See You on the Other Side: A Crosswalk Navigation System with Multimodal Alert System for Distracted and Visually Impaired Crosswalk Users

Distracted and visually impaired crosswalk users are at increased injury and death risk. A system that redirects the attention of distracted crosswalk users and helps both distracted and visually-impaired crosswalk users safely navigate crosswalks could mitigate that risk. We tested the effectiveness of four feedback systems on crosswalk navigation: no feedback (baseline), auditory (whistle), vibrotactile, and multimodal (auditory and vibrotactile). Twelve participants were recruited and blindfolded to cross an in-lab mock crosswalk. Analysis showed that multimodal auditory and vibrotactile feedback significantly increased the success rate of navigating through a crosswalk compared to the baseline. Among the participants, 83.3% (10 participants) preferred vibrotactile feedback, and 75% (9 participants) found vibrotactile feedback to be most intuitive. These findings can inform the development of infrastructure-embedded alert systems that promote the safety of distracted crosswalk users.

INTRODUCTION

Use of smartphones, multi-tasking, and overall distraction while locomoting is increasingly common (Mwakalonge et al., 2015; Liechtenstein et al., 2012; Bungum et al., 2005). Talking or texting on mobile devices decreases the identification of hazards in peripheral vision (Haque and Washington, 2014). Almost 40% of traffic fatalities in 2012 resulted from mobile device use while crossing the street (Mwakalonge et al., 2015). Moreover, people with vision impairments are at an increased disadvantage and safety risk in independently navigating crosswalks (Cheng et al., 2017). A system that warns distracted and visually impaired crosswalk users of deviation out of crosswalks into danger may fill crucial gaps in pedestrian and crosswalk user safety.

Several researchers have conducted research on pedestrian warning signals, some of which have addressed distracted pedestrians. Liu et al. (2021) reported a pedestrian-oriented forewarning system utilizing a smartphone-based app to send warning alerts to pedestrians via smartphone-obtained information regarding location, speed, and travel direction (Liu et al., 2021). Pedestrian warning signals, particularly auditory and visual signals, can be tuned out or obscured when pedestrians are distracted. Such is the case when competing auditory and visual stimuli of the surrounding environment and personal electronics (e.g., cell phones, headphones, and gaming devices) divert attention from the primary task of navigating crosswalks. Vladyko et al. (2020) found that using distinct pauses and customized messages in feedback systems is most crucial for increasing pedestrian awareness.

Research into multimodal pedestrian warning systems is not new; yet none were identified that specifically addressed visually impaired persons. Multimodal feedback systems, i.e. auditory, visual, and vibrotactile, have been used to warn pedestrians of impending danger at least as early as 2014 (Ishida et al., 2014). Lee et al. (2022) discussed a warning system that utilized auditory, visual and olfactory feedback while participants walked in a virtual environment. These systems were tested for people with no major health conditions and excluded people with disabilities and impairments. Our study focuses on distracted (visually and cognitively) or visually impaired crosswalk user responsiveness to various feedback.

The aims of this study are to: a) improve crosswalk safety for distracted and vision-impaired crosswalk user safety, b) investigate the crosswalk user perception, interpretation and behavioral responses to different feedback types, and thereby feedback effectivenesses, c) identify the type of feedback that best conveys a warning to crosswalk users, best commands crosswalk user attention, d) discover if and where attention is diverted by different feedback, and e) provide design considerations for wearable and infrastructure-embedded feedback systems for distracted and visually impaired crosswalk users.

METHOD

The primary aim of the designed system is to improve the safety of distracted and vision-impaired crosswalk users. The task under investigation is crossing a crosswalk. The crosswalk users should be warned if they veer from the crosswalk towards roadway hazards. We developed a multimodal feedback system by combining auditory and tactile feedback (at the ankle). The ankles were selected in the present study due to their proximity to the ground and predicted more-direct association with improper foot placement. Furthermore, near-foot sensation data would explore the potential utility of infrastructure-embedded vibrotactile warning systems that vibrate the walking surface underneath the foot.

We tested different feedback modalities and combinations to identify the condition that elicits the highest alertness and quickest, most appropriate stimulus responses. We excluded visual and olfactory feedback. Visual feedback is the least salient for our design scenario and target populations. Lee et al. (2022) found that human olfaction does not accurately localize scent (Lee et al., 2022). Olfaction is also unsuitable for brief duration and rapid onset dangers on account of its poor temporal resolution.

For this study, the participants were asked to cross a 30-foot-long, 4-foot-wide in-lab crosswalk. There were two 3-foot-wide feedback zones–one on each side of the crosswalk. Walking into the feedback zone triggered the feedback. If the participants walked outside the feedback zone, then the trial would be considered unsuccessful. **Figure 1** shows the crosswalk design for this study.

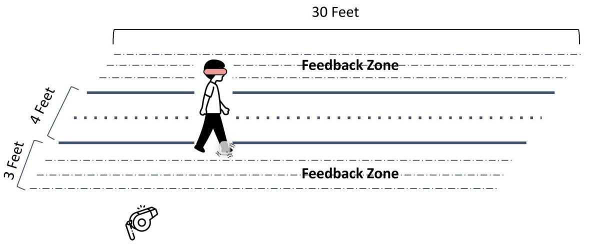

Figure 1. Crosswalk and feedback zone for the in-lab study. The whistle depicts the auditory feedback device, and the buzzing square depicts the vibrotactile feedback device.

Experimental Design and Observed Variables

To simulate the distracted condition, we asked the participants to count down from 100 by threes (i.e., 100, 97, 94,...). The participants were blindfolded to simulate vision impairment and visual distraction. Research findings suggest that complete visual occlusion indeed simulates visual distraction from texting while walking (Krasovsky et al., 2017). Furthermore, complete visual occlusion has previously been used to simulate visual distraction from walking and texting (Tian et al., 2022; Foerster et al., 2014). The research is mixed on whether complete visual occlusion effectively simulates either congenitally blind or late-blind persons (Spiers et al., 2018; Akpinar et al., 2020). The independent variable was the feedback type with four levels, i.e., no feedback (NF), auditory-only (A), vibrotactile-only (V), and combined auditory and vibrotactile (A+V). Each feedback condition was repeated twice. The dependent variables included time to cross, time outside the crosswalk, number of deviations from the crosswalk, number of re-entries back to the crosswalk, and success in crossing.

Feedback Design and Equipment

During the no feedback condition, participants did not receive any feedback. For all administered feedback, the feedback was provided from the direction towards which the participant deviated. If the participants were on the left side of the feedback zone, the auditory and/or vibrotactile feedback was sent from the left side (or to the left ankle) and vice versa. Feedback was provided in a cyclic on-off feedback pattern with a cycle time of 0.6 seconds (0.3 seconds on followed by 0.3 seconds off) for two-second intervals as long as the participant remained at least partially in the stimulus zone. The feedback-administering tasks were assigned to experimenters based on experimenter availability and task understanding at the time of each participant session. Two Metamotion sensors (Mbient Lab, USA) with a coin vibration motor were placed on the ankle of each participant.

For the auditory-only condition, a whistle sound was emitted on the side of deviation. A whistle sound was selected for its understood association with crossing guard auditory warnings. Thus, whistle sounds already have a defined meaning at intersections that would not need to be learned and are unlikely to cause excessive alarm or distress. Whistles are also low-tech, low-cost auditory feedback sources. The vibrotactile feedback was transmitted via the Metamotion sensors at a frequency of 165 Hz. During the combined auditory and vibrotactile feedback, participants received both the auditory alerting whistle and the vibrotactile feedback from the Metamotion sensors.

Procedure

The experiment was conducted as per Institutional Review Board-approved protocol (22-982). Twelve participants (Five male, Seven female, Age: 26 ± 2.9 yrs) were recruited to attend an hour-long in-lab experiment session. Upon entering the lab, participants reviewed and signed a consent form, then a demographics survey.

Participants walked to the starting point of the crosswalk. Participants were rotated three times, plus or minus a few degrees and oriented such that they were not directly facing the other end of the crosswalk. The participants were asked to count down from 100 by threes and walk across the crosswalk. Feedback was provided based on the experiment's condition and the participant deviation. Participants practiced navigating the crosswalk with occluded glasses approximately eight times prior to introduction of the alerting conditions. After participants transitioned to the blindfold, participants underwent trials as follows. Trial 1 of each condition was conducted (no feedback, then auditory feedback, then vibrotactile feedback, then combined auditory and vibrotactile feedback). After participants experienced all conditions, they completed the second trial for each condition in the same order as trial 1. After the completion of all trials, participants filled out a post-experiment survey regarding preferences and usability regarding the feedback.

Data Analysis

Participant survey responses were reported using descriptive statistics. We applied one-way repeated measures ANOVA to the dependent variables to determine the effectiveness of feedback. We performed paired sample t-tests with the Bonferroni adjustment for post hoc analysis. Post hoc Bonferroni adjusted pairwise paired sample t-test indicated which differences between conditions were statistically significant for each metric. The pairwise significance was decided by the adjusted alpha value, less than 0.0083 (0.05/6 pairs). Statistical analyses were performed using *R v4.1.1* (R Core Team, 2019).

RESULTS

Each participant completed the same number of trials under all the conditions regardless of the success or failure of the trials due to time and participant payment constraints, and to preserve participant continued participation and engagement. Two of the dependent variables were time measures, and three of the variables were frequency measures. The mean and standard deviation of each variable are summarized in **Table 1.**

We examined five metrics: 1) completion time of the trials (regardless of success or failure), represented in **Figure 2-(a)**, 2) percentage of time spent outside the crosswalk, represented in **Figure 2-(b)**, 3) number of deviations outside the crosswalk, shown in **Figure 2-(c)**, 4) number of re-entries into the crosswalk following crosswalk departures, displayed in **Figure 2-(d)**, and 5) success rate for navigating the crosswalk, depicted in **Figure 2-(e)**.

One-Way Repeated Measures ANOVA

The differences in completion times were significant for the different feedback conditions ($F(3,84) = 13.73$, $p = 0.03$). Differences in the percentages of time were significant for the different feedback conditions ($F(3,84) = 5.11$, $p = 0.003$). Differences in number of deviations was significant for the different feedback conditions ($F(3,84) = 3.884$, $p = 0.02$). A significantly different number of re-entries for the different feedback conditions ($F(3,84) = 8.83$, $p < 0.001$). A significant difference in completion time for the different feedback conditions ($F(3,84) = 13.73$, $p < 0.001$).

Bonferroni Adjusted Pairwise Paired Samples t-tests

The no-feedback condition had a significantly lower completion time than the vibrotactile ($p < 0.001$) and combined auditory and vibrotactile ($p = 0.004$) feedback conditions. The combined auditory and vibrotactile feedback condition had a significantly lower percentage of the time outside the crosswalk than the no feedback condition ($p < 0.001$). The no-feedback condition had significantly fewer deviations than the vibrotactile feedback condition ($p < 0.001$). The no-feedback condition has a significantly lower success rate and significantly fewer re-entries than all the other feedback conditions.

Subjective Ratings

Among the 12 participants, ten (83.3%) thought vibrotactile-only feedback best for a warning signal during crosswalk navigation, followed by auditory (8.3%) and combined auditory and vibrotactile (8.3%). Auditory was the least desirable feedback mode for the participants (66.6%), followed by vibrotactile (16.7%) and combined auditory and vibrotactile feedback (8.3%). One participant (8.3%) selected none as least desirable. Nine participants (75%) deemed vibrotactile as the most intuitive feedback, and half of the participants (50%) deemed auditory as the least intuitive. Half of the participants (50%) felt that auditory feedback was the most difficult to understand. Similarly, half of the participants felt that vibrotactile was the least difficult to understand. A plurality of participants (41.7%) felt vibrotactile feedback most signaled that they were veering out of the crosswalk, followed by auditory (33.3%) and combined auditory and vibrotactile (25.0%). Nonetheless, participants felt auditory and combined auditory and vibrotactile best signaled danger (41.7% each), followed by vibrotactile-only (16.7%).

DISCUSSION

General Findings and Key Takeaways

We observed that the combined auditory and vibrotactile feedback yielded the highest success rate in navigating the crosswalk and the lowest amount of time outside the crosswalk, indicating that this feedback was effective in keeping the participants within the crosswalk. In the no-feedback condition, participants spent less time crossing as they quickly went out of the feedback zone. Participants spent significantly more time in the feedback zone during the no feedback condition as they had no way of knowing that they were outside the crosswalk. Both unimodal and multimodal feedback were able to redirect the participants into the crosswalk from the feedback zone and significantly increased crosswalk navigation success compared with no feedback. The number of re-entries was significantly higher when feedback was provided.

The number of deviations was higher in the vibrotactile condition, which indicates that participants quickly steered away from the feedback zone after returning to the crosswalk. This indicates that having an auditory component present helped the participants better orient themselves inside the crosswalk and reduced the number of deviations outside the crosswalk. This finding supports Wickens' Multiple Resource Model, which theorizes that the human mind has separate dedicated channels with their own capacities for registering and processing different modes of feedback (Wickens et al., 2021). Thus, distributing information among channels aids information processing and tempers cognitive load (Wickens et al., 2021).

A previous study found that vibrotactile feedback improved the number of turns taken by older adults while navigating on the road (Cœugnet et al., 2018). This finding is consistent with our results. Prior studies also corroborate our finding that providing multimodal feedback in response to the movement of a user improves performance (Wilson et al., 2017; Islam et al., 2022). Rotella et al. (2012) found that vibrotactile feedback significantly improved motion accuracy and reduced the average number of errors in a remote balance training activity compared to no feedback. We similarly found improved successful crossing rates when feedback was provided. This result was especially notable for multimodal auditory and vibrotactile feedback compared with no feedback. Moreover, past studies found that a combination of multisensory cues improved task performance, accuracy, and spatial attention (Islam and Lim, 2022; Hecht et al., 2008). Those findings are consistent with multimodal auditory and vibrotactile feedback yielding the highest crosswalk navigation success rate in our study.

Design Considerations/Practical Implications

Our findings can inform the development of wearable and infrastructure-embedded feedback systems that guide distracted and visually impaired crosswalk users along crosswalks. For example, the number and placement of feedback devices are crucial aspects to consider in developing such systems. The upper body extremities are more sensitive to vibrotactile stimuli than the lower body parts (Islam and Lim, 2022). Participants in our study placed the vibrotactile feedback devices at the anterior ankle. Results showed that this placement provided intuitive and understandable feedback.

Table 1. Mean and SD for different types of feedback on different variables.

Feedback Type	**Variable Name (Mean ± SD)**				
	Time to cross (sec)	Time outside crosswalk (%)	Deviations (no.)	Re-entries (no.)	Success (%)
No Feedback	14.36 ± 7.30	46.2 ± 26.3%	0.86 ± 0.47	0.09 ± 0.29	22.7 ± 43.0%
Auditory	33.22 ± 36.34	35.9 ± 29.3%	1.63 ± 1.29	1.31 ± 1.49	68.2 ± 47.7%
Vibrotactile	29.72 ± 15.65	28.5 ± 25.7%	1.91 ± 1.01	1.77 ± 1.19	86.3 ± 35.1%
Auditory + Vibrotactile	29.59 ± 19.17	17.7 ± 16.9%	1.63 ± 1.29	1.54 ± 1.37	90.9 ± 29.4%

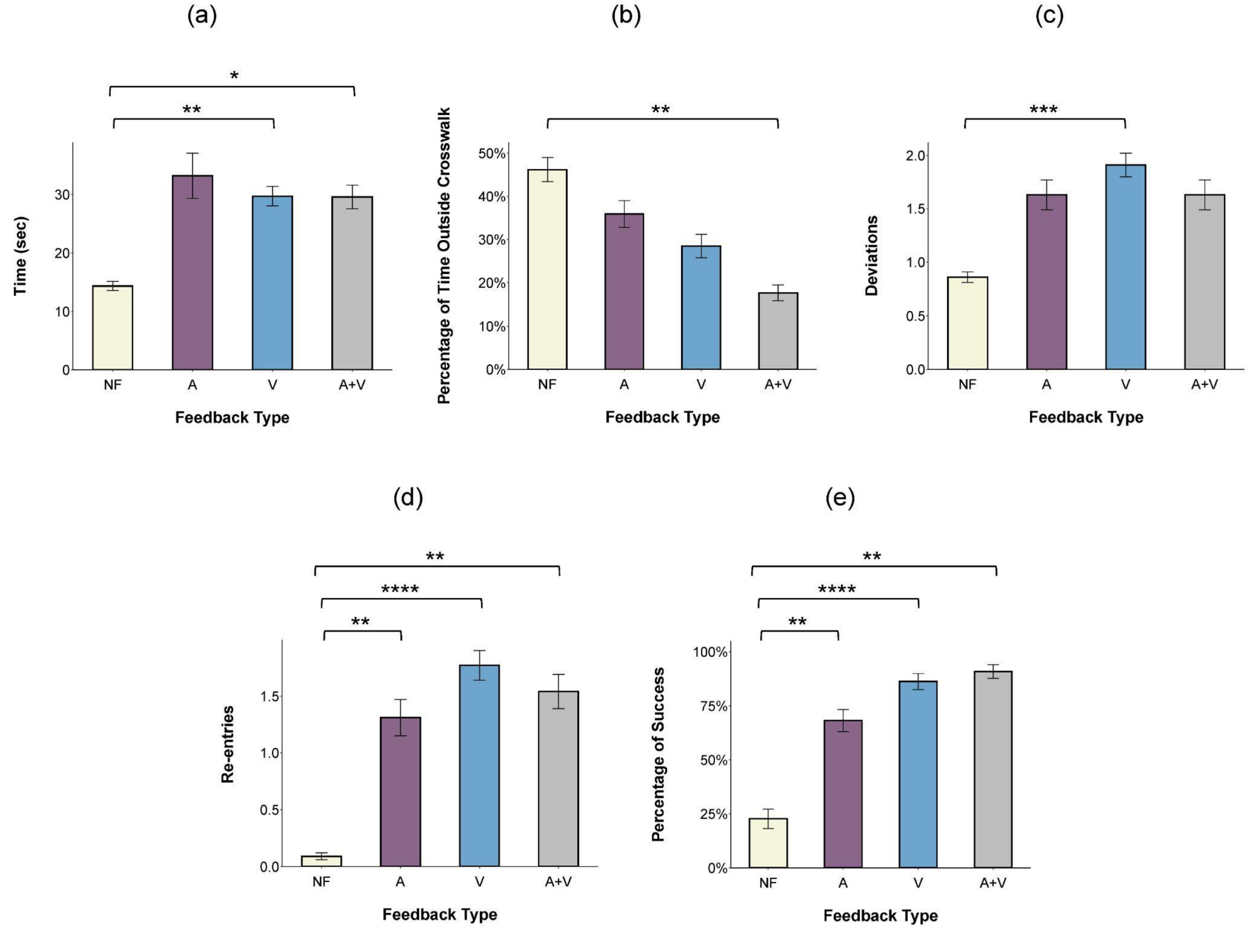

Figure 2. Effect of different types of feedback on the measured dependent variables. The error bar indicates standard error. "*", "**", "***", and "****" indicates statistically significant pairwise comparisons for which $p <$ "0.05", "0.01", "0.001", and "0.0001" respectively.

In service to a universal design approach, research is needed to investigate the relative intuition, understandability, feedback sensitivity, and accessibility of feedback device placements within the infrastructure or on the upper body (i.e., in the wrist or the hand). Piezoelectric technology embedded in the crosswalk infrastructure can also directly convert pressure detected outside of the crosswalk boundaries into vibrotactile feedback. Finally, the findings of our study can be integrated with computer vision-based technology. Crosswalk cameras can detect the orientation and estimate the deviation of the crosswalk user and then can send the signal to the wearable or localized infrastructure-embedded feedback device to address the individual deviating outside a threshold value. These approaches can automate feedback transmission. Additionally, the type of auditory feedback used in this study was somewhat difficult for the participants to understand and was comparatively less intuitive. Changing the whistle sound to a more intuitive alert/warning sound may make the auditory feedback more effective.

LIMITATION AND FUTURE WORK

One of the biggest limitations of our study included use of a small convenience sample of university students that experimenters recruited primarily via peer networks (i.e. small sample size and biased sample population with limited diversity). Another limitation of our study was the absence of physically and sensory-impaired participants, particularly visually impaired participants. Participants were blindfolded to simulate visual distraction as well as visual impairment, but those findings cannot necessarily translate to people with visual impairments (Spiers et al., 2018; Akpinar et al., 2020). Blindfolding also removed the visual component of cognitive load that would occur during tasks involving visual distraction. Future studies should randomly sample a broader population and the sample should include visually impaired participants, such that results are generalizable to a broader population.

Additional limitations included a limited number of trials per condition and lack of counterbalanced condition order. Lack of counterbalancing streamlined data reduction but potentially inflated the relative effectiveness of multimodal feedback over unimodal feedback. The limited number of trials per condition was insufficient for a thorough, comprehensive analysis. Additionally, the vibrotactile feedback devices were placed inside the shoe and were applied only to a single foot upon deviation outside of the boundaries. In the future, more trials, varying vibrotactile feedback application sites, and measuring the distance successfully traveled within the crosswalk would provide greater-resolution insights.

Real-life applications in infrastructure-embedded implementations of this feedback design may target both feet from outside the bottom of the shoes. Future work would involve the vibration of the floor itself, ideally with an increasing vibrotactile gradient (intensity and application rate) with increasing distance from the crosswalk boundaries. A tactile paving condition may also reveal the utility of a potentially lower-cost application. Another limitation is our use of a single fixed length and width simulated crosswalk, while real-world crosswalks have a different texture and varying lengths and widths. Future studies may include different simulated crosswalk lengths and boundaries to ascertain length and width cutoffs for which such a display actually helps.

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