Directional guidance from audible pedestrian signals for street crossing

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Typical audible pedestrian signals indicate when the pedestrian walk interval is in effect but provide little, or even misleading information for directional alignment. In three experiments, blind and blindfolded sighted adults crossed a simulated crossing with recorded traffic noise to approximate street sounds. This was done to investigate how characteristics of signal presentation affected usefulness of the auditory signal for guiding crossing behaviour. Crossing was more accurate when signals came only from the far end of the crossing rather than the typical practice of presenting signals simultaneously from both ends. Alternating the signal between ends of the crossing was not helpful. Also, the customary practice of signalling two parallel crossings at the same time drew participants somewhat toward the opposite crossing. Providing a locator tone at the end of the crossing during the pedestrian clearance interval improved crossing accuracy. These findings provide a basis for designing audible pedestrian signals to enhance directional guidance. The principal findings were the same for blind and sighted participants and applied across a range of specific signals (e.g. chirps, clicks, voices).

1. Introduction

The opportunity for pedestrians to cross streets is essential for environmental accessibility, yet this is a risky activity. In the USA 4906 pedestrians were fatally injured by motor vehicles in 1999, accounting for 11.2% of all transportation-related deaths (US Department of Transportation 2000). Half of these fatalities were attributed to pedestrians being in the roadway at an unsafe place or time. Safe pedestrian travel requires prudent decisions about when to cross streets as well as the ability to cross accurately and efficiently (Bentzen et al. 2000, Carroll and Bentzen 2000, Yauch and Davis 2001). The concept of universal design of the built environment assumes that many individuals with disabilities can travel independently if they have access to the right information (Bentzen 1997). However,
pedestrians with visual impairments have limited information about the layout of streets, crossings, signs, light signals, and traffic movements.

One aspect of universal design is provision of accessible pedestrian signals (APSs) at crossings where visible signals are employed. Accessible signals are usually auditory but may include tactile arrows and vibration (Hulscher 1976, Oliver 1989, Szeto *et al*. 1991). In the UK, APSs are generally presented from the unit containing a pushbutton used to request a crossing signal (Traffic Advisory Unit 1991). Although the signal may be audible to pedestrians at other locations in the vicinity, this system is not designed for directional beaconing and the remote audibility of signals is regarded as potentially confusing. In fact, the policy is to avoid using audible signals at intersections unless there is a signalized traffic interval when all vehicles at the intersection are stopped, to avoid confusion about which crossing has the walk signal. The primary purpose of such installations of audible signals is to convey when the pedestrian walk interval is in effect, just like a visible WALK signal. However, to best serve the needs of pedestrians with sensory impairments the wider scope of information should be taken into account (Bentzen and Tabor 1998). This includes directional guidance provided by audible signals; tones indicating the presence and location of a push-button; tactile arrows parallel to the crossing; speech messages identifying streets and providing information about the intersection; and tones to acknowledge button presses.

With the increasing complexity of modern intersections and the need to deal with high levels of traffic volume, pedestrians with visual impairments often require assistance in making safe street crossings. Previous research has shown that lowering signal-to-noise ratios or introducing competing signals raises minimum audible angles (Jacobsen 1976, Perrott 1984) and decreases localizability of sounds (Lorenzi *et al*. 1999a,b). Good and Gilkey (1994, 1996) found that the ability to accurately localize sounds decreased when signal-to-noise ratios were decreased and documented that front/back accuracy was most strongly affected, followed by up/down differences, then left/right differences. All these results point to an increased level of difficulty in using auditory information for guiding street crossing when there is a background of noise such as traffic.

The present report focuses on how APSs support directional guidance during a crossing in the presence of masking background traffic noise. Pedestrians with visual impairments use auditory sources of information for alignment, most notably the sound of traffic flow on the street parallel to their direction of travel (Hill and Ponder 1976, Jacobson 1993, Wiener *et al*., 1997). Audible signals may provide further useful acoustic beaconing (Peck and Uslan 1990). However, the typical design of audible signal installation in the USA often works against good directional guidance (San Diego Association of Governments 1988). Consider a four-way intersection having crossings on each leg with audible walk signals. In the USA, the walk interval is typically shared by two parallel crossings, with the audible signal presented simultaneously from overhead loudspeakers at both ends of both crossings. At the onset of the walk signal a pedestrian tends to hear a single sound source dominated by the nearby overhead loudspeaker. While this arrangement enhances the detectability of the signal, it may not convey the direction of the far end of the crossing, or even which of the two crossings meeting at the pedestrian’s corner has the walk interval. Thus, the pedestrian knows when the walk interval begins, but there is limited directional guidance, even to the point where it may be unclear which street is available for crossing.
In this paper we consider several factors contributing to directional guidance from audible pedestrian signals: the mode, duration, and character of the signal, as well as the effects of signalling two parallel crossings at once. As noted, the typical signal mode, simultaneous signals presented from both ends of two parallel crossings, is not ideal for directional alignment because the nearby loudspeaker dominates. Several groups have investigated presenting signals alternately from each end of the crossing (e.g. Stevens 1993, Tauchi et al. 1998, Laroche et al. 2000, Yoshiura et al. 2002). This signal mode provides a nearby signal for detectability, a far end signal for localizability, and information for pedestrians crossing the street in either direction. On measures such as crossing time and veering, these investigators reported that performance was better in the alternating mode than in the simultaneous mode. Another mode is to have the signal come only from the far end of the crossing. Poulsen (1982) reported more accurate walking in a simulated crossing setting with a far end signal than when the signal came simultaneously from both ends, and that the far end signal was regarded favourably by a group of blind pedestrians in a field test at a real intersection. Poulsen (1982) mentioned a plan for a signal alternating end to end but did not report findings from that signal mode. To our knowledge the far-end-only and alternating signal modes have not been directly compared. In this study we compare pedestrian crossing performance with simultaneous, alternating, and far-end-only signal modes.

Directional guidance may also be affected by the timing of the audible pedestrian signal. Standard practice in the USA is to present a walk signal during the interval when pedestrians may initiate a crossing. During the pedestrian clearance interval no audible signal is presented, to discourage pedestrians from starting to cross when there is not enough time (this corresponds to a flashing DON’T WALK signal). A disadvantage of this signal cycle is that the audible walk signal typically ends when a pedestrian is only about halfway across the street, limiting the acoustic beaconing effect of the signal at the far end of the crossing. We consider the addition of a ‘locator tone’ presented from the end of the crossing during the pedestrian clearance interval. This tone is already used in some systems, at a low intensity, to inform blind pedestrians that a button push is required to actuate a pedestrian phase, and to facilitate location of the pushbutton. This tone, aimed toward the crossing, may provide directional guidance during the latter part of a crossing. In our studies, the locator tone was set up as it is used in typical street installations: active whenever the WALK signal was not active and set to be audible approximately 3 m from the pushbutton.

Another factor which may affect directional guidance is the acoustic characteristic of the signal. Audible pedestrian signals should be detectable, localizable, distinctive, and environmentally acceptable. A variety of signals have been adopted, with only a limited research basis (Bentzen and Tabor 1998). Some research has been reported on directional guidance (Stevens 1993, Hall et al. 1996, Crandall et al. 1998, Tauchi et al. 1998, Laroche et al. 1999, Standards Australia Committee LG/6, Road Traffic Signals, 1999). Tran, Letowksi and Abouchacra (2000) reported localizability and quality ratings of a diverse set of signals used in military and industrial settings. Errors on a head pointing task ranged from 3° to 4° for a ‘sonar blip,’ speech sounds, a wood bang sound, a twang, and a two-tone alternating signal. Errors were 5° to 6° for chirp-like and bell sounds. Quality ratings were lower for the chirp and bell than for other sounds. This study suggests that a range of sounds is acceptable in terms of directional localizability and overall acceptability. The poorer results for chirp and
bell were attributed to their lack of low- and mid-frequency sound energy. Laroche et al. (1999) reported localization and quality ratings of cuckoo, chirp, and several melody sounds. On their measure (variable error) most similar to that of Tran et al. (2000), localization was 3.8° to 5.0° across the signals. Both localization and quality ratings were worse for the chirp sound and one of the melodies that was being considered as a Canadian standard. They noted that even small differences in localizability of signals are important because of the distances involved in street crossings.

When two parallel crossings have audible walk signals at the same time there could be interference across the signals. In experiments 2 and 3 of the present report we investigated whether directional beaconing from the two crossings interacts, possibly drawing pedestrians toward the street with active traffic.

In summary, these experiments investigated several factors related to directional guidance provided by audible pedestrian signals, with emphases on which end(s) of the crossing the signal is sounded from, whether one or two crossings are signalled, and whether acoustic directional guidance is provided during the latter half of a pedestrian’s crossing. In addition, a range of specific signals was tested and the findings were compared across groups of blind and sighted participants. All experiments were approved by the institutional review board of the university and all participants completed approved consent forms.

2. Experiment 1

This experiment included five audible signals: chirp and cuckoo sounds used in North America, a percussive sound used in Scandinavian countries, a click train, and a voice signal. The mode of signal presentation was investigated by presenting signals either simultaneously from both ends of the crossing, or from the end opposite the pedestrian’s starting location. The participant’s task was to stand at one end of the crossing, wait for the audible walk signal, then walk across the simulated street. The dependent variable was a measure of lateral deviation from the centreline of the crossing, taken at the halfway and end points.

2.1. Method

2.1.1. Participants: The participants were six blind and six sighted adults with mean ages of 44 (30–54) and 31 (27–38) years, respectively. Each group had four women and two men. One of the blind participants had minimal light perception and the others had no light perception, so none could visually detect the experimental apparatus. All blind participants were experienced long cane users with occasional to frequent independent travel including street crossings. They were allowed to use a cane during testing, but only one chose to do so and her performance did not differ from the others. The sighted participants wore a blindfold which did not interfere with their hearing. All participants passed a pure tone hearing screening for each ear with audiometer tones of 25 dB HL at frequencies of 0.5, 1, 2, and 4 kHz played through Telephonics TDH39P earphones.

2.1.2. Apparatus: The setting was a large parking lot containing an artificial crossing as shown in figure 1. On each end of the 20 m crossing were Tannoy System 600 loudspeakers on 8-ft stepladders, pointing toward one another. The loudspeakers have excellent transmission from 100 through 10,000 Hz. Commercially available audible pedestrian systems have loudspeakers with poorer trans-
mission, especially in the low frequencies, because of the demand for weather tolerance and small size. In this experiment, however, we wanted to compare various signals without the complication of loudspeaker characteristics. Start/finish lines were marked in chalk 2 m in front of each loudspeaker. These lines, corresponding to the curb location, defined the starting and finishing points for each traversal of the crossing. The crossing distance was therefore 16 m, or equivalent to about four lanes of traffic. The start/finish lines, as well as a halfway line, had hash marks every 0.2 m. As the participant walked, an experimenter recorded the lateral deviation from an ideal straight crossing at the halfway and end points. In experiments 2 and 3 the audible pedestrian signals for crossing B were activated in addition to those for crossing A on half the trials.

Figure 1. Arrangement for simulated crossings. The study space was a large open parking lot extending in all directions. The grey shading indicates streets for purposes of this illustration, but there were no actual pavement structures corresponding to streets or sidewalks. Open triangles show locations of loudspeakers for audible pedestrian signals. Filled diamonds show loudspeakers through which background traffic noise was presented. Participants used crossing A in all experiments. The curved line diverging from crossing A shows an example of a veering path as a pedestrian walks from south to north. Error scores were lateral deviations from the ideal straight travel path, measured at the halfway and end points. In experiments 2 and 3 the audible pedestrian signals for crossing B were activated in addition to those for crossing A on half the trials. The drawing scale is not exact.
loudspeakers placed on the ground. The traffic noise averaged 70 dB (A-scale) at the middle of the crossing.

By using four loudspeakers for the background traffic noise, these studies studied only the ability of pedestrians to make use of signal information within the context of a noisy background. No attempt was made to provide directional information as would be available from the movement of traffic at an actual intersection. As such, performance of the task in these studies is a 'worst case scenario' in which a pedestrian relies only on the signal for guidance and makes no use of the auditory cues for alignment and/or guidance from the traffic. This was done so that the effect of the signal could be separated from the effect of traffic cues. Other research has performed similar tasks under actual traffic conditions (Laroche et al. 2001).

The five walk signals (chirp, cuckoo, toks, clicks, and voice) are representative of signals in wide use or which show promise for directional beaconing. Table 1 summarizes characteristics of the signals.

Each signal was stored as a digital file. The duration of each signal presentation was 7 s from start to finish, although the number of repetitions within that time period varied by signal. The 7 s duration corresponds to the standard walk interval for a crossing in the USA. All signals were presented at a level of 72 dB (C-scale) measured at ear level for a participant standing 2 m from the loudspeaker. The C-scale was used because the click signal was concentrated at low frequencies which were filtered out by the A-scale. For the sound level measurements only one loudspeaker was active. Signal output was through a 16-bit computer sound card and Crown D75-A amplifiers. By adjusting the amplifiers the signal could be presented from a single loudspeaker at one end of the crossing or from both loudspeakers. These signal modes are designated, respectively, as far end only or simultaneous. The sound level from a single loudspeaker dropped by approximately 6 dB for every doubling of distance to about 54 dB-C at the far end of the crossing.

2.1.3. Design and procedure: The independent variables were signal (chirp, cuckoo, toks, clicks, voice) and signal mode (far end only, simultaneous) as repeated-measures factors, and vision status (blind, sighted) as a between-groups factor. Each participant completed five blocked trials of each combination of signal and signal mode, for a total of 50 trials. For a given signal, the far end only and simultaneous

<table>
<thead>
<tr>
<th>Signal</th>
<th>Description</th>
<th>Predominant frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chirp</td>
<td>Bird chirp-like frequency glide, duration 150 ms, repeated at 1 Hz</td>
<td>2 to 4 kHz</td>
</tr>
<tr>
<td>Cuckoo</td>
<td>‘Cuckoo’ two-note sound, duration 450 ms, repeated at 1 Hz</td>
<td>0.8 to 3 kHz</td>
</tr>
<tr>
<td>Toks</td>
<td>Percussive ‘clack’ repeated at 10 Hz</td>
<td>Considerable low frequency, extending to 7 kHz</td>
</tr>
<tr>
<td>Clicks</td>
<td>Rectangular waveform click train, individual click duration 2 ms, repetition rate 8 Hz</td>
<td>Predominantly low, extending to 4 kHz</td>
</tr>
<tr>
<td>Voice (woman)</td>
<td>‘Peachtree. Walk sign is on to cross Peachtree’ said twice</td>
<td>Mostly below 1 kHz, extending to 2 kHz</td>
</tr>
</tbody>
</table>
trials were presented as two consecutive blocks of five trials each, using random
orders for the two blocks. Thus, the orders were balanced to distribute any order
effects across conditions.

Participants began each trial standing at one end of the crossing. An experimenter
aligned participants within a range of $\pm 15^\circ$ of the direction of the crossing, which is
consistent with pedestrians’ initial alignment for street crossings (Guth et al. 1989).
Instructions were to commence walking as soon as the audible walk signal started.
An experimenter walked behind the participant, recording lateral deviations at the
halfway and end lines. When participants reached the far end they were told to stop
and then taken by a sighted guide to prepare for the next trial. Trials were run
alternately in opposite directions along the crossing to save time and effort. There
was a ten minute introductory period for participants to practise walking and
become accustomed to the traffic noise. At the start of each condition participants
were told which signal and signal mode would be used and were allowed to listen to a
sample.

As noted, the error scores were lateral deviations from the ideal straight walking
path. Separate error scores were computed for measurements taken at the crossing
halfway and endpoint, but the findings were similar and for brevity only the
endpoint errors are reported in detail. In the following definitions, the error score on
a given trial is designated as $Y$ (signed negative for leftward, positive for rightward),
and for this study there were $n = 5$ trials per condition. The following error scores
were computed:

- **Total error**: $\sqrt{\frac{\sum Y^2}{n}}$
- **Constant error (bias)**: $\frac{\sum Y}{n}$ or $\bar{Y}$
- **Random error**: $\sqrt{\frac{\sum (Y - \bar{Y})^2}{n}}$

These formulas are based on a linear additive model in which each error score
comprises two components, a constant error or bias and a random error (Hartmann
1983). The constant error expresses any systematic tendency to err leftward or
rightward, while the random error shows consistency of performance regardless of
any bias. This model leads to the sums of squares relation:

$$(\text{Total error})^2 = (\text{Constant error})^2 + (\text{Random error})^2$$

The total error is a useful overall measure but it needs to be supplemented by the
constant and random errors. Consider two individuals with similar total error scores.
One could have zero constant error (no systematic bias to go left or right) but high
random error (inconsistent performance across trials). The other could have a strong
bias to err in one direction but a very consistent performance from trial to trial. The
distinction between a highly variable pattern and a very consistent (though biased)
pattern is important for theory and practice. For all statistical tests a Type I error
rate of $p < 0.05$ was used unless otherwise noted. Effect size is reported by the $\eta^2$
statistic.
2.2. Results and discussion

For total error at the endpoint of the crossing there were main effects of vision status, $F(1,10) = 9.320$, $\eta^2 = 0.482$, and signal mode, $F(1,10) = 10.277$, $\eta^2 = 0.507$. As figure 2 shows, blind participants had larger errors than sighted participants, and errors were smaller when the signal came from the far end of the crossing than when it came simultaneously from both ends.

The vision groups differed substantially in age, but when age was taken into account by an analysis of covariance there was no significant difference between blind and sighted participants. The findings for random errors resembled those for total errors, with significant main effects only for vision status, $F(1,10) = 6.571$, $\eta^2 = 0.397$, and signal mode, $F(1,10) = 22.172$, $\eta^2 = 0.689$. For the blind participants the mean random errors were 1.97 ($SE = 0.37$) and 2.49 ($SE = 0.37$) m in the far end and simultaneous signal modes, respectively. For the sighted participants the means were 0.84 ($SE = 0.11$) and 1.82 ($SE = 0.10$) m. The overall differences between blind and sighted participants could be confounded with the fact that blind participants were older as a group. However, all participants passed the same hearing screening test, and there was no evidence from individual data that age was associated with total or random errors. Whatever the reason for the overall difference between blind and sighted participants, both groups had the same pattern of findings in that crossing was more accurate when the signal came from the far end of the crossing than when it came simultaneously from both ends.

In the analysis of variance on constant errors no effects were significant. The mean constant errors were 0.68 m to the left for blind participants and 0.11 m to the right.
for sighted participants. Although some individual participants showed consistent leftward or rightward errors, there was no evidence that the independent variables had any directional biasing effects. None of the analyses indicated any systematic differences between the five signals. Note that all signals were adjusted to a common sound level making them similarly audible. In this context the various signals seem equally useful for directional guidance of walking.

The advantage of presenting signals from the far end only versus both ends simultaneously was apparent in the individual data. Figure 3 shows the mean total errors for each participant by signal mode, averaged across the five signals.

All six sighted participants and five of the six blind participants had smaller errors in the far end condition than in the simultaneous condition, a significant effect, $\chi^2(1) = 8.333$. Despite a wide range of errors across participants there was a strong individual tendency to cross more accurately when the signal came only from the far end of the crossing.

### 3. Experiment 2

The principal purposes of this experiment were to replicate the finding of reduced error when the signal came from the far end of the crossing rather than from both ends, to evaluate a signal mode in which the signal alternated from end to end, and to investigate whether adding signals on a parallel crossing affects performance. Audible pedestrian signals are typically presented on parallel crossings sharing the same walk interval, but the extent to which the signals on one crossing affect a
pedestrian using the other crossing has not been investigated. In experiment 1 there were no differences across the five signals so in experiment 2 only the chirp and toks signals were used. In experiment 2 there were three signal modes (simultaneous from both ends, far end only, and alternating between ends), two crossing conditions (signal on pedestrian’s crossing only, signal on pedestrian’s crossing and a parallel crossing), two signals (chirp, toks), and two vision status groups (blind, sighted).

3.1. Method
3.1.1. Participants: Participants included five adults who were blind (three women, two men, mean age 41 years, range 23 – 61) and five adults with normal vision (two women, three men, mean age 43 years, range 31 – 57). All passed the hearing screening test described for experiment 1.

3.1.2. Apparatus and procedure: The procedure and design were similar to experiment 1 with several changes. As noted above, only two signals were used. Also, a second crossing, parallel to and 12 m alongside the one used by participants, was signalled (see figure 1, crossing B). Finally, signals were played through an audible pedestrian signal system manufactured by Novax Industries, Inc. (DS-2000). This system uses Quam 30C25Z80T 3-inch all-weather loudspeakers mounted in metal boxes. The use of this system allowed the addition of an alternating signal mode in which, during the 7 s walk interval, a signal was played alternately from the two ends of the crossing. Also, this system is typical of commercial signal devices in which the weather proof loudspeaker transmits mid- to high-frequency sound better than low-frequency sound, shifting the net signal energy toward higher frequencies.

![Figure 4](image.png)  
**Figure 4.** Experiment 2, mean total error at the endpoint of the crossing for the three signal modes on trials with one versus two crossings being audibly signalled. Error bars show +1 SE.
Each participant was tested on a block of five trials in each of the twelve conditions (three signal modes by two numbers of crossings by two signals).

3.2. Results and discussion
In this experiment there were no significant differences between blind and sighted participants, and no interactions involving sightedness. In an analysis of variance on total errors the main effect of signal mode was significant, $F(2,16) = 8.04, \eta^2 = 0.501$, and there was a significant interaction between signal mode and the number of crossings $F(2,16) = 4.37, \eta^2 = 0.353$, as shown in figure 4.

The main effect of signal mode was analysed further with three planned contrasts. When the signal was presented from the far end only, errors were lower than in the alternating mode, $F(1,8) = 13.49, \eta^2 = 0.628$, and the simultaneous mode, $F(1,8) = 11.70, \eta^2 = 0.594$. Errors did not differ significantly between the alternating and simultaneous modes ($\eta^2 = 0.103$). These findings show better performance when signals came only from the far end of the crossing. This finding is in agreement with Laroche et al. (2001) testing at a noisy intersection and with Poulsen (1982) but fails to replicate previous reports of better crossing accuracy with the alternating mode than the simultaneous mode (Stevens 1993, Tauchi et al. 1998, Laroche et al. 2000 – testing in quiet, Yoshiura et al. 2002). As in experiment 1, the differences between signal modes were evident in the total error scores of individuals. Eight of the 10 participants, including all of the blind participants, had the smallest total error when the signal was presented from the far end of the crossing. This proportion did not quite exceed the significance criterion, $\chi^2(2) = 3.600, p < 0.058$, but it does indicate that most participants did best in that condition.

The interaction between the number of crossings and the three signal modes shown in figure 4 was followed up with three contrasts. In the alternating mode, total errors were significantly larger with the dual crossing than the single crossing, $F(1,8) = 22.88, \eta^2 = 0.741$, suggesting that it was problematic to hear an alternating end-to-end pattern when it was presented on two parallel crossings. The differences in total errors between the dual and single crossing conditions for the far end and simultaneous signal modes were not significant ($F(1,8) = 4.31, \eta^2 = 0.35$ and $F(1,8) = 0.19, \eta^2 = 0.023$, respectively).

For random errors there was also a significant effect of signal mode, $F(2,16) = 14.24, \eta^2 = 0.640$. The mean random errors were 1.30 m ($SE = 0.16$) when the signal came only from the far end of the crossing(s), 2.61 m ($SE = 0.42$) when the signal alternated between ends, and 3.06 m ($SE = 0.40$) when the signal came simultaneously from both ends. The errors in the far end signal mode were significantly smaller than in the alternating, $F(1,8) = 15.53, \eta^2 = 0.660$, and simultaneous, $F(1,8) = 23.08, \eta^2 = 0.743$, modes, which did not differ from one another. This indicates that participants were more consistent at reaching an average location on the far end of the crossing when only the far end was sounding, regardless of the number of crossings or type of signal used.

The question addressed by the analysis of constant errors is whether participants were drawn toward the parallel crossing when it was audibly signalled. This required an analysis that distinguished between trials on which the second crossing was to the left or right of the participant’s walking direction. In figure 1, crossing B is to a pedestrian’s left as the pedestrian walks northward on crossing A but it is on the pedestrian’s right when the pedestrian walks southward on crossing A. Because of an oversight this information was not recorded reliably for many of the trials. To
address this problem the following analysis was used, and the issue was replicated in experiment 3. Since participants walked back and forth on the crossing, on each set of five trials the parallel crossing was to the left (or right) either on trials 1, 3, 5 or trials 2, 4. Constant errors were calculated separately for trials 1, 3, 5 and trials 2, 4. Whichever of those two constant errors was more positive (‘more rightward’) was designated as corresponding to the trials on which the crossing was on the participant’s right, and the other was designated as the participant’s left. Of course this approach capitalizes on chance and could therefore produce a specious difference between the ‘left’ and ‘right’ trials. The design of the study, however, provides a check on this. If participants were drawn toward the parallel crossing when it was audibly signalled, there should be an interaction between sidedness (parallel crossing on left versus right) and the number of crossings signalled (one vs. two). In other words, the difference in constant error between left and right trials should be greater when both crossings were signalled than when only the participant’s crossing was signalled. In an analysis of variance this interaction approached significance, $F(1,8) = 4.103$, $p < 0.077$, $\eta^2 = 0.339$. The mean constant errors when just one crossing was signalled were $-0.61$ m when the parallel crossing was on the participant’s left and $1.39$ m when it was on the right, for a left–right difference of $2.00$ m. When both crossings were signalled, the mean constant errors were $-1.54$ and $1.25$ m for the left and right trials, respectively, for a difference of $2.79$ m. The interaction effect is the difference between differences, or $2.79 - 2.00 = 0.79$ m. This interaction is largely uncontaminated by the scoring system’s capitalization on chance. Thus, our best estimate is that there was a modest ‘drawing’ effect of about three-fourths of a metre when the parallel crossing was signalled in addition to the pedestrian’s own crossing.

4. Experiment 3

In contrast to some previous reports, experiments 1 and 2 showed that performance in the simultaneous and alternating modes was similar, and not as good as in the far end only mode. In order to confirm these findings, these three signal modes were used again in experiment 3. Also, the single versus dual crossing comparison was included so as to replicate the possible ‘drawing’ effect of the second crossing. A new feature investigated in experiment 3 was whether it would be helpful to supply a ‘locator tone’ during the pedestrian clearance interval. This sound source provides the pedestrian with a spatial referent to aim for during the latter portion of the street crossing. A crossing signal that includes sound during the pedestrian clearance interval has been shown to be preferred over signals that sounded only during the walk interval (Houtgast and Mimpen 1978, Laroche et al. 2001).

4.1. Method

4.1.1. Participants: Participants were seven adults who were blind (six women, one man, mean age 51 years, range 39–61) and six adults with normal vision (five women, one man, mean age 32 years, range 24–46). All passed the same hearing screening test as in the previous experiments.

4.1.2. Apparatus and procedure: Experiment 3 replicated the conditions of signal modes and number of crossings from experiment 2, and added a test of the usefulness of presenting the locator tone from the far end of the crossing after the walk interval ended and the walk signal stopped. The locator tone was an 880 Hz
square wave tone with a duration of 100 ms (linear rise time of 2.5 ms, constant amplitude through 18 ms, exponential fall to zero amplitude at 100 ms) repeated at 1 Hz. This tone was presented through a Novax Industries push-button/tone module, with the loudspeaker (Misco A2WP, 2.5-inch) mounted 1 m above ground and directed toward the crossing. The locator tone was active whenever the WALK signal was not active. In experiment 3 only one signal, the toks sound, was used as the WALK signal. In summary, the conditions in experiment 3 were based on three modes of presenting the signals (far end only, simultaneously from both ends, and alternating between ends), the number of crossings signalled (one, two), and the availability of the locator tone after the walk interval ended (on, off). Each participant was tested on a block of five trials in each of the twelve conditions.

4.2. Results
An analysis of variance was performed on total error scores, with vision status as the between-groups factor and signal mode (far end only, alternating, simultaneous), number of crossings signalled (1, 2), and locator tone status (on, off) as repeated-measures factors. The significant results were the main effects of signal mode, $F(2,22) = 7.560, \eta^2 = 0.407$, locator tone status, $F(1,11) = 22.039, \eta^2 = 0.667$, and number of crossings signalled, $F(1,11) = 6.052, \eta^2 = 0.355$. Figure 5 shows means related to the effects of signal mode and locator tone status.

The effect of signal mode was analysed further by separate tests for trials when the locator tone was on or off. When the locator tone was off (see right-hand side of figure 5), errors in the far end signal mode were lower than in the alternating mode, $F(1,11) = 5.755, \eta^2 = 0.343$, and the simultaneous mode, $F(1,11) = 18.218, \eta^2 = 0.624$. Errors did not differ significantly between the alternating and simultaneous signal modes ($\eta^2 = 0.194$). When the locator tone was on (left-hand side of figure 5) there were no significant differences among the signal modes. The findings for when the locator tone was off replicate the results of experiment 2, showing the best performance when the signal came from the pedestrian’s destination at the far end of the crossing. When the locator tone was on, the endpoint errors did not differ across the signal modes, but on average the errors were about 1 m less when the locator tone was sounding than when it was not, as seen in figure 5. This difference was apparent during testing in the form of obvious course corrections during the second half of the crossing.

When the locator tone was on during the pedestrian clearance interval the total errors at the endpoint were equivalent across the three signal modes. This might initially suggest that any of these signal modes will do, provided the locator tone is available. But we observed that participants tended to walk inefficient paths, straying off course during the early and middle portions of a crossing, then angling back toward the locator tone as they neared the end. Analysis of the halfway point errors helps elucidate this. Participants generally reached halfway across the crossing or a little further when the walk interval (and walk signal) ended. Therefore, any directional beaconing up to the halfway point came from the walk signal, not from the locator tone. An analysis of variance was conducted on the halfway point total error scores, with independent variables of vision group, signal mode, number of crossings, and locator tone (albeit if the tone came on, it was not until later in the trial). The only significant result was the main effect of signal mode, $F(2,22) = 11.328, \eta^2 = 0.507$. The mean (SE) errors for the far end only, alternating, and simultaneous signal modes were 1.18 (0.115), 1.59 (0.163), and 2.00 (0.104) m.
The mean error in the far end only signal mode was significantly lower than the alternating mode, $F(1,11) = 9.865$, $\eta^2 = 0.473$, and the simultaneous mode, $F(1,11) = 23.590$, $\eta^2 = 0.682$, which did not differ from one another ($\eta^2 = 0.260$). Thus at the halfway point, before the locator tone was available, the crossing accuracy was best when the walk signal came from the far end of the crossing. In terms of signal design this suggests that beaconing information from both a walk signal at the far end of the crossing and provision of a locator tone during the pedestrian clearance interval is desirable. With respect to the number of crossings, total errors were lower when just one crossing was signalled than when two were signalled, with means of 2.20 ($SE = 0.26$) and 2.72 ($SE = 0.20$) m, respectively.

The pattern of findings for random errors was the same as for total errors. There were main effects of signal mode, $F(2,22) = 12.721$, $\eta^2 = 0.536$, number of crossings signalled, $F(1,11) = 5.582$, $\eta^2 = 0.337$, and locator tone status, $F(1,11) = 21.836$, $\eta^2 = 0.665$. The effect of signal mode indicates that participants were most consistent when the signal came from the far end of the crossing. The mean ($SE$) random errors were 1.23 m (0.13) when the signal was presented only from the far end of the crossing(s), 1.86 m (0.20) when the signal alternated end to end, and 2.31 m (0.17) when the signal came simultaneously from both ends. Errors in the far end signal mode were significantly smaller than in the alternating, $F(1,11) = 13.613$, $\eta^2 = 0.553$, and simultaneous, $F(1,11) = 22.719$, $\eta^2 = 0.674$, modes, which did not differ significantly from each other, $\eta^2 = 0.240$. This pattern of significantly smaller random errors in the far end signal mode compared to the other modes was observed in separate sets of analyses on the single and dual crossing trials. For single crossing trials
the means \((SE)\) were 0.91 m (0.16) in the far end mode, 1.53 m (0.24) in the alternating mode, and 2.35 m (0.19) in the simultaneous mode. For dual crossing trials the means for the respective modes were 1.56 (0.22), 2.19 (0.26), and 2.26 m (0.28).

With regard to the locator tone, random errors averaged 1.46 m \((SE = 0.13)\) with the tone compared to 2.14 m \((SE = 0.14)\) without it, so participants were more consistent at reaching a point at the far end of the crossing when the locator tone was available. Random errors were smaller when one crossing was signalled than when a parallel crossing was also signalled, with means of 1.60 \((SE = 0.12)\) and 2.00 \((SE = 0.16)\) m, respectively.

The constant error scores provide a measure of whether participants were drawn toward the parallel crossing on trials when both crossings were signalled. To address this question error scores were computed separately for those trials on which the parallel crossing was to the participants’ left or right. Thus, the side of the parallel crossing was an independent variable. A mixed model analysis of variance was performed in which the between-groups variable was vision status and the repeated-measures variables included the side on which the parallel crossing was placed (left or right), whether one or two crossings were signalled simultaneously, the signal mode used, and whether there was a locator tone. The principal finding with respect to whether participants were drawn to the parallel crossing was a significant interaction between the number of crossings signalled and the side of the parallel crossing. \(F(1,11) = 5.822, \eta^2 = 0.346.\) Figure 6 shows the average constant errors across these combinations of conditions.

On average participants erred to the right, but overlaid on this was a tendency to be drawn in the direction of the parallel crossing if the acoustic signals on that crossing were active. While participants always tended to err to the right, they did so by half as much when a parallel crossing was signalled on their left side as opposed to when only one crossing was signalled (0.6 vs. 1.3 m) and about twice as much when a parallel crossing was signalled on their right compared to when a single crossing was signalled (1.1 vs. 0.7 m). Note that in each case, when one crossing was signalled, the errors were roughly the same (1.3 and 1.1 m).

The principal finding from the group analyses was that errors were smaller when the signal was presented only from the far end of the crossing, and when the locator tone sounded after the walk interval had ended. These findings were reflected strongly in the data from individuals. Nine participants did best when the signal came from the far end only, two when the signal alternated between ends, and two when the signal came simultaneously from both ends. This is a significant difference, \(\chi^2(2) = 7.538.\) Eleven of the 13 participants had smaller errors when the locator tone was available, a significant difference, \(\chi^2(1) = 6.231.\)

5. General discussion

These experiments evaluated the usefulness of different signal modes for auditory directional guidance during pedestrian street crossing. Crossing was more accurate when the signal was presented only from the far end of the crossing, compared with when it was presented simultaneously from both ends (experiments 1, 2 and 3) or alternately between ends (experiments 2 and 3). In contrast to previous reports, there was little if any advantage of the alternating signal mode over the simultaneous mode, especially when two parallel crossings were signalled. Laroche et al. (2000) tested 15 blind participants in a simulated street-crossing task with a 20 m crossing set up in a quiet paved lot. Lateral errors at the endpoint of the crossing did not
differ significantly between simultaneous and alternating signal modes, but with the alternating mode the average crossing time was faster (22.1 vs. 25.3 s) and the root-mean-square deviation from the centre line was smaller. A difference between our method and that of Laroche et al. (2000) was that their walk signal (lasting 36 s) was audible throughout the time that participants typically took to make a crossing, whereas our signal was silenced after 7 s, when participants were about halfway across. This may account for their finding that lateral error measured at the endpoint was equivalent for the simultaneous and alternating signal modes, in that a signal from the far end of the crossing was available during the late stage of the crossing. Their root-mean-square measure suggested that with the alternating signal mode pedestrians were more accurate in the early to middle parts of the crossing, presumably because of directional beaconing. However, our findings for the midpoint errors in experiment 3 failed to replicate this advantage of the alternating mode, showing instead that pedestrians were more accurate when the signal came only from the far end of the crossing.

Another difference between the studies is that Laroche et al. (2000) used a quiet parking lot setting, whereas the present experiments had pre-recorded traffic noise. In a subsequent study with alternating and simultaneous signals at a real traffic intersection, Laroche et al. (2001) found no difference in crossing performance. They suggested that by using the sound of parallel traffic flow to orient themselves, participants nullified any difference in directional guidance across the two signal modes. The added benefit of having access to acoustic information from moving vehicles may offset many of the differences in signal presentation modes. However, when there is a lack of consistent moving traffic, the findings of the present study become more relevant.
Stevens (1993) tested 18 participants with visual impairments on street crossings at an offset intersection with real traffic, comparing simultaneous and alternating signal modes. Participants crossed successfully (within 24 s without more than 1.5 m of deviation from the centre of the crossing) on 85% of the alternating trials compared to only 33% of the simultaneous trials. A separate task, in which participants made initial alignments but did not attempt a crossing, showed better alignment in the alternating signal mode (6 vs. 28° alignment errors), suggesting that the alternating mode provided directional beaconing not available in the simultaneous mode. This beaconing effect may have been especially useful at an offset intersection because the direction of traffic flow does not specify the crossing direction. Since a far end only signal mode was not included we cannot tell whether the end-to-end alternation was uniquely useful. Poulsen (1982) reported that crossing accuracy in a laboratory courtyard setting was more accurate with a far end signal mode than with a simultaneous mode. Although the alternating mode was proposed as a desirable specification, no evaluation of that mode was reported. Poulsen’s findings, not reported in detail, agree generally with our finding of best accuracy in the far end signal mode.

The present findings offer less promise than previous reports for the usefulness of an alternating signal mode, especially when the findings for single versus dual crossings are considered. In previous studies only one crossing was signalled, but we compared single and dual crossing signalling in experiments 2 and 3. In experiment 2 errors were lower in the alternating mode than in the simultaneous mode, but only when a single crossing was signalled. This pattern of findings was also found in experiment 3, suggesting that when the signal alternates between ends on each of two parallel crossings the directional beaconing effect is compromised. To some extent the dual crossing signalling also compromised directional beaconing in the far end only signal mode, suggesting that the problem stems from hearing two sound sources on the far end of the street, but from different locations.

In all three experiments performance was best with the far end only signal mode. Many participants reported that in this mode they could tell directly where the far end of their crossing was located as soon as the signal started. Also, some participants reported being confused on alternating signal trials, to the extent that they lost track of which end of the crossing they were supposed to be walking toward. Several times participants made a loop and walked back toward the starting position, thinking that they were approaching the far end of the crossing. It is well known from research on sound localization that there are front–back confusion errors for sounds presented along the midline. This may have contributed to occasional spatial disorientation. Given the overall perceptual and cognitive demands of pedestrian crossing at busy intersections, it is questionable whether the alternating signal mode would be helpful.

Implementation of a signal from the far end of a crossing would present both technical and policy issues. Signal systems might have to be re-engineered to respond to an audible signal request from an arbitrary corner going in an arbitrary direction. In terms of policy, a far end only signal would not provide the same information to a pedestrian crossing in the opposite direction. Also, there could be a risk that a pedestrian waiting to cross a different crossing would mistake the signal (although this risk must be considered for any audible signal mode). Finally, the far end only signal could be masked by traffic noise to a greater extent than near end signals. This would compromise the signal’s announcement that the walk interval had begun,
particularly for pedestrians with hearing impairments. Possibilities such as presenting the first 2 s of the walk signal from both ends of the crossing or using a walk alert tone preceding the walk signal as is used in Australia (Standards Australia Committee LG/6, Road Traffic Signals 1999) merit consideration. Despite these concerns, the directional beaconing effect of the far end signal mode seems very promising.

There was some evidence for a drawing effect in the dual crossing, far end only conditions in experiments 2 and 3. This would occur if pedestrians were influenced by the two far end locations, aiming somewhere between them. Although participants were informed about the experimental conditions in effect on each trial, they did not report being aware of the signal on the parallel crossing, except on some occasions when they suspected they had veered strongly in that direction. This suggests that the effect of signalling the parallel crossing is rather subtle and might be difficult to counteract. This is important because the effect is to draw pedestrians into the street with moving traffic. On the other hand, at busy intersections there tends to be moving traffic along the street parallel to the crossing, and pedestrians can use the sound from that traffic to avoid walking into the street.

In experiment 3 we tested the usefulness of a locator tone sounded from the far end of the crossing during the pedestrian clearance interval. This had a clear beneficial effect on crossing performance. By design, the walk signal ends before most pedestrians complete a crossing in order to prevent newly arriving pedestrians from initiating a late crossing. Participants reported that hearing the locator tone after the walk signal ended and for the duration of the rest of their crossing was reassuring because it provided an aiming point for the remainder of the crossing. The locator tone was so useful that errors at the endpoint of the crossing did not differ across the signal modes, but accuracy at the midpoint (generally before the locator tone was available) was best in the far end only signal mode. Therefore, the signal mode appears to be an important factor for directional guidance during the first half of a crossing, while the availability of a locator tone is helpful during the second half. This supports findings by Laroche et al. (2001) on the usefulness of providing a locator tone.

In experiment 1 we used five different signals, chosen to include some with a high frequency emphasis that might be less easy to localize. In that experiment the loudspeakers were high quality, with excellent transmission across the frequency range of human hearing. There was no support for differences in crossing performance across these signals. All signals were set to a similar audibility level, as would be true with automatic volume control in a real traffic signal installation. In experiment 2 only two signals were used, the chirp and toks. In that experiment the loudspeakers were typical of outdoor audible pedestrian signals in having a reduced transmission in the lower frequency range. Again there were no differences in crossing performance across the signals. We tentatively conclude that there is a wide range of signals all of which, given similar audibility via automatic volume control, provide a comparable basis for pedestrian crossing performance. Obviously there are many possible signals, some of which might not be good candidates, but factors such as signal mode and provision of a locator signal during the pedestrian clearance interval may warrant more consideration than the signal itself. There are good reasons for standardization of an audible pedestrian signal in a given country or region, but there is probably a wide range of signals which would have similar benefits in terms of directional beaconing. Note that Laroche et al. (2000) have
found the chirp signal to be confusing in quiet environments. Laboratory data for a range of signals in quiet and noisy environments have demonstrated significant differences between signals, with the chirp and cuckoo requiring much more gain to become noticeable both in quiet and in noise (Wall et al., in preparation).

In statistical terms there were few interactions between vision status and other factors in the experiments, indicating that the findings about signal modes, etc. applied to both blind and sighted participants. However, the impetus for this research was to investigate accessible pedestrian signal characteristics and presentation to assist people with visual impairments in crossing intersections more safely. Creation of a standard signal and signal mode for accessible pedestrian signals would help travellers with visual impairments to apply travel strategies to a wide range of intersections. The present findings suggest that the type of signal used is not as important as the way it is presented. Directional guidance is enhanced by presenting the walk signal from the far end of the crossing and by providing a locator tone during the pedestrian clearance interval. The provision of directional beaconing signals does not exhaust the kinds of information that are of interest for audible signal systems. There is considerable interest in spoken signals, use of distinct signals for different crossing directions (e.g. chirp for east–west and cuckoo for north–south), and use of receiver-based technology in which speech messages are heard from personal receivers. A general approach underlying the experiments reported here is to provide pedestrians with perceptual information that can be utilized directly with minimal need for interpretation or deductive reasoning. To the extent that signal systems engage natural perceptual processes such as sound localization, they provide guidance without imposing strong cognitive demands. This is important because street crossing by pedestrians with visual impairments requires a high degree of vigilance and strategic thinking.

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