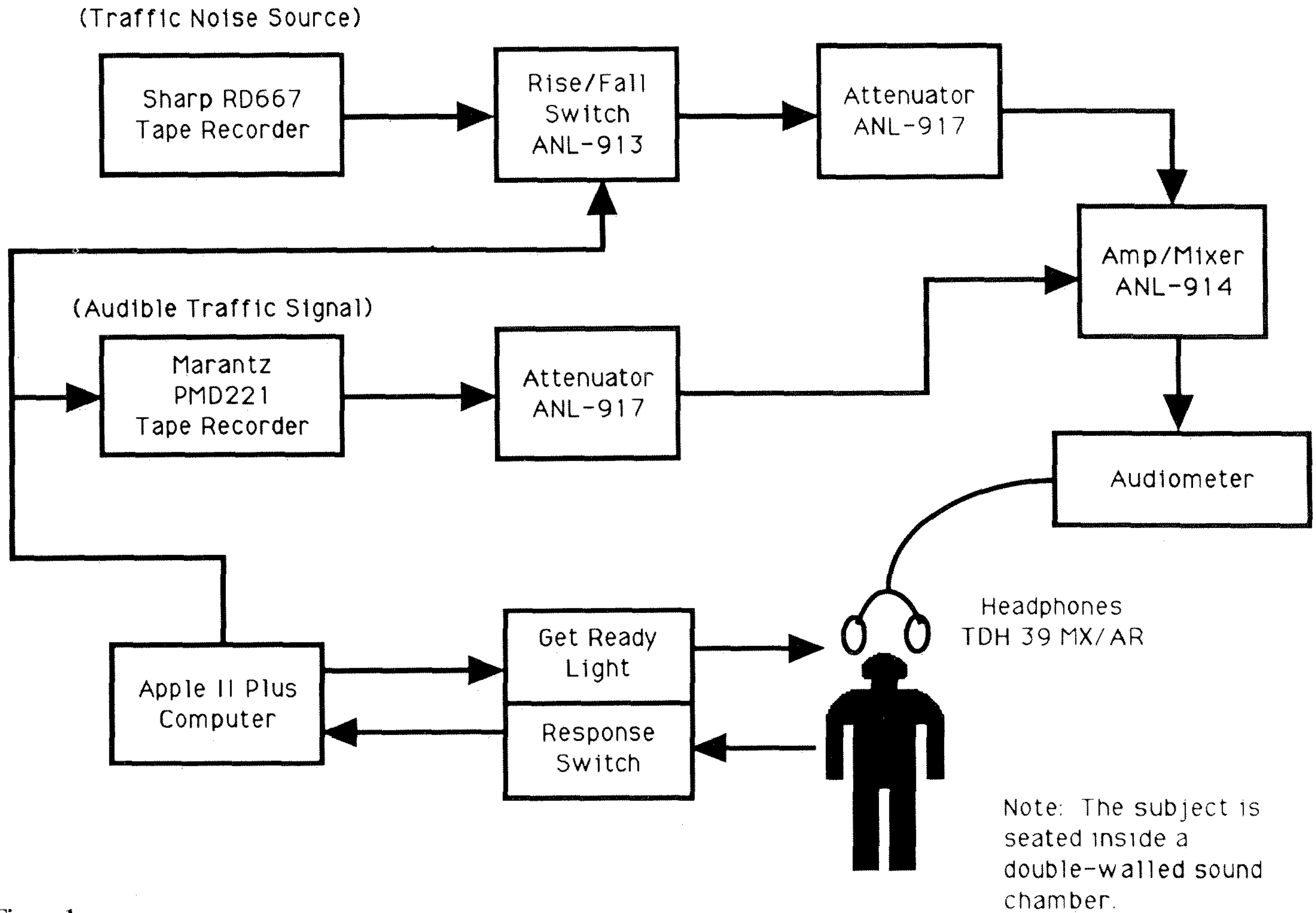

Figure 1.
Block diagram of the audiological test set-up.

the subjects with the task, testing began with a practice trial (five presentations of the auditory stimulus) at zero dB S/N ratio. The two APTS signals (cuckoo and chirp) were tested separately with the presentation order of the S/N ratios randomized.

RESULTS

For each stimulus presentation, a response time was recorded in milliseconds. If the subject did not hear the signal and therefore did not respond, a "no response" score was recorded by the computer. The five presentations in each trial and for each stimulus condition (e.g., −5 dB S/N ratio, trial 1, north-south signal) were averaged together to obtain the response time for that test condition. Detectability of the two sounds under various S/N ratios was calculated by converting the raw data into percentage correct response scores. The response data from all the subjects and all test conditions were then prepared for analysis by the Statistical Package for the Social Sciences (SPSS/PC+) computer program (2). The criterion for statistical significance was set at $p \leq 0.05$.

Percent correct detection

A multivariate analysis of variance (MANOVA) with repeated measures determined if there were statistically significant differences in percentage of correct detection as a function of group membership, signal type, S/N ratio, and trial number. One-way analyses of variance were applied to the significant components obtained from the MANOVA. The Scheffé post hoc procedure was applied to all significant ($p \leq 0.05$) results. The bar graphs in **Figure 2** and **Figure 3** depict the average percent correct detection of both signals under the tested S/N ratios.

The multivariate analysis of variance (summarized in **Table 1**) revealed that:

- For both the cuckoo and chirp signals, the elderly sighted group had noticeably poorer signal detection at the more difficult S/N ratios (−20 through −30 dB). At the −35 dB S/N ratio, all groups achieved 0 percent detection.
- For the north-south cuckoo signal, the elderly sighted group had a significantly poorer ($p \leq 0.05$) detection rate at the −25 dB S/N ratio than either the young sighted or elderly blind groups.
- For the east-west chirp signal, all three test groups were similar (i.e., not significantly different) in their ability to detect this signal.
- One hundred percent correct detection was achieved by all subject groups for S/N ratios of −15 dB or better.

Response time

A second multivariate analysis of variance (MANOVA) with repeated measures determined if there were statistically significant differences in response time as a function of group membership, signal types, S/N ratio, and trials. Due to the lack of responses at −30 dB and −35 dB S/N ratio, they were excluded from the statistical analysis. The Scheffé post hoc procedure was performed on all significant ($p \leq 0.05$) results. **Table 2** lists the average response times of the three groups, with means and standard deviations for each stimulus condition.

The multivariate analysis of subjects' response times (summarized in **Table 3**) revealed that the elderly sighted group had significantly longer response times than the young sighted group and elderly blind group at −20 and −25 dB S/N ratios for the north-south signal. The performance of the elderly sighted group was significantly poorer on their first listening trial. For the east-west signal, there were no significant differences between the groups under any of the S/N ratios studied.

Table 1.
Summary of multivariate analysis of variance (MANOVA) with repeated measures for percent correct detection as a function of group, signal type, S/N ratio, and trials. (Abstracted from Brand [2])

Source of variance	SS	df	MS	F	F prob.
Between Subjects					
Group	1.22	2	0.61	5.15	0.019*
Error	1.90	16	0.12		
Within Subjects					
Signal type	0.13	1	0.13	4.38	0.053
Signal × group	0.22	2	0.11	3.56	0.052
Error	0.48	16	0.03		
Trial	0.05	1	0.05	3.61	0.075
Trial × group	0.00	2	0.00	0.02	0.982
Error	0.21	16	0.01		
S/N ratio	86.83	6	14.47	208.73	0.000**
S/N × group	2.83	12	0.24	3.41	0.000**
Error	6.66	96	0.07		
Signal × trial	0.00	1	0.00	0.01	0.933
Signal × trial × group	0.01	2	0.01	0.67	0.525
Error	0.13	16	0.01		
Signal × S/N ratio	0.27	6	0.05	1.88	0.092
Signal × S/N × group	0.84	12	0.07	2.93	0.002**
Error	2.30	96	0.02		
Trial × S/N ratio	0.10	6	0.02	2.19	0.051
Trial × S/N × group	0.12	12	0.01	1.32	0.221
Error	0.71	96	0.01		
Signal × trial × S/N	0.01	6	0.00	0.36	0.933
Signal × trial × group	0.05	12	0.00	0.82	0.633
Error	0.50	96	0.01		

*$p < 0.05$
**$p < 0.01$

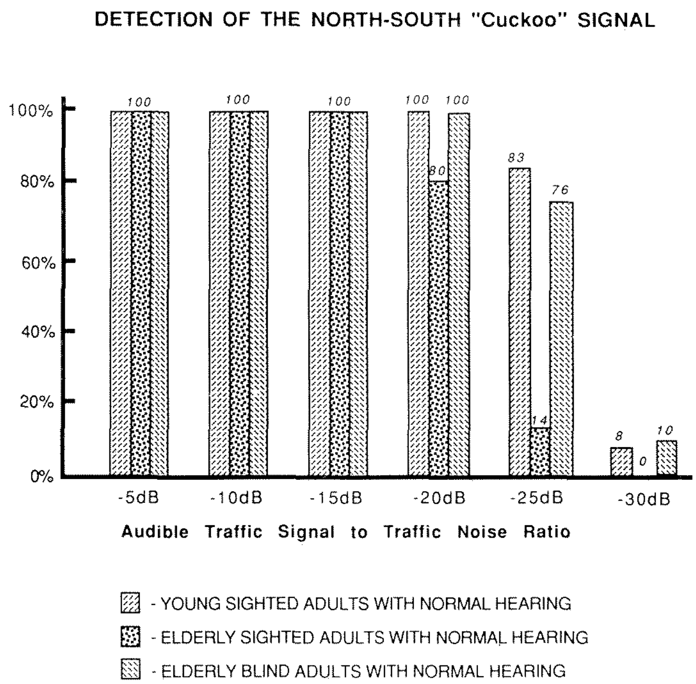

Figure 2.
Percent correct detection of the north-south "cuckoo" signal under various S/N ratios for all three test groups.

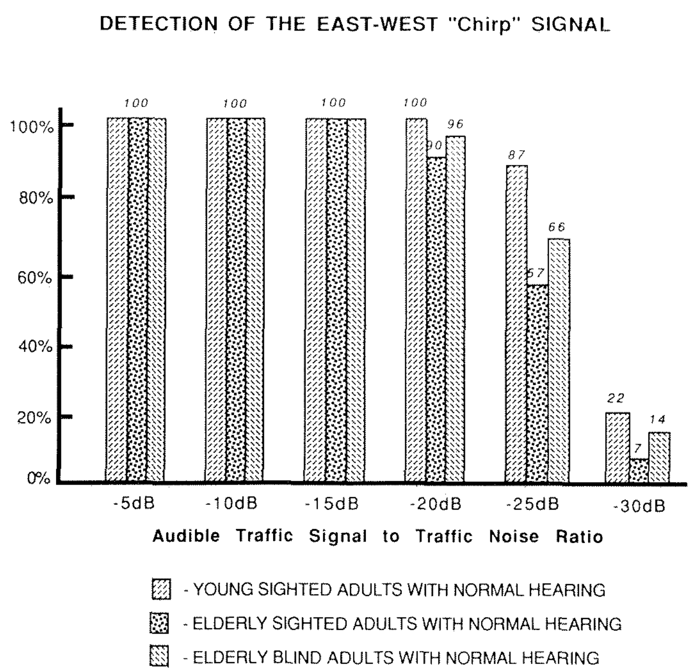

Figure 3.
Percent correct detection of the east-west "chirp" signal under various S/N ratios for all three test groups.

DISCUSSION

The blind-elderly group seemed more resistant to the effects of traffic noise on their detection of and reaction time to both the north-south and east-west audible traffic signals. Their performance was similar to that of the young sighted controls for all stimulus-response conditions. Although all subject groups exhibited longer reaction time as the S/N ratio worsened, only the elderly sighted subjects were significantly poorer than the other two groups at detecting the north-south signal at the more difficult S/N ratios (−20 and −25 dB). The elderly sighted group also required a significantly longer time to react to the appearance of the north-south signal at these S/N ratios in comparison to the other two groups. Because blind persons depend so much on their auditory sense, the elderly blind subject group performed better than their sighted counterparts, particularly when both groups were asked to detect the north-south cuckoo in heavy traffic noise (−20 to −30 dB S/N ratios).

For all three test groups, the electronic chirp was more easily detected than the cuckoo. The reason for this outcome is because the chirp was very spectrally different from the low frequency traffic noise. The chirp had frequencies in the 2000 to 7000 Hz range whereas most of the traffic noise was below 1000 Hz. The chirp was also temporally continuous for about 140 ms whereas the longer cuckoo consists of two quick bursts of low frequency (950 to 1250 Hz) sounds, each of which lasts less than 90 ms (14).

This controlled study occurred in a safe laboratory environment without the danger associated with crossing a street. Based on the theory of signal detection, these same test subjects would reset their decision criteria so that their response times to the "chirp" or "cuckoo" would be longer under the same S/N ratios. Their response times for a "yes" decision would be especially longer as detection becomes more difficult (5,7,12).

Many older pedestrians have bilateral sensory-neural hearing loss above 2000 to 3000 Hz. For them, the detection of the chirp signal will be more difficult due to its higher frequencies and short duration. Thus, even poorer performance under most S/N ratios in terms of response latency and accurate detection of the audible signal can be expected for people with high frequency hearing loss.

Table 2.
Average response times (in seconds) to the north-south and east-west signals with means and standard deviations for the young sighted, elderly sighted, and elderly blind groups, for each of the S/N ratios. (Abstracted from Brand [2])

S/N	Young sighted		Elderly sighted		Elderly blind	
ratio	mean	SD	mean	SD	mean	SD
North-south						
−5 dB	0.44	0.16	0.45	0.18	0.50	0.17
−10 dB	0.44	0.11	0.46	0.15	0.63	0.25
−15 dB	0.44	0.12	0.56	0.18	0.60	0.28
−20 dB	0.47	0.12	1.11	0.62	0.71	0.30
−25 dB	0.96	0.49	3.11	0.98	1.84	1.14
East-west						
−5 dB	0.27	0.07	0.31	0.06	0.38	0.17
−10 dB	0.32	0.07	0.32	0.10	0.47	0.22
−15 dB	0.34	0.13	0.39	0.07	0.38	0.13
−20 dB	0.48	0.12	0.69	0.60	0.60	0.33
−25 dB	1.34	0.48	1.50	0.49	1.61	0.64

Table 3.
Summary of multivariate analysis of variance (MANOVA) with repeated measures for response time as a function of group, signal type, S/N ratio, and trials. (Abstracted from Brand [2])

Source of variance	SS	df	MS	F	F prob.
Between subjects					
Group	5.90	2	2.95	3.32	0.062
Error	14.20	16	0.89		
Within subjects					
Signal type	1.48	1	1.48	8.44	0.010*
Signal × group	3.58	2	1.79	10.23	0.001**
Error	2.80	16	0.18		
Trial	0.09	1	0.09	1.61	0.223
Trial × group	0.90	2	0.45	7.64	0.005**
Error	0.94	16	0.06		
S/N ratio	66.88	4	16.72	88.50	0.000**
S/N × group	5.45	8	0.68	3.60	0.002**
Error	12.11	64	0.19		
Signal × trial	0.85	1	0.85	7.42	0.015*
Signal × trial × group	0.97	2	0.48	4.21	0.034*
Error	1.84	16	0.11		
Signal × S/N ratio	0.05	4	0.01	0.07	0.990
Signal × S/N × group	6.58	8	0.82	5.34	0.000**
Error	9.86	64	0.15		
Trial × S/N ratio	2.96	4	0.74	11.94	0.000**
Trial × S/N × group	2.94	8	0.37	5.94	0.000**
Error	3.96	64	0.06		
Signal × trial × S/N	1.22	4	0.30	3.50	0.012*
Signal × trial × group	1.01	8	0.13	1.45	0.194
Error	5.55	64	0.09		

*p < 0.05
** < 0.01

CONCLUSIONS AND RECOMMENDATIONS

The acoustic characteristics of an optimal audible pedestrian traffic signal must balance the low frequency (below 1000 Hz) masking potential of traffic noise and the high frequency (above 2500 Hz) sensorineural hearing loss common in older adults. Regardless of the acoustic signal, how well one hears will ultimately determine the effectiveness of these signaling devices. Based on analysis of the collected data, the following conclusions and/or recommendations seem to be indicated:

- Both signals should always yield at least a −15 dB S/N ratio in relation to the existing ambient traffic noise level.
- The audiological study results and foregoing literature review suggest that the north-south cuckoo signal be changed to raise the frequency components to include primary frequencies within the 2000 to 3000 Hz range with harmonics as high as 7000 Hz. The current incremental change of the cuckoo from 1250 to 950 Hz is too easily masked by the louder low frequencies contained in the traffic noise and is too temporally similar to incremental patterns of traffic noise (e.g., automobile horns, passing motorcycles, diesel trucks and buses, and engine acceleration/deceleration).
- An audible pedestrian traffic signal should emit a complex array of frequencies temporally continuous and have a duration of 500 ms. A warble tonal complex with fundamental center frequency of 2500 Hz varying between 2000 and 3000 Hz is recommended. The duration of the east-west chirp signal should also be lengthened to 500 ms per presentation.
- For more effective use of APTS, the WALK phase of the traffic signal should be lengthened 1.5 to 2.0 s when the APTS is in use and when there is loud traffic noise. This amount of additional time for the WALK phase would compensate for the greater response latencies caused by poorer S/N ratios and the element of danger associated with crossing a major roadway.

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