Street Crossing by Sighted and Blind Pedestrians at a Modern Roundabout

Daniel H. Ashmead¹; David Guth²; Robert S. Wall³; Richard G. Long⁴; and Paul E. Ponchillia⁵

Abstract: Pedestrian behavior and safety at roundabouts are not well understood, particularly for pedestrians with sensory or mobility impairments. A previous study in which participants indicated when they would cross suggested that blind pedestrians miss more crossing opportunities and make riskier judgments than sighted pedestrians. The present study replicated these findings and analyzed actual street crossings. Six blind and six sighted pedestrians negotiated a double-lane urban roundabout under high and low traffic volumes. Blind participants waited three times longer to cross than sighted participants. About 6% of the blind participants’ crossing attempts were judged dangerous enough to require intervention, compared to none for sighted pedestrians. Drivers yielded frequently on the entry lanes but not the exit lanes. Sighted participants accepted drivers’ yields, whereas blind participants rarely did so. Blind-sighted differences are interpreted in terms of auditory access to information about traffic, and policy implications are discussed regarding accessibility of transportation systems.

DOI: 10.1061/(ASCE)0733-947X(2005)131:11(812)

CE Database subject headings: Pedestrians; Traffic safety; Handicapped persons; Intersections.

Introduction

The modern roundabout is a roadway intersection designed to facilitate vehicle flow and reduce the incidence of serious accidents. A roundabout has one-way traffic in a circulatory roadway around a central island, along with entry and exit lanes separated by splitter islands (see Fig. 1). Entering vehicles yield to those in the circulatory roadway. Since the mid-1960s roundabouts have been widely installed in Europe and Australia, and they are predicted to become common in the United States (Federal Highway Administration 2000). In contrast to traditional traffic circles, the circulatory roadway and central island are considered off limits to pedestrians. Instead, pedestrians use crosswalks over the entry and exit lanes set back from the circulatory roadway, with the splitter island providing a refuge midway through the crossing.

1Associate Professor, Dept. of Hearing and Speech Sciences, Vanderbilt Univ. Medical Center, Nashville, TN 37232-8700. E-mail: david.guth@wmich.edu
2Professor, Dept. of Blindness and Low Vision Studies, Western Michigan Univ., 1903 W Michigan Ave., Kalamazoo, MI 49008-5218. E-mail: daniel.h.ashmead@vanderbilt.edu
3Assistant Professor, Dept. of Blindness and Low Vision Studies, Western Michigan Univ., 1903 W Michigan Ave., Kalamazoo, MI 49008-5218. E-mail: rpbert.s.wall@wmich.edu
4Associate Professor, Dept. of Blindness and Low Vision Studies, Western Michigan Univ., 1903 W Michigan Ave., Kalamazoo, MI 49008-5218. E-mail: richard.g.long@wmich.edu
5Professor, Dept. of Blindness and Low Vision Studies, Western Michigan Univ., 1903 W Michigan Ave., Kalamazoo, MI 49008-5218. E-mail: paul.e.ponchillia@wmich.edu

The U.S. Americans with Disabilities Act (ADA) stipulates that public rights-of-way be accessible to pedestrians with disabilities, and the U.S. Access Board develops regulations to ensure access when transportation systems are newly built or altered. The extent to which roundabouts can be safely used by pedestrians with disabilities or age-related limitations has not been investigated extensively, although the issue is controversial (Alphand et al. 1991; Jacquemart 1998; U.S. Access Board 2001).

Accident statistics suggest that replacing traditional intersections with roundabouts reduces the severity of vehicle-to-vehicle crashes (Retting et al. 2001), but the impact on pedestrian safety is less clear. Pedestrian accident rates at roundabouts have been reported to be similar to or lower than rates at traditional intersections (Lalani 1975; Maycock and Hall 1984; Alphand et al. 1991; Seim 1991; Schoon and van Minnen 1994; Tumber 1997).

However, with one exception (Brüde and Larsson 1999), these studies have not reported the frequency of pedestrian travel at the intersections being compared. Without such exposure data, it is unclear whether lower accident rates derive from genuine safety differences or from pedestrian avoidance of roundabouts. Another limitation of the extant accident data is a lack of differentiation of subpopulations such as older pedestrians or those with sensory and/or mobility impairments. For example, elderly persons are overrepresented in pedestrian accidents at traditional intersections (Koepsell et al. 2002), but it is not known whether this is the case at roundabouts. The present paper focuses on totally blind pedestrians. Given the low incidence of blindness in the United States and the lack of information about the extent to which blind pedestrians frequent or avoid roundabouts, it is unlikely that accident statistics will reveal much about roundabout accessibility for this population. Our approach is therefore to analyze crossing decisions made by groups of blind and sighted pedestrians.

Guth et al. (2005) used an indicator task to compare sighted and blind adults’ judgments about when to cross at roundabouts. Participants stood on the sidewalk near the ends of roundabout crosswalks, then pressed a button to indicate when they would begin crossing. At a low-volume, single-lane roundabout, blind
and sighted participants performed similarly, but at moderate to high traffic volume double-lane roundabouts blind participants waited longer than sighted participants to indicate that they would begin crossing, missed more crossing opportunities, and were more likely to indicate that they would cross when approaching vehicles were nearby. To our knowledge, this study provided the first behavioral analyses of pedestrians at roundabouts but the indicator task leaves open the possibility that participants would have used different decision criteria for actual crossings. Consequently, one objective of the current study was to compare crossing judgments on an indicator task and actual crossings. Additionally, we compared performance under two levels of traffic volume at a double-lane roundabout because traffic volume is likely to be a key consideration as planners try to predict the impact of roundabouts on pedestrian travel.

Method

Participants

Six totally blind and six normally sighted adults participated, with mean ages of 51.8 years for the blind group (range 27–62) and 48.5 for the sighted group (24–69). All blind participants used the long white cane as their primary mobility device and reported daily independent travel including street crossings. Participants had normal hearing in both ears for pure tones at 0.5, 1, 2, and 4 kHz. None had a significant amount of experience with roundabouts.

Procedure

The test site was the Music Row roundabout in Nashville, Tenn., an urban double-lane roundabout in an office and light commercial district. Fig. 1 shows three of the five street legs adjoining the roundabout, including the leg used for data collection which has a two-lane entry and a two-lane exit. The crosswalk, made of distinctive brick pavers that contrasted with the asphalt entry/exit lanes, was cut through the splitter island at street level. The crosswalk measured 9.5 m across the entry lanes and 9.5 m across the exit lanes, with setbacks from the circulatory roadway of 7.5 and 6.4 m, respectively. We used a stopwatch to estimate the average speed of vehicles on the exit lane for the 25 m of roadway that ended at the crosswalk. Speeds were normally distributed with a mean of 19.8 mph (SD=2.8), and most vehicles clearly accelerated through the crosswalk area. For the entry lane we estimated average speed for a 25-m segment ending 11 m before the crosswalk (most drivers began braking at this point), finding a mean of 24.6 mph (SD=4.25). Most vehicles slowed substantially as they approached the roundabout.

Blind participants learned the roundabout layout by exploring a tactile map, then by a guided walk once around, and finally by repeated back and forth traversals of the crosswalk used for the study. Sighted participants walked once around, with an experimenter pointing out the same features described to blind participants, then traversed the crosswalk several times. Participants understood that the entry lanes had yellow signs with an image of a pedestrian (MUTCD 2000, sign W11-2), alerting drivers to the pedestrian crossing area but not stipulating that drivers should yield to pedestrians. State law requires drivers to yield to pedestrians who are in a crosswalk, but not to pedestrians waiting on the curb.

Each participant had two sessions, during periods of lower and higher vehicle volume. High volume sessions occurred during the noon hour and late afternoon, and low volume sessions during midmorning, midafternoon, and early evening. We estimated traffic volume during each session by a 5-min count of all vehicles entering the roundabout, and then extrapolated to vehicles per hour. High volume sessions averaged 2,309 vehicles per hour [standard error (SE)=100] and low volume sessions 1,019 (66). The order of high and low volume sessions was counterbalanced across participants.

During each session participants performed six trials. On three trials the participants crossed independently, followed by an experimenter who acted as a spotter. On the other three trials participants used a hand signal to indicate when they would have started crossing, but they did not actually cross until an experimenter directed them. Half the participants crossed on even-numbered trials and indicated crossings on odd-numbered trials, and half vice versa. Each trial entailed a round trip from one side of the street to the other and back, comprising four segments: from one end of the crosswalk to the splitter island; from the island to the opposite side of the street; from the opposite side back to the island; and from the island back to the starting position. A given participant began all trials (on both sessions) from the same side of the street, with the starting side counterbalanced across participants.

The experimenter accompanying the participants was a Certified Orientation and Mobility Specialist. The field of orientation and mobility (OM) focuses on training persons with visual impairments to travel independently, including training for crossing streets. At the beginning of each leg of the crossing the experimenter directed the participant to a starting position about one step back from the street, facing the crosswalk. Although establishing one’s initial walking direction and maintaining it while crossing are important components of the street crossing task, they were not the focus of this study. Hence the experimenter sometimes gave blind participants verbal guidance such as “a little left” when they began to veer out of the crosswalk. All blind participants used a long cane that presumably could be easily seen by drivers.
Once the participant was in position, the experimenter instructed them either to cross the first leg when ready or to indicate that they would have crossed. Additional experimenters, stationed on a wall overlooking the crosswalk, coded various aspects of the participant’s crossing performance as well as traffic activity. These data were stored on a laptop computer. In the crossing trials, when participants thought it safe to cross, they briefly raised their right hand at the wrist and then immediately started crossing. In the indicator trials they raised their hand but did not cross. These hand signals were inconspicuous to approaching drivers. During crossing trials, once the crossing had begun, either the participant or the experimenter could initiate an “intervention” if they judged the crossing too dangerous to proceed. A self-intervention occurred when participants started to cross but then deemed the crossing too dangerous to proceed and stepped back to the curb. Experimenter interventions were practiced before the first test session and included both instructions (e.g., “stop”) and physical contact (e.g., grasping a participants’ upper arm to halt them). Experimenter interventions followed the standard criterion used during orientation and mobility training. Experimenter “pulled” the participant back when he or she was in imminent danger of being struck by a vehicle if evasive action was not immediately taken by either the pedestrian or the driver. These were pedestrian–vehicle conflicts in which nearby approaching vehicles did not yield, perhaps because the drivers assumed that the pedestrian ahead would speed up or slow down in order to avoid a collision. After the participants initiated a crossing, they proceeded to the other end of the crosswalk on their own, with the experimenter following at a distance of about 1 m. Upon arrival at the splitter island, the experimenter directed the participant to the starting location for the next segment of the crossing at the far side of the island. On indicator trials the experimenter and participant crossed together sometime after the participant indicated they would have crossed.

Each computer data entry consisted of a letter code and time stamp in one-hundredth second intervals, although the actual temporal precision of the observers was approximately one-half second. One observer recorded information about the participant and one recorded information about traffic. For crossing trials, the observers coded when the trial began, when the experimenter gave a hand signal identifying the start of the trial segment, when the participant gave the hand signal identifying that he or she was starting to cross, when the participant completed a segment of the crossing (e.g., when the splitter island was reached), and whether there was a self-initiated or experimenter-initiated intervention during the segment. The traffic activity coded included each vehicle’s arrival at the crosswalk, periods of queued traffic (two or more stopped vehicles in line), and when drivers yielded to the participant (i.e., drivers stopped short of the crosswalk and watched the participant). We also recorded the location of the nearest approaching vehicle when the participant signaled the start of a crossing. The code was “near” if the vehicle was 0–13.7 m (45 ft) from the crosswalk for entry lanes and 0–27.4 m (90 ft) for exit lanes; “middle” if 13.7–27.4 m (45–90 ft) for entry lanes and 27.4–54.9 m (90–180 ft) for exit lanes; “far” if more than 27.4 m (90 ft) for exit lanes and more than 54.9 m (180 ft) for exit lanes; and “stopped” if the vehicle was stopped in the near region. Landmarks along the street served as guides for coding the location of the nearest vehicle. The difference in distances used for coding the proximity of the nearest vehicle for entry and lanes was necessary to roughly equate entry and exit for time to arrival at the crosswalk, taking into account that drivers on the entry lanes almost always slowed substantially before reaching the crosswalk. The reliability of the coding of the location of the nearest vehicle was established by having two observers simultaneously observe and code six crossing trials (thus 24 crossing segments) by a sighted participant. For all categorical measures presented in the results section there was perfect agreement, and the agreement for time measures was within 1 s on 90% or more of observations.

The following description of an actual trial of a blind participant illustrates the data collected. This trial started with crossing of the exit lanes. The computer clock began at time zero and there was a delay of 16 s before the trial got underway. The participant received the ready signal at 16.7 s, and it was another 10.9 s until the next vehicle entered the crosswalk. This might have been enough time for a crossing, but the participant did not attempt to cross. Three vehicles came by the crosswalk at 27.6, 33.5, and 36.1 s. About 6 s after the third vehicle, at 42.0 s, the participant began crossing. The observer recorded that the pedestrian began crossing when the nearest approaching vehicle was at the “mid” distance. The participant reached the splitter island at 53.1 s, and slightly afterward, at 53.9 s, a vehicle entered the crosswalk behind the participant. A few features from the remainder of the trial (extending into further crossing segments) are as follows. At 159.0 s a vehicle in the entry lanes yielded to the pedestrian. The participant did not take this yield. At 213.6 s another vehicle yielded, and the participant did take this yield, starting to cross at 216.5 s. At 311.9 the participant began crossing the exit lanes but pulled herself back. There were actually no approaching vehicles in the vicinity when the self-intervention occurred, and the participant was given the ready signal to continue with the crossing at 317.5 s.

Results

Sighted Pedestrians Making Street Crossings

Averaging across entry/exit lanes and low/high traffic volume, a sighted participant’s typical crossing began with a wait of about 8 s during which two or three vehicles passed by. The crossing lasted about 7 s, with 3 to 4 s passing before the next vehicle reached the crosswalk. On 41% of crossings, however, sighted participants saw right away that there was sufficient time to cross and started crossing before any vehicles passed by. Sighted participants did not necessarily wait for naturally occurring gaps that were long enough to afford a crossing. Instead, they selected gaps that could be extended by accommodative driver behavior. Exchanges of gaze and hand signals between drivers and the sighted participants occurred frequently and appeared to be an important component of this process.

The effects of several experimental variables were considered: traffic volume (low, high); traffic lanes (entry lanes, exit lanes); direction of pedestrian travel (to or from the splitter island); and trial number (1, 2, 3). Trial number was included as a check for practice effects, which were not observed. Statistical tests included analysis of variance and chi-square. Findings are presented first for the crossing trials, then, in a separate section, for the indicator-task trials.

Wait time began when the participants received the start signal on a particular leg of the crossing and ended when they started walking. Wait time at high traffic volume averaged 10.2 s (SE = 1.0) compared to 6.1 s (0.5) at low volume, a significant difference, $F(1,5)=10.59, p<0.023$. Wait time was also longer for crossing segments from the ends of the crosswalk to the
Sighted participants’ crossing times for each 9.5 m leg were normally distributed with a mean of 6.6 s (SE=0.1) and did not vary across experimental conditions. This corresponds to an average walking speed of 4.6 ft/s. One index of pedestrian safety is the time from the start of crossing until the next-arriving vehicle enters the crosswalk. If the crossing is completed before the next vehicle arrives, the crossing can be considered safe, although even shorter times were occasionally observed when a driver passed safely behind a participant toward the end of the two-lane crossing. The time from the start of crossing until the next vehicle arrived at the crosswalk is reported in terms of medians rather than means because the distributions included some very long times. The median time for all of the real crossing trials for sighted participants was 8.9 s. However, this time differed significantly according to traffic volume, from 14.1 s at low volume to 7.1 s at high volume, $\chi^2(1)=12.423$, $p<0.001$. The relationship between this time measure and actual walking time was explored further by computing, for each trial, the difference between the time-to-next-vehicle and the pedestrian crossing time. The median differences were 6.8 s at low traffic volume and 0.7 s at high volume, a significant difference, $\chi^2(1)=11.270$, $p<0.001$. The 25th percentiles were at −0.1 s at low traffic volume and −0.9 s at high volume, indicating that, on about one-fourth of their crossings, sighted participants were still in the crosswalk when a vehicle came through. In most cases the vehicle passed safely behind the participant, although there were some crossings on which the participant began crossing when a vehicle still had time to pass safely in front. These findings indicate that sighted participants timed many of their crossings with small but safe time margins. Although detailed observations of pedestrian–driver interaction were outside the focus of this study, it was obvious that sighted participants and drivers communicated visually through eye-gazing and manual gestures.

Analyses of the location of the nearest vehicle when the sighted participants started crossing suggested that they adjusted their criteria based on traffic volume, especially when crossing the exit lanes. For the sake of clarity just one of these analyses is presented. The category of “near” usually meant that the vehicle was close enough that the pedestrian’s entry into the crosswalk required slowing or stopping by drivers. Note that these were legal pedestrian crossings, since state law requires drivers to yield to pedestrians who are in an established crosswalk. For the entry lanes, a vehicle was near on 28% of crossings at low traffic volume compared to 42% at high volume. This difference was not significant. For the exit lanes, the vehicle was near on only 17% of crossings at low volume compared to 50% of crossings at high volume [$\chi^2(1)=9.000$, $p<0.003$]. Thus sighted participants were more likely to cross when an approaching vehicle was nearby if the traffic volume was high, especially when crossing the exit lanes. Participants told us that they made sure to establish visual contact with the driver as they commenced these crossings.

In the course of the 144 crossing legs by sighted participants, drivers clearly yielded 12 times while a participant was still waiting to begin crossing. All 12 occurred on the entry lanes, four at low traffic volume and eight at high volume, and the participants took advantage of all the yields. There were no occasions when the experimenter pulled a sighted participant back during a crossing. Once a sighted participant began to cross and then pulled herself back. Thus sighted participants selected safe crossing opportunities quite reliably.

### Table 1. Summary of Intervention Counts for Blind Participants on Actual Crossing Trials

<table>
<thead>
<tr>
<th>Type of Intervention</th>
<th>Entry Lanes (10 total)</th>
<th>Exit Lanes (10 total)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low volume 2</td>
<td>Low volume 2</td>
</tr>
<tr>
<td></td>
<td>High volume 0</td>
<td>High volume 3</td>
</tr>
<tr>
<td></td>
<td>Low volume 6</td>
<td>Low volume 1</td>
</tr>
<tr>
<td></td>
<td>High volume 7</td>
<td>High volume 4</td>
</tr>
</tbody>
</table>

**Comparison of Blind and Sighted Pedestrians**

Whereas sighted participants waited 8.2 s on average to begin crossing, blind participants waited an average of 26.2 s during which five or six vehicles typically passed by. The median accepted gap for blind participants was about 20 s long, compared to 12 s for sighted participants. The crossing itself took about 8.5 s for blind participants, slightly longer than the 6.6 s average for sighted participants, perhaps because blind participants tended to veer somewhat, requiring redirection by the OM instructor who followed the participant during the crossing. On 15% of crossings, the blind participants started walking before any vehicles came by, compared to 41% for sighted participants. A general conclusion from these findings is that sighted participants found crossing opportunities sooner than blind participants, resulting in a threefold difference in average waiting time.

With respect to safety, the most dramatic difference between the blind and sighted participants was the frequency of interventions. It was noted earlier that among sighted participants there was never an experimenter-initiated intervention and there was only one self-initiated intervention. In contrast, on a number of occasions blind participants were pulled back by the experimenter after starting to cross, or they pulled themselves back, as summarized in Table 1. Over the 144 crossings there were 15 times when blind participants pulled back on their own initiative after starting to cross. These interventions were instances in which the participants believed it was safe to cross but, as they started walking, heard something that caused them to abort the crossing. This illustrates the uncertainty surrounding crossing decisions by blind pedestrians at this intersection. In some cases they were surprised to hear vehicles pass close by when they had thought there were no vehicles present, while on other occasions it would have actually been safe to cross, but they apparently heard vehicular sounds from elsewhere in the area which led them to believe a vehicle was approaching. In addition to the self-initiated interventions, there were 10 experimenter-initiated interventions of blind participants. Five of the six blind participants had at least one experimenter-initiated intervention. These 10 interventions are noteworthy because the blind participants, by self-report, did not realize that they were walking into a potentially dangerous situation. The situation is all the more risky because from a driver’s perspective it would be very unusual for a pedestrian to begin crossing with an approaching vehicle so close. Interventions occurred on both the entry and exit lanes, and at low and high traffic volumes, indicating that the failure to detect approaching vehicles before starting to cross generalized across traffic conditions at this roundabout.

An analysis based on the 10 experimenter-initiated interventions estimates the odds of a blind pedestrian initiating an especially risky crossing. There were 144 crossing segments for these participants. However, the total number of crossing
then the exit lanes crossings on the way to work to get from a bus stop to work. The individual must complete two crossings. Fig. 2 shows how the odds of at least one risky crossing attempt grows with repeated crossings, for three different values of the assumed probability on a per-crossing basis. The probability is calculated as 1−(1−\(P_{\text{per crossing}}\))^n. For example, if \(P_{\text{per crossing}}\) is 0.06 or 6% then the probability of a risky crossing in 25 attempts is 1−(1−0.06)\(^{25}\) = 0.787 or about 79%.

Attempts was 169 because whenever there was an intervention of either kind the participant was guided back to the waiting position for that crossing segment and instructed to start again. Since there were 25 interventions (10 experimenter-initiated and 15 self-initiated), the total number of crossing attempts was 144+25 = 169. Thus the rate of experimenter-initiated interventions was 10/169 or just under 6%. Given the number of crossing attempts, a 90% confidence interval on this intervention rate has a lower bound of 2.9% and an upper bound of 8.9%. Of course a pedestrian must consider safety over the long run with repeated crossings. Fig. 2 shows how the odds of at least one risky crossing increase with repeated crossings. Even if the likelihood of a risky crossing is as low as 3% per crossing, over the course of 100 crossings the pedestrian has a 95% chance of making one or more such crossings. Keeping in mind that a “crossing” as discussed here refers only to an entry or exit lane segment, suppose a blind pedestrian has to cross one leg of the roundabout to get from a bus stop to work. The individual must complete two crossings on the way to work (e.g., crossing the entry lanes and then the exit lanes) and two more on the way home (e.g., the exit lanes, then the entry lanes), for a total of four crossings per day. As Fig. 2 illustrates, the pedestrian would be highly likely to make a risky crossing within 1 or 2 weeks (20–40 crossings). Consistent with this analysis, all six of the blind participants said in postsession discussions that they would seek an alternative route to avoid the roundabout in daily travel because they lacked sufficient information about vehicle movements.

Wait times were longer for blind than sighted participants, \(F(1,10)=20.151, p<0.001\), and this difference was greater at high traffic volume than low volume, \(F(1,10)=9.077, p<0.013\). Fig. 3 shows mean wait times by vision group and traffic volume. Blind participants waited about three times as long to begin crossing as sighted participants at both low and high traffic volume.

The group difference in waiting time was supported by analyses of gaps that were accepted or not. The upper panel of Fig. 4 shows the gaps not accepted by blind and sighted participants, while the lower panel shows gaps accepted. With respect to gaps not accepted, blind participants altogether waited through more than twice as many gaps as sighted participants. For sighted participants only 3% of the gaps not accepted were longer than 7 s, meaning that they rarely missed an opportunity to cross. In contrast, 19% of the gaps not accepted by blind participants were longer than 7 s. The lower panel of Fig. 4 shows that sighted participants tended to initiate crossings with gaps of about 5–15 s, whereas blind participants waited for longer gaps. The category “Longer” in this figure designates gaps so long that data collection was stopped for that crossing, typically 45 s or more when traffic volume was very low. Focusing on measured gaps of 30 s or less, 90% of the sighted participants’ crossings occurred with gaps of 14 s or less, compared to only 33% for blind participants. These numbers indicate that sighted participants felt comfortable starting to cross the street with traffic gaps considerably shorter than those accepted by blind participants. Sighted participants accepted gaps of about 5–15 s compared with 10–25 s for blind participants. Since the longer gaps were infrequent at this roundabout, this difference in gap acceptance translated into a threefold difference in wait time between blind and sighted pedestrians.

Analyses of the actual crossing time, from the start of a crossing until the participant reached the curb area or splitter island, showed that blind participants took longer than sighted participants, \(F(1,10)=9.706, p<0.011\), and that the group difference interacted with entry/exit lanes, \(F(1,10)=6.927, p<0.025\). When crossing the entry lanes blind participants averaged 9.2 s (SE=0.3) compared to 6.7 s (0.1) for sighted participants. On the exit lanes the means were 8.3 s (0.2) for blind participants and 6.6 s (0.1) for sighted participants. One interpretation is that blind participants crossed faster on the exit lanes because they perceived those crossings as more risky than the entry lanes (the physical distance of the crossing was the same for entry and exit). This is consistent with the observation, noted by all participants, that vehicle speeds through the crosswalk zone were considerably higher on the exit lanes than the entry lanes.

Another measure of interest is the accepted gap, that is, the time between successive vehicles spanning the actual crossing. This time was significantly longer at low traffic volume than at high volume, \(F(1,10)=13.411, p<0.004\), and it was longer for blind than for sighted participants, \(F(1,10)=8.962, p<0.013\), although the interaction between the traffic volume and vision group was not significant. Mean gap lengths for blind participants were 21.7 s (SE=0.7) at low traffic volume and 17.1 s (0.7)
at high volume, and for sighted participants the means were 17.4 (1.0) and 13.3 (0.7). The fact that accepted gaps were shorter at high traffic volume suggests that both groups of participants shifted their decision criteria across the low and high volume test conditions. However, the measurement of accepted gaps is complicated by the fact that a pedestrian’s entry into the crosswalk tends to lengthen a gap when drivers slow to accommodate the pedestrian. Our impression was that blind participants tried to select long gaps when no vehicle was nearby, whereas sighted participants accepted gaps that would be long enough if approaching drivers yielded. According to postsession interviews, blind participants did not feel that they had sufficiently accurate information about vehicle locations and speeds for this kind of “gap stretching.”

The locations of the nearest vehicle when participants began crossing are summarized in the top half of Table 2. More crossings were initiated with a car stopped “near” on the entry lanes than on the exit lanes, with drivers rarely stopping at the exit lane crosswalk. The patterns of vehicle locations did not differ substantially across the vision groups. However, the numbers do not adequately convey an important group difference. For the exit lanes, both groups had a vehicle nearby on about one-third of their crossings. Sighted participants appeared always to know that these vehicles were nearby, and they confirmed visually that the drivers would slow for them to cross. In contrast, blind participants frequently were unaware of the nearby vehicles until the vehicles passed behind them during the crossing.

Table 3 shows the number of times during crossing trials that drivers yielded to a waiting participant. Yielding occurred 43 times on the entry lanes compared to only six times on the exit lanes, $\chi^2(1)=27.939, p<0.001$. This presumably reflects exiting drivers’ concern about yielding in the presence of the circulating traffic behind them (e.g., their concern about potential rear-end collisions). Drivers were more apt to yield to blind participants than to sighted participants, $\chi^2(1)=12.755, p<0.001$. It was clear that many drivers saw the blind participants’ long canes and made an effort to be accommodating, as reflected not only in the frequency of overt yielding but also in slowing, which we did not code. However, blind participants usually did not take advantage of yields. As Table 3 shows, sighted participants crossed on all 12 of the yields offered to them, whereas blind participants

<table>
<thead>
<tr>
<th>Trial type</th>
<th>Lane</th>
<th>Group</th>
<th>Stopped</th>
<th>Near</th>
<th>Medium</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing</td>
<td>Entry</td>
<td>Blind</td>
<td>13</td>
<td>14</td>
<td>9</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sighted</td>
<td>7</td>
<td>25</td>
<td>2</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Exit</td>
<td>Blind</td>
<td>1</td>
<td>26</td>
<td>13</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sighted</td>
<td>2</td>
<td>24</td>
<td>18</td>
<td>28</td>
</tr>
</tbody>
</table>

| Indicator | Entry| Blind  | 7       | 16   | 6      | 43  |
|          |      | Sighted| 10      | 23   | 8      | 31  |
|          | Exit | Blind  | 1       | 20   | 16     | 35  |
|          |      | Sighted| 2       | 33   | 22     | 15  |

Note: Each entry indicates the number of trials. The total of 72 for each row is based on six participants per group and 12 trials per participant. Near, medium, and far distances are specified in the “Method” section.

<table>
<thead>
<tr>
<th>Lane</th>
<th>Group</th>
<th>Yields (made)</th>
<th>No yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry</td>
<td>Blind</td>
<td>31 (9)</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Sighted</td>
<td>12 (12)</td>
<td>60</td>
</tr>
<tr>
<td>Exit</td>
<td>Blind</td>
<td>6 (0)</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Sighted</td>
<td>0</td>
<td>72</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses show yields that were taken by the pedestrian, e.g., for trials on the entry lane blind participants took advantage of 9 out of 31 yields.
crossed on only 9 of 37 yields, \( \chi^2(1)=21.189, p<0.001 \). Drivers sometimes expressed annoyance by gesturing or honking, perhaps because they did not understand that the blind pedestrian was unaware of the yield or because the pedestrian’s sighted companion seemed to be ignoring the yield offer.

When vehicles are queued, pedestrians may have an opportunity to cross between stopped vehicles. During our data collection sessions traffic queues never occurred on the exit lanes, reflecting the adequate traffic-handling capacity of the roundabout. On the entry lanes, there were only two queues during 144 crossings at low traffic volume in contrast to 28 queues on 144 crossings at high volume (queues occurred on 18 of the high volume crossings but sometimes there were multiple queues, for a total of 28 occurrences). Sighted participants were presented with a total of four queues and they crossed on two of these occasions. Queues occurred on 26 occasions for blind participants and they crossed on four of these. The greater number of queues for blind participants is probably attributable to their longer wait times. In general, traffic queues did not provide a substantial window of opportunity for crossing at this roundabout.

**Crossings Versus Indicator Trials**

The results of previous research (Guth et al. 2005) using the indicator-task method suggest that, under some conditions, there are important differences in crossing judgments made by blind and sighted pedestrians at roundabouts. One purpose of the present study was to assess the validity of the indicator task. We did this by comparing the findings from the indicator and crossing trials. The information available to participants was the same across trial type, but it is possible that participants’ decision criteria depend on whether they would be acting on their judgments by crossing the street.

There were several measures on which data from the indicator trials and the crossing trials could be directly compared. Fig. 5 shows this comparison for wait time. Wait times were comparable across the indicator and crossing trials, except that for the blind participants at high traffic volume, wait time was considerably longer for crossing trials than indicator trials. This was supported by a three-way interaction between the vision group, traffic volume, and task, \( F(1,10)=14.244, p<0.004 \). Thus the differences in performance between blind and sighted participants were similar across the indicator and crossing trials, except that when traffic volume was high, the blind–sighted difference in wait time was even higher on the real crossings than on the indicator trials.

Another measure which could be compared across tasks was the time from the initiation of the actual crossing (or indication that a crossing was appropriate) until the arrival of the next vehicle at the crosswalk. The crossing and indicator trials were nearly identical on this measure. For sighted participants, the time averaged 10.3 s (SE=0.6) and 10.2 s (0.6) in the crossing and indicator trials, respectively, and for blind participants, it averaged 12.3 s (0.5) and 11.9 s (0.6). For both the crossing and indicator trials, the time to arrival of the next vehicle at the crosswalk was about 2.5 s shorter (9.9 versus 12.5 s) during the high volume condition than the low volume condition. These findings further suggest that both blind and sighted participants made crossing and indicator decisions based on similar criteria.

As noted earlier, traffic queues occurred 30 times during crossing trials, exclusively on the entry lanes and mostly during the high volume condition. Sighted participants crossed during two of four queues and blind participants crossed during four of 26. The results for the indicator trials were similar. Queues occurred 23 times during indicator trials, all on the entry lanes, with 19 at high volume and 4 at low volume. Sighted participants indicated that they would cross during 3 of 9 queues and blind participants during 4 of 14 queues. In sum, comparable results were generally obtained for those measures for which it was appropriate to compare the crossing and indicator trials.

**Discussion**

To our knowledge this is the first report of observations of pedestrians making actual street crossings at a roundabout. The sighted participants crossed safely and after waiting only briefly. With average waiting times of only 8 s for each of the two crossing segments, even at high traffic volumes, sighted participants may have waited less than they would have at some traditional signalized intersections with similar traffic volumes. It would be premature, however, to generalize the findings to all sighted pedestrians. For example, our sample did not include children, elderly people who walk slowly, or people with mobility impairments such as users of wheelchairs and walkers.

The roundabout crossing task appears to require careful monitoring of traffic activity and an understanding of driver behavior. This applies especially to crossing the exit lanes of a roundabout when traffic volume is high. The sighted participants in this study accepted many gaps that afforded crossing only if drivers slowed or delayed their acceleration. This requires awareness of the locations and speeds of approaching vehicles, prediction of whether such vehicles could safely yield, and consideration of how drivers may respond based on other traffic in the roundabout. Before crossing, the sighted participants tended to establish visual contact and nonverbal communication with approaching drivers to confirm that the drivers would allow them to cross. In contrast, blind participants said that their opportunities for such communication were very limited (e.g., waving in appreciation if a driver tapped his or her horn to signal yielding).

**Visual Versus Auditory Perception of Traffic**

The observed similarities and differences between pedestrian crossing performance of blind and sighted participants can be considered in the context of differences between visual and auditory perception of traffic. Under daylight conditions vehicles
are readily seen by individuals with normal vision at distances that permit them to make appropriate crossing decisions. Beyond detection, it is another matter whether sighted pedestrians can make accurate decisions about the distances and arrival times of vehicles they see. Research indicates that adults are moderately accurate at the pedestrian’s task of judging when an approaching object will arrive, or the driver’s task of judging when a moving observer will arrive at a location (Cavallo and Laurent 1988; Schiff et al. 1992; Stewart et al. 1993; Hoffman 1994; Tresilian 1999). Children and elderly adults appear to be less accurate than young adults at making visually based street crossing decisions, although it is not clear whether this is because of perceptual limitations or differences in driving and walking experience and knowledge (Demetre et al. 1992; Oxley et al. 1997; Connelly et al. 1998; Pitcairn and Edllman 2000; Whitebread and Neilson 2000; Tabibi and Pfeffer 2003). Findings from the present study as well those of Guth et al. (2005) suggest that sighted adults have adequate information to select safe traffic gaps at roundabouts, and that they continue to visually monitor traffic during the crossing.

In contrast, Guth et al. (2005) interpreted differences between blind and sighted pedestrians as suggesting that auditory perception of traffic patterns is less reliable than visual perception. It is widely recognized that there are significant information limitations for performance of pedestrian tasks without vision (Gerusch and Smith 1997; Guth and Rieser 1997; Wiener et al. 1997). If traffic volume is low and there is little background noise, then an absence of engine or tire noise suggests that a pedestrian crossing is possible. However, the increasing prevalence of quiet vehicles—including those that are virtually silent at low speeds and silent when stopped—is affecting the ability of blind pedestrians to rely on auditory cues for initiating street crossings in some situations. When traffic is heavy, it sometimes becomes difficult to detect critical information about approaching vehicles within the background of traffic noise. In addition to the challenge of detecting approaching vehicles, the present findings suggest that hearing provides unreliable information about the status of vehicles whose drivers are yielding to a pedestrian. Blind participants typically failed to detect that drivers were yielding to them. This implies that efforts to encourage driver yielding may be of limited use to blind pedestrians unless they have access to information about the driver’s intention.

**Risks and Inconveniences Associated with Crossing Decisions**

Although most of the blind participants’ actual crossings were made when the gaps between vehicles were sufficient, about 6% of their crossing decisions resulted in an experimenter-initiated intervention. On these occasions the participants reported that they did not realize that one or more vehicles were nearby and approaching so as to pose an imminent threat. This is a high error rate for a potentially life-threatening situation. Even a conservative interpretation of the analysis shown in Fig. 2 suggests that a blind pedestrian who crossed the roundabout daily could make at least one such error every several weeks. Not every such occurrence would result in a pedestrian–vehicle crash, since drivers would attempt to avoid the pedestrian. However, few pedestrians would consider it acceptable to experience such close calls on a routine basis. The lack of reliable information about the status of approaching vehicles led these six blind participants, all skilled independent travelers, to spontaneously state that they would not routinely cross unassisted at this set of crosswalks. One potential concern regarding our intervention measure is whether the experimenters may have been biased to overuse the intervention option with blind participants. This is possible, but the experimenters were experienced Orientation and Mobility Specialists accustomed to letting blind clients experience close calls, but not highly dangerous ones.

With respect to research on pedestrian safety at roundabouts, the risk perceived by blind participants suggests that assessments of blind pedestrians’ safety at roundabouts that are based on crash data, if available, would be difficult to interpret without accompanying exposure data. In interviews of blind pedestrians in the United Kingdom and France, Guth et al. (2000) found that these individuals devised routes that avoided roundabouts they considered to be high risk, despite the marked inconvenience of some of the alternative routes. This is consistent with our participants’ statements that they would avoid this roundabout as a regular travel route.

In addition to differences between blind and sighted participants related to safety, there were those related to convenience. For example, when traffic volume was high, blind participants waited about 40 s to begin each segment of the crossing compared to 10 s for sighted participants. For a typical crossing scenario, this would translate into a large overall difference. Suppose that a pedestrian has to cross two legs of a roundabout while walking to and from his or her office to lunch on the diagonally opposite corner. This entails four crossing segments on the way to lunch and four on the way back. Extrapolating our findings to this situation suggests that this would require an average of 80 s (8 × 10) of wait time for a sighted pedestrian and 400 s (8 × 50) for a blind pedestrian. This does not take into account possible differences in the time required for the other street-crossing subtasks such as locating the crossing points, identifying the direction of the crosswalk, and traveling between the first and second legs of the roundabout. It is not known at what point the additional waiting time experienced by blind pedestrians would, for some pedestrians, shift from an inconvenience to a barrier which would preclude crossing there.

**Validity of “Indicated” Crossing Decisions**

In a previous study of pedestrian judgments at roundabouts that used an indicator task, Guth et al. (2005) reported that blind participants missed more crossing opportunities and made more potentially risky judgments than sighted participants. It may have been the case, however, that those participants would have used different decision criteria had they been asked to actually cross instead of indicating that they would cross. In the present study, the same participants made indicator judgments and actual crossings during the same test sessions. The same general patterns of difference between blind and sighted participants were observed for both tasks, supporting the validity of the indicator task paradigm. If anything, blind participants were less conservative on the indicator task than when actually crossing the street. It appears that indicator tasks are a useful methodological tool for studies in which the objective is to learn about pedestrians’ judgments.

**Effects of Traffic Volume and Entry/Exit Lane**

The volume of traffic at a roundabout appears to be related to its usability by blind pedestrians. By collecting data at the same roundabout for the same participants under conditions of lower and higher traffic volume, we were able to examine the effect of
volume while holding constant the roundabout geometry and local driving habits. The wait time differences between blind and sighted participants were much greater when traffic volumes were higher. This agrees with previous work by Guth et al. (2005) in which blind/sighted differences were greater at two fairly large, busy roundabouts than at a small, lightly traveled one. However, the findings on interventions from the present study (Table 1) suggest that, even at lower traffic volumes, blind pedestrians may be at risk for initiating crossings while unaware of nearby approaching vehicles.

The wait time data and participants’ self-reports indicated that participants found the exit lanes to be more difficult to cross than the entry lanes, especially when the traffic volume was high. Further, drivers almost never yielded on the exit lanes, whereas they often yielded on the entry lanes. An incident during data collection illustrates why drivers exiting the roundabout were reluctant to stop for pedestrians. An off-duty policeman, seeing one of the blind participants waiting to cross the exit lane, stopped his unmarked vehicle in the circulatory roadway and called out for the pedestrian to cross. Within seconds, traffic was backed up in the roundabout and drivers angrily honked their horns. Although crossing data varied substantially by entry versus exit lane, there was little in our findings to suggest that the direction of pedestrian travel, toward the splitter island or away from it, had an effect on performance.

Policy and Design Implications

The present findings have implications for engineering approaches to promote pedestrian safety at roundabouts. One consideration is driver yielding behavior. Since pedestrians crossing at roundabouts must select gaps between vehicles that are not legally required to stop, unless the yield-on-entry requires it or a pedestrian is already in the crosswalk, design features that promote yielding to waiting pedestrians have been considered. In the present study, drivers were fairly likely to yield to participants on the entry lanes, especially to the blind participants, but yielding almost never occurred on the exit lanes. At this roundabout the crosswalks were located less than 10 m from the circulatory roadway, which may have discouraged yielding on the exit lanes. Drivers may have estimated that the risk of a rear-end crash with another vehicle outweighed the burden of added waiting time for the pedestrian. Further, drivers in the circulatory roadway may have been too preoccupied with nearby traffic flow and preparation for their own exit to allocate much attention to pedestrians not in the roadway. We suggest that efforts to promote yielding at busy roundabouts are more likely to be productive for entry than exit lanes.

For pedestrians with visual impairments, the benefits of driver yielding will be of little use if the pedestrian cannot perceive the yield. Many drivers yielded to blind pedestrians identifiable by a cane, yet the participants usually failed to take advantage of the yields. In some cases, blind participants could hear that a car was stopped or slowing to stop, but they considered that there might be an undetected moving vehicle approaching in the other lane moving in the same direction and therefore chose not to cross. In other cases, blind participants did not detect, by later self-report, that a driver had yielded. Improved methods of identifying yields for blind pedestrians are needed, perhaps utilizing automated vehicle detection methodologies. It is important to note that identifying a vehicle that has yielded for a pedestrian is not the same as identifying a vehicle that has stopped near the pedestrian. A driver may have indeed yielded in response to the pedestrian, but may also have stopped due to factors such as queues. It appears to be important that yield detection distinguishes between these scenarios.

The site used for the present study comprised crosswalks spanning double traffic lanes, so a comparison with single lane crossings was not possible. However, participants made some observations relevant to this. At a single lane crossing, a pedestrian can usually count on a stopped vehicle to block traffic behind it, but this is not the case with double-lane crossings where vehicles yielding in the first lane can be passed by vehicles in the second lane. Auditory detection of the status of vehicles in the “open” lane can be difficult due to the masking sounds of the yielding vehicle’s engine as well as the sounds of other vehicles in the vicinity. Even some of the sighted participants reported that they occasionally watched a vehicle in one lane but failed to pay attention to the other lane. Systematic exploration of one- versus two-lane crossings is an important topic for future research.

A design consideration that has been suggested to improve nonvisual access to roundabouts is to place a noise-making feature, such as a contrasting pavement surface treatment that alters tire noise, on the roadway to indicate by sound when vehicles are at that location. If this technology is to provide information about when to initiate a crossing, then the point at which the vehicle is marked must be quite far in advance of the crosswalk, perhaps too distant to be practical in terms of the information needed by the pedestrian. For example, if vehicles are moving at 24.1 km per h (15 mi per h) and a pedestrian requires a 7-s gap to make a crossing, then, unless one assumes that all approaching vehicles will yield, the vehicle would have to be marked about 45.7 m (150 ft) from the crosswalk. For the exit lanes of the roundabout we studied, this would mean monitoring back to the far side of the circulatory roadway and out on two of the entry lanes at other legs. An alternative use of vehicle marking by sound would be a “late warning” signal when a vehicle is fairly close to the crosswalk, but far enough away so that a pedestrian who had started crossing could pull back. For example, noise devices 9–12 m from the crosswalk might help.

The present paper suggests that there are substantial differences between sighted and blind pedestrians at busy roundabouts with respect to safety, convenience, and overall acceptability as a travel route. Since the study did not compare roundabouts with traditional intersections, it should not be concluded that roundabouts are less accessible to blind pedestrians than traditional intersections, signalized or not. For example, although a traditional four-way intersection might have traffic and pedestrian signals enabling a blind pedestrian to identify the crossing phase readily, the pedestrian must still be concerned about drivers who ignore red lights or make legal turns on red. A comprehensive comparison of pedestrian performance at roundabouts and traditional intersections would require attention to the full pedestrian task (locating crosswalks, establishing alignment, etc.) and recognition that the perceptual and cognitive demands may be quite different across types of intersections. The present study takes a first step by documenting some specific ways in which sighted and blind pedestrians face challenges at roundabouts.

Conclusions

Based on the evidence from this study, in which pedestrians crossed entry and exit lanes at a two-lane modern roundabout, blind pedestrians experienced greater delays and risk exposure than sighted pedestrians. Blind pedestrians had longer wait times,
usually failed to perceive driver yielding, missed many crossing opportuni
ties, and had to be pulled back from risky crossing attempts. While the auditory information available to blind pe
destrians often allowed them to make safe crossing decisions, dan
gerous situations arose often enough so that all six blind partici
cipants said they would not make unassisted crossings at this rou
dabout. The study was not designed to compare roundabouts with other types of intersections, but all of these blind participants travel independently at traditional stop control intersections. The double lane structure of the roundabout may have made ped
estrian crossings more difficult because of increased vehicle speeds, longer crossing distances, and the fact that a yielding vehicle in one lane does not block traffic in the other lane. Efforts to promote driver yielding will be of little use to blind pedestrians without provision of information that a yield has occurred. The findings from this study provide a starting point for considering modifi
cations which may promote accessibility of roundabouts to pedes
trians with disabilities.

Acknowledgments

The writers thank the participants for completing a challenging street crossing task; Bob Weithofer, Transportation Manager for Metro Nashville Public Works, for guidance on working at the test site; Alice Ashmead for assistance with data collection; Janet Barlow, Billie Louise Bentzen, Duane Geruschat, David Harkey, Ron Hughes, and Nagui Rouphail for helpful discussions; and Brasfield & Gorrie construction company for building access to the test site; Alice Ashmead for assistance with data collection; Janet

References


Federal Highway Administration. (2000). Roundabouts: An informational guide (FHWA-RD-00-067). Federal Highway Administration, Turner-
Fairbank Highway Research Center, McLean, Va.


