Analysis of Walking Speeds Involving Individuals with Disabilities in Different Indoor Walking Environments

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Abstract: Walking facilities are important infrastructures in communities. These facilities should be designed to accommodate the needs of all types of pedestrians. Unfortunately, existing design guidelines fail to offer adequate consideration for individuals with disabilities owing to a lack of empirical data. To address this knowledge gap, a controlled large-scale research project was conducted at Utah State University (USU) to study the walking behavior of people with various types of disabilities in various indoor walking facilities. These facilities included a passageway, different types of angles (right and oblique), bottleneck, and stairwells. The purpose of this paper is twofold: to examine the impacts of individuals with disabilities on crowd walking speed, and to study the impacts of different indoor walking facilities on the movements of various pedestrian groups. Results show that the presence of individuals with disabilities in a crowd significantly reduces the overall crowd speed. Statistical analysis also reveals similarities and differences between the walking speeds of various pedestrian groups. A regression model is calibrated to predict the speed of various types of individuals with disabilities in different indoor walking facilities. The findings of this paper may help urban planners and walking facility designers consider the needs of people with disabilities. **DOI: 10.1061/(ASCE)UP.1943-5444.0000288.**

Author keywords: Pedestrian walking behavior; Walking speed; Individuals with disabilities; Walking environment; Built environment.

Introduction

Walking facilities like walkways and stairs are important infrastructures in buildings and urban areas (e.g., transit transfer stations, shopping malls, and urban plazas). Individuals frequently use these facilities for traveling short distances, and some also use them for recreation. To provide safe and comfortable walking environments for all types of pedestrians, evidence-based research is a necessary building block. In the literature, researchers have used pedestrian traffic-flow relationships and characteristics (Chen et al. 2010) to assess different types of walking facilities. Although individuals with disabilities represent a significant portion of the population (i.e., 16.6% of the working age population and 18.7% of the total population of the United States (U.S. Census Bureau 2010), most existing designs and assessments overlook heterogeneity in crowd composition. Little is understood concerning the effect of the built environment on individuals with disabilities or their interactions with people without disabilities in a congested environment. Failing to address people with disabilities is possibly related to the significant lack of empirical studies on the pedestrian behavior of individuals with disabilities (Christensen et al. 2013).

The Highway Capacity Manual (HCM) (TRB 2010) is generally consulted for the design of walking facilities in the United States. The HCM documents some regulations for designing public pedestrian facilities but lacks specifications for individuals with disabilities. To account for the needs of individuals with disabilities, the Americans with Disabilities Act Accessibility Guidelines (ADAAG 2002) provides guidelines for the design of pedestrian facilities. However, this code is based primarily on physical properties and does not consider the interactions between people with and without disabilities. To consider interactions among heterogeneous populations and between people and environments, a set of large-scale controlled experiments was carried out by a multidisciplinary research team at Utah State University (USU). The team included individuals from the following disciplines: disability studies, landscape architecture and environmental planning, transportation engineering, electrical engineering, and information management. The goal of the experiments was to study the walking behavior of different types of pedestrians in various indoor walking facilities: passageways, angles (right and oblique), bottlenecks, and stairwells.

This paper presents the statistical analysis of the impacts of individuals with disabilities on crowd walking speed and the impacts of different indoor walking facilities on the movement of various types of pedestrians. The first objective was to determine whether there is a significant difference, in terms of mean walking speed, between a homogeneous crowd (a crowd excluding individuals with disabilities) and a heterogeneous crowd (a crowd including individuals with disabilities). The second objective was to collect and analyze the walking speed of different types of pedestrians. The results will allow planners to improve built environment design policies to better accommodate the needs of diverse individuals with disabilities.

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Note. This manuscript was submitted on March 2, 2014; approved on April 6, 2015; published online on June 17, 2015. Discussion period open until November 17, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Urban Planning and Development***, © ASCE, ISSN 0733-9488/04015010(10)/$25.00.

Background

Many researchers have extensively studied pedestrian walking behavior. In early efforts, pedestrian studies were conducted in many cities through manual data collections (Polus et al. 1983; Tanaboriboon et al. 1986; Koushki 1988). In recent years, more advanced technology is used in pedestrian studies. Laxman et al. (2010) conducted research to examine relationships between pedestrian speed, volume, and density in India by using video graphic techniques. Al-Azzawi and Raeside (2007) collected pedestrian movement data through video recordings to estimate pedestrian speed and flow on sidewalks. Rastogi et al. (2011) presented pedestrian crossing speeds at midblock sections for three cities in India, determining the walking speed of different types of pedestrians categorized by gender and age groups. In some cases, it is difficult to observe pedestrian behavior in desired conditions (i.e., behaviors in congested situations). Hence, many controllable walking experiments have also been conducted to draw inference for urban facilities such as sidewalks with different geometric configurations. For example, Daamen and Hoogendoorn (2003) conducted walking experiments to collect pedestrian behaviors in passageway and bottleneck walking environments. A series of controlled walking experiments were conducted in Germany to derive walking behaviors in a circular passageway (Seyfried et al. 2005), bottleneck (Seyfried et al. 2009), T-junction (Zhang et al. 2011), and stair (Burghardt et al. 2013).

Most mentioned studies overlooked the heterogeneity of physical ability in pedestrian compositions. Only a limited number of studies considered people with low mobility, including individuals with disabilities. Christensen et al. (2014) conducted a review literature with emphasis on the behavioral measurements of individuals with disabilities in navigating the built environment. The review found only a few studies in this research area. For example, Boyce et al. (1999a, c) determined movement capabilities of 155 individuals in different walking facilities (level surfaces, ramps, and stairs) in an emergency situation. Results were reported in four categories of disabilities: unassisted ambulant, unassisted wheelchair users, assisted ambulant, and assisted wheelchair users. They also conducted another study to measure the ability of people with disabilities to negotiate the environment in emergency conditions (Boyce et al. 1999b). Clark-Carter et al. (1986) measured the walking speed of people with visual impairments in environments of varying complexity. Results showed that the walking speed of individuals with visual impairments is negatively affected by the increasing complexity of the travel environment. Yet, individuals with visual impairments who use guide dogs are not as affected by complex built environments as those who use long canes. Furthermore, Miyazaki et al. (2003) evaluated the behavior of 30 pedestrians and a wheelchair user, finding that the behavior of the pedestrians influenced the behavior of the wheelchair user and vice versa. Moreover, pedestrian speed changed depending on the psychological condition (e.g., competitive or noncompetitive). The researchers developed a model demonstrating psychological phenomena (e.g., group psychology) and pedestrian behavior (e.g., speed) in relationship to the distance from an individual using a wheelchair. Rubadiri et al. (1997) conducted an experiment to estimate speed of individuals with mobility impairments in an obstacle-free route and two evacuation routes. They provided a quantitative attribute called the Evacuation Performance Index (EPI) for measuring and predicting the evacuation performance of individuals with mobility impairment. Their proposed index measures the relative ease of evacuating people with impaired movements using different factors such as evacuation speed and escape route layout. Wright et al. (1999) examined speed of individuals with visual impairments through an evacuation route, finding that visually impaired individuals walk at 43–69% of typical walking speed on level routes and 70–80% on stairs. Passini et al. (1998) evaluated the ability of individuals with cognitive impairments to navigate various built environments and concluded that complexity of the built environment could decrease the ability of participants to navigate the environment. Arango and Montufar (2008) investigated the walking speed of older pedestrians who use walkers or canes in Winnipeg, Canada, concluding that crossing walking speed is significantly higher than normal walking speed for older pedestrians with or without walkers/canes. Recently, Kuligowski et al. (2013) studied the stair evacuation speed of older adults and people with mobility impairments of 45 residents with various mobility impairments evacuating a six-story building. Table 1 summarizes the studies of the behavior of vulnerable populations in various built environments.

Table 1. Behavioral Studies of Vulnerable Populations in the Built Environment

Reference	Locale	Limiting condition	Par num	Dep var	Reported results
Boyce et al. (1999a, c)	United Kingdom	Mobility/elderly	155	Speed	Various travel speeds on level passageways, ramps, corners, and stairs
Boyce et al. (1999b)	United Kingdom	Various	113	Time to negotiate	Ability of participants to negotiate doors in emergency situations
Clark-Carter et al. (1986)	United Kingdom	Visual	4	Speed	Walking speed of participants is negatively affected by the complexity of the built environment
Miyazaki et al. (2003)	Japan	Mobility	30	Speed	Behavior of the pedestrians influences the behavior of the wheelchair user and viceversa
Rubadiri et al. (1997)	United Kingdom	Mobility	6	Speed	Providing a quantitative index to measure evacuation performance
Wright et al. (1999)	United Kingdom	Visual	30	Speed	Participants walk at 43–69% of typical walking speed on level routes and 70–87% on stairs
Passini et al. (1998)	Canada	Cognitive	28	Ability to negotiate	Complexity of the built environment decreases the ability of participants to navigate the environment
Arango and Montufar (2008)	Canada	Mobility	63	Speed	Normal walking speed is lower than the crossing walking speed
Kuligowski et al. (2013)	United States	Mobility	45	Speed	Comparing stair evacuation of older adults and people with mobility impairments

Note: Dep var = dependent variable; Par num = number of participants.

Three conclusions can be drawn from the preceding literature review. First, it is unfortunate that individuals with disabilities have received less scholarly attention. Second, the majority of the existing studies used egress speed to describe the behavior of an individual with a disability in response to the built environment. This indicates a lack of understanding of the walking behavior of individuals with disabilities. Thus, the question remains as to whether the build environment imposes constraints on individuals with disabilities. Third, almost none of the past studies examined the walking speed of individuals with disabilities in crowd conditions. Therefore, the question remains as to what extent the walking speed of individuals with disabilities is affected by interactions of people with disabilities in crowd conditions.

Methodology

The objectives of this research were to study the impacts of individuals with different types of disabilities on crowd speed, and the impacts of different walking facilities on the movement of various pedestrian groups. These objectives can be expressed by hypotheses. The first objective was to examine the effect of pedestrian characteristics on crowd moving speed in different walking facilities. The null hypothesis can be expressed as follows:

Hypothesis 1: There is no significant difference in the mean walking speed (μ) between homogeneous (populations excluding individuals with disabilities) and heterogeneous populations (populations including individuals with disabilities) in various walking facilities. For this hypothesis, five different walking facilities were considered: a level passageway, oblique angle, right angle, bottleneck, and stairs.

$$H_n^1{:}\mu_{\text{homogenous population}} = \mu_{\text{heterogeneous population}}$$

$$H_a^1{:}\mu_{\text{homogenous population}} < \mu_{\text{heterogeneous population}}$$

The second objective was to study the walking speed of different types of pedestrians in different walking facilities. Specifically, the impact of different walking facilities on the mean speed of people with and without disabilities was examined as follows:

Hypothesis 2: Mean walking speed of people with different types of disabilities is not affected by walking facility configuration.

$$H_n^2{:}\mu_{\text{facility typeA}} = \mu_{\text{facility typeB}} \text{ for different types of pedestrians}$$

$$H_a^2{:}\mu_{\text{facility typeA}} \neq \mu_{\text{facility typeB}} \text{ for different types of pedestrians}$$

Four classifications of individuals were used in this research: individuals without disabilities, individuals with visual impairments, individuals who use nonmotorized ambulatory devices (e.g., wheelchair/cane/roller), and individuals using motorized wheelchairs. Although there are many different types and degrees of disability, these three types were identified as those most likely to be impacted by conditions in the built environment.

The third objective was to quantify the impact of different walking facilities on walking speed. For this objective, it was desirable to investigate to what extent mean walking speed is affected by various environmental configurations for different disability types. This research question is investigable if the second null hypothesis is rejected.

Experimental Area

The research goal was to examine the behavior of different types of pedestrians, including people with disabilities, in a variety of walking facilities at varying congestion levels. To accomplish this research goal, a controlled environment was adopted to conduct different walking experiments. To this end, large-scale walking experiments were conducted at Utah State University's (USU) motion analysis lab. The 3,000 square foot laboratory, similar to a gymnasium, is conducive to the instrumentation necessary for data collection. A temporary circuit with the necessary walking facilities (level passageway, right angle, oblique angle, and bottleneck) was constructed using 2.43 m (8-ft) self-standing walls. The circuit was designed to include various walking facilities based on the Americans with Disabilities Act Accessibility guidelines (ADAAG 2002) and the International Building Codes (ICC 2012). In addition, a standard stairwell near the motion lab was used for the stair experiments. The stairwell had 18 steps with each step measured at 0.9 m wide with a 0.18-m rise and 0.25-m deep tread. Fig. 1 shows the layout of the circuit and staircase.

Participants

To recruit a representative sample of individuals, an electronic advertisement was distributed among respective populations to select the participants without disabilities. The recruiting advertisement offered a \$50 stipend for each day of experiments. The recruitment process considered only working age individuals without disabilities who are between 18 and 64 years of age (U.S. Census Bureau 2010). Except age constraint, the recruitment process did not require any conditions for applicants to participate in walking experiments, and all participants were randomly selected among the received applications for both sexes. The number of invited participants was determined to observe a congested condition during the experiments. Participants with disabilities were recruited through the Center for Persons with Disabilities (CPD) at USU. They possessed a mobility-related physical, sensory, or Go-Outside-Home disability. The criteria for a mobility-related disability were based on the U.S. Census Bureau's American Community Survey (ACS) definition (U.S. Census Bureau 2010). Individuals over 80 years of age were not included in the study owing to health protection concerns.

The walking experiments were conducted over 4 days (November 2, 9, 15, and 22 of 2012). In total, 302 individuals between 18 and 80 years old participated in the experiments. Specifically, 202 individuals (180 without disabilities and 42 with disabilities) participated in the circuit experiments and 100 participants (80 without disabilities and 20 with disabilities) participated in the stair experiments. Individuals using wheelchairs were excluded in the stair experiments. For the circuit experiments, approximately 5% of the participants had a visual impairment, 9% had a physical impairment, and 6% had other impairments. Similarly, for the stair experiments, 10% of the participants had a visual impairment, 6% had a physical impairment, and 6% had other impairments. According to the 2010 disability status report (Erickson et al. 2012), the prevalence of visual and ambulatory disability among persons of all ages in the United States was 2.1 and 6.8% respectively. Therefore, the number of disabled participants was considered representative of their respective populations.

Experimental Design

Two types of experiments were conducted for the circuit experiments: unidirectional and bidirectional. In the unidirectional experiments, all participants walked in the same direction. Bidirectional experiments were conducted with different scenarios of flow compositions (90% major stream 10% minor stream; 80% major 20% minor; 70% major 30% minor; 60% major 40% minor; and 50% major 50% minor). For each experiment, participants

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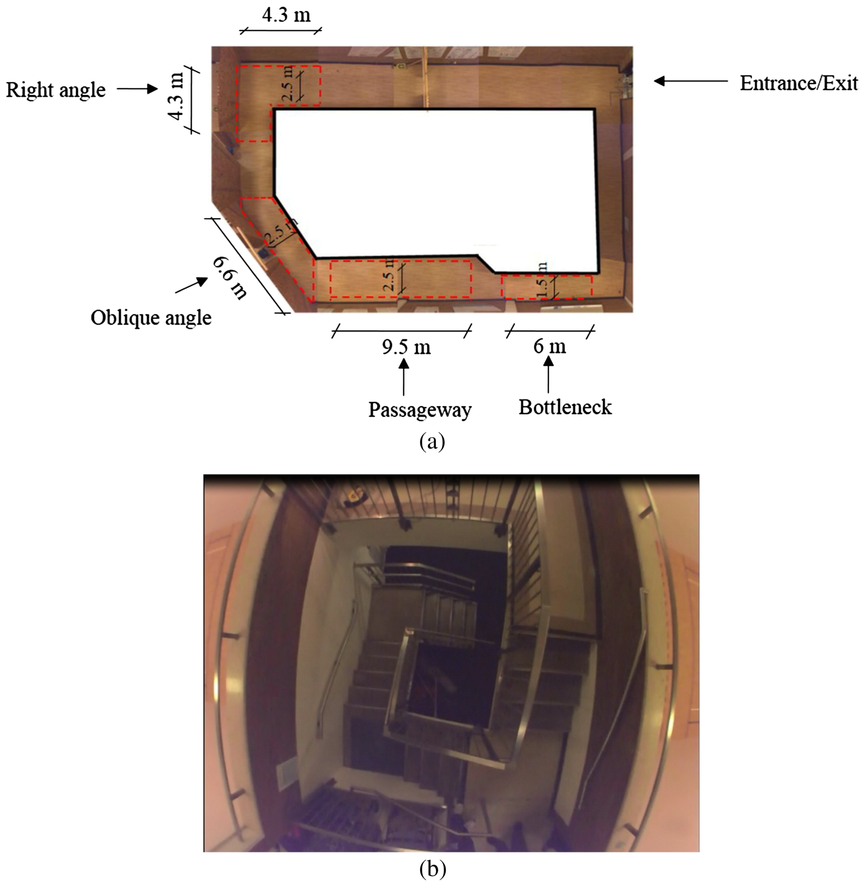

Fig. 1. Experimental areas: (a) circuit; (b) staircase

moved at their maximum (or comfortable) speed, without endangering their safety. Each scenario was split into 10-min recording sessions with approximately 2 h of data collection. To control and manage the experimental process, one researcher acted as a ramp meter to distribute participants and generate a wide range of crowd density levels. In this way, data at various congestion levels was collected.

Data Collection

Automated video identification and tracking technology was used for data collection to track participant positions within an average of 0.3 meter or one footstep, which enables tracking and collection of each individual participant's walking trajectory. Derived from augmented reality, ARToolKitPlus (ARTKP) is a software library that allows the tracking of up to 512 identifiable markers in a camera field at once (Wagner and Schmalstieg 2007). A system was designed using this technology to track and uniquely identify the participants. To utilize this system, markers were attached to participants using graduation caps, and read by cameras suspended above the experimental area. Power-over-Ethernet (POE) cameras, which only need one cable for power and communication, were used. The chosen POE camera is compact at $29 \times 29 \times 41$ mm, but still affords a high resolution of 1280×1024 pixels at a maximum frame rate of 50 frames per second. Twelve cameras provided a full coverage with overlap for the circuit experiments and one camera was sufficient per stairwell. For detailed information about the tracking system and technical setup, readers are referred to Stuart et al. (2013).

Analysis and Results

The collected trajectory data was organized according to the different days, scenarios, and facilities and diagramed for validation and quality checking as shown in Fig. 2. Fig. 2 shows a sample of visualized trajectory data for 10 participants in the circuit experiment, and the 3D trajectories of four participants in the stairwell experiment. Data visualization shows formation consistent with the built environment and validates the quality of the trajectory data. Time-space trajectories of pedestrian crowd dynamics are depicted in Fig. 3. These time-space diagrams were created by plotting the position of each participant, given at a distance from a reference point (e.g., entrance of the circuit) against time. The vertical distance between two consecutive lines indicates the spacing between the pedestrians, whereas the horizontal distance between two consecutive lines indicates the time headway between pedestrians. The time-space trajectories are especially useful in identifying patterns of walking behavior. For example, it can be observed that individuals without disabilities maintain a more conservative spacing from individuals with disabilities, and the time headway between individuals without disabilities is lower compared with the time headway between individuals without and with disabilities. In addition, the slope of the trajectories represents the speed of participants with the curved portions indicating speed changes. To show these changes more clearly, a segment of the time-space diagram is enlarged and labeled with the location within the circuit. The expanded diagram indicates that the speed of participants reduces in the bottleneck area more than other segments, especially under crowd conditions where the concentration of lines is high.

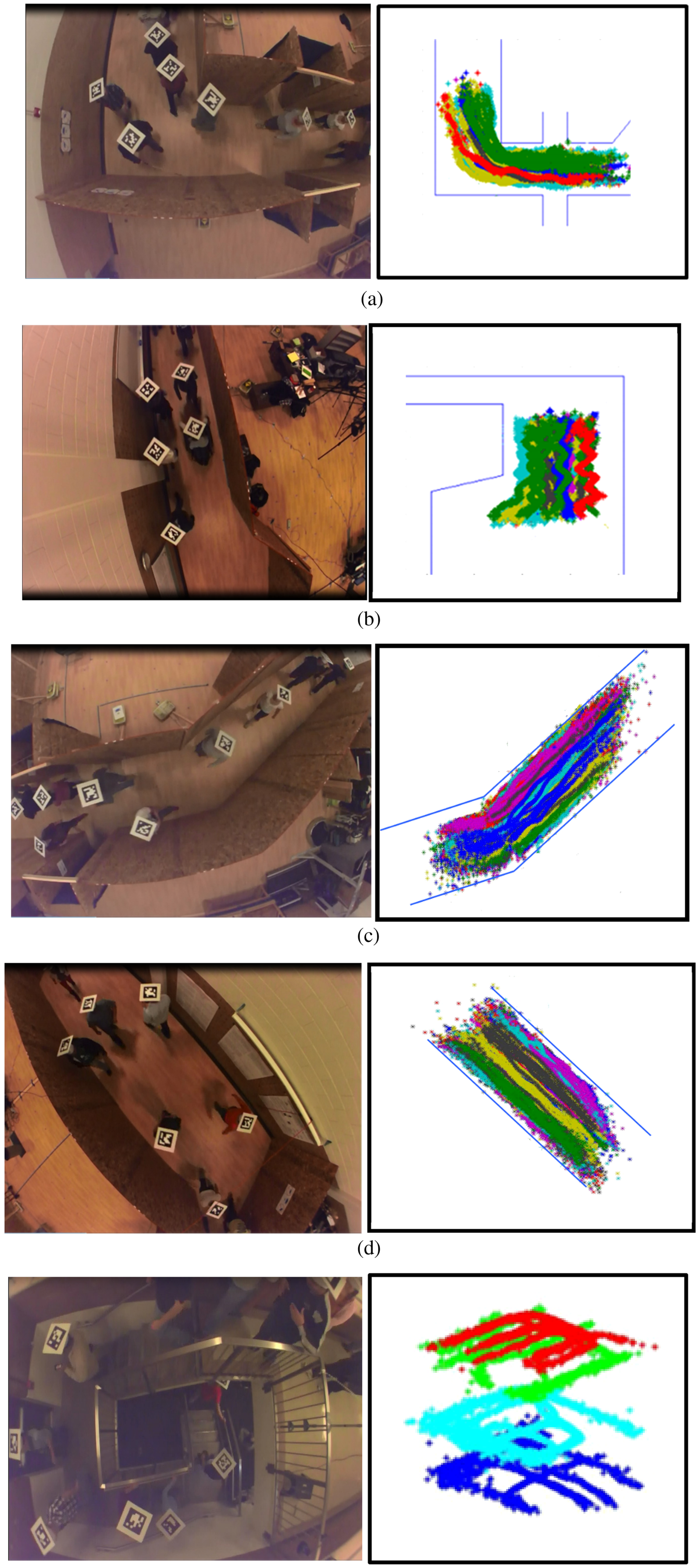

Fig. 2. Trajectories at different facilities: (a) right angle; (b) bottleneck; (c) oblique angle; (d) passageway; (e) stairwell

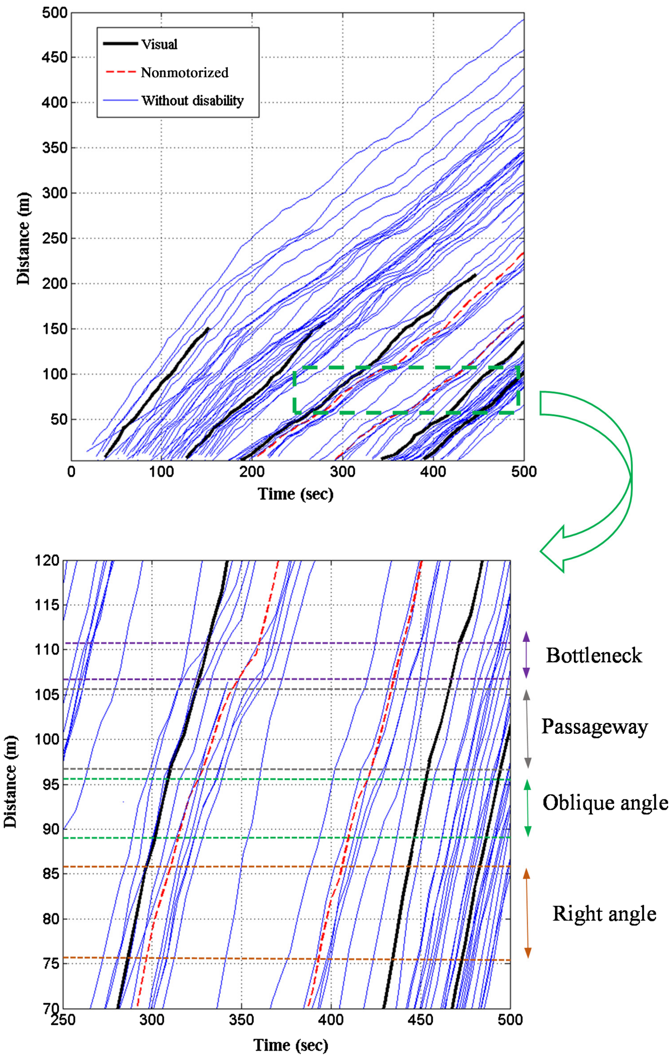

Fig. 3. Time-space diagram

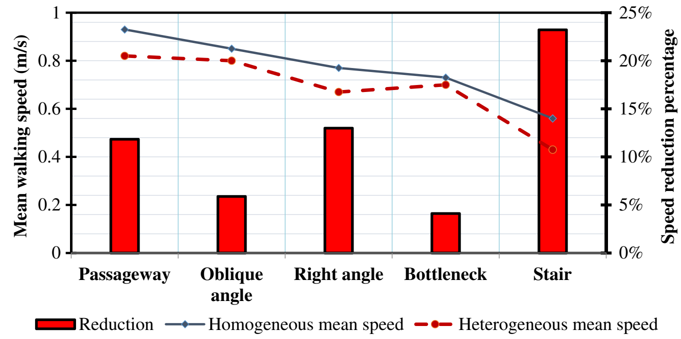

Fig. 4. Mean walking speeds of homogeneous and heterogeneous populations in different walking environments

Table 2. Statistical Analysis of Mean Walking Speeds of Homogenous and Heterogeneous Populations in Different Walking Environments

Facility	Population	Mean speed (m/s)	SD	N	*P*-value	H_n^1
Passageway	HM	0.93	0.22	577	<0.01	Reject
	HT	0.82	0.22	3,057		
Oblique angle	HM	0.85	0.21	578	<0.01	Reject
	HT	0.8	0.22	3,078		
Right angle	HM	0.77	0.19	573	<0.01	Reject
	HT	0.67	0.21	3,203		
Bottleneck	HM	0.73	0.19	398	<0.01	Reject
	HT	0.7	0.21	2,785		
Stair	HM	0.56	0.27	1,517	<0.01	Reject
	HT	0.43	0.26	1,258		

Note: HM = homogeneous; HT = heterogeneous; N = number of observations; SD = standard deviation.

Hypothesis 1

The purpose of the first hypothesis was to examine the effect of involving individuals with disabilities on crowd walking speed. The first day of experiments involved only individuals without disabilities and subsequent days used the same procedure and equivalent number of participants, but included both individuals with and without disabilities. Thus, it was possible to compare the effect of individuals with disabilities in crowd speed. To test the hypothesis, it was necessary to determine the speed of participants and density caused by the volume of pedestrians using the trajectory data. A straightforward procedure was used to extract the population speed and density as follows:

1. A time interval was selected to extract the speed data. Walking distance is determined during the time interval used to compute the walking speed. Based on the preliminary analysis, a 30-s interval was considered appropriate for data extraction of the circuit experiments. It is neither too short that can lead to instability nor too long that can negatively reduce the number of data points as well as smooth out the differences. For the stair experiments, a 1-s time interval was considered appropriate.
2. Position of each participant was recorded every second using the trajectory data. For the stair experiments, only horizontal movement was used to calculate the walking speed.
3. Walking distance of each participant during the time interval was determined using the recorded positions.
4. Walking speed of each participant during the time interval was computed by dividing the walking distance by the time interval.
5. Population mean speed was obtained by averaging the speeds of all participants.
6. To obtain the corresponding density for the time interval of interest, the number of participants was recorded in each second, and the arithmetic mean of the number of participants was divided by the observation area.

Crowd mean speeds were computed for both homogeneous and heterogeneous population scenarios. Fig. 4 compares and illustrates the impact of individuals with disabilities on crowd speed reduction in various walking facilities.

In Fig. 4, the two lines compare the walking speeds of homogeneous and heterogeneous populations in different walking facilities, whereas the bar graphs show the speed reduction percentage for each facility. These reductions were most evident for the stair facility. Results showed that the mean speed of the heterogeneous population was approximately 23% lower than the mean speed of the homogenous population in the stair facility. Table 2 presents the quantitative comparison of mean walking speed for the two population scenarios. In Table 2, the number of observations (N) represents the number of extracted speed data obtained from Step 4 of the data extraction procedure. Analysis indicated that populations reached their maximum and minimum speeds in the passageway and stair facilities, respectively. Mean walking speeds of the homogeneous and heterogeneous populations in the passageway were 0.93 (3.05) and 0.82 m/s (2.69 ft/s), respectively, whereas their

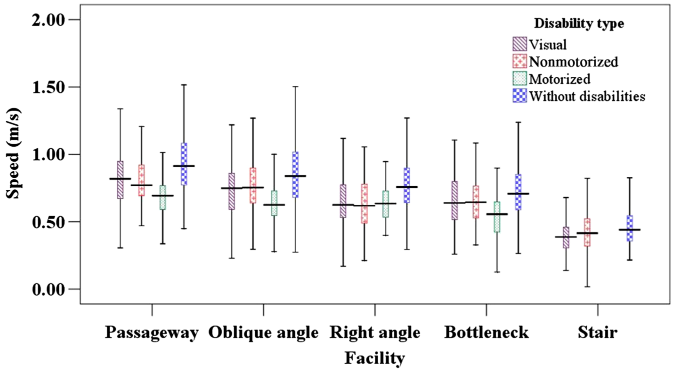

Fig. 5. Walking speed statistics for different pedestrian groups and walking environments

respective mean walking speeds were 0.56 (1.84) and 0.43 m/s (1.41 ft/s) in the stair.

The mean speed of each scenario was statistically compared using ANOVA as presented in Table 2. For all facilities, the P-value was lower than 0.01, indicating a significant difference between the mean walking speed of a homogenous and a heterogeneous population. Therefore, the first null hypothesis was not supported because the walking speed of individuals with disabilities was much lower than that of the general pedestrian population, resulting in clogging and congestion within different walking facilities. As expected, this phenomenon was more critical for complex geometries like stairs. The findings suggested that individuals with disabilities, albeit the minority in the pedestrian stream, had a major impact on crowd speed.

Hypothesis 2

To test the second hypothesis, walking speed data of participant groups was extracted separately for different walking environments as presented in Fig. 5, from which the minimum, maximum, median, quartiles of speed data, and speed ranges can be inferred. The purpose of this hypothesis was to examine the effect of different walking facilities on the mean walking speed of different individual types. In general, walking speed is dependent on the density level (i.e., number of pedestrians divided by the observation area) in addition to the physical ability and types of walking environment.

To compare walking speed of individuals, speed and density were computed for each time interval. Then, speed data were categorized based on the density levels obtained from the HCM level of service (LOS) definitions (TRB 2010). This guideline classifies the LOS performance of walkways and stairs using different measures such as density level. HCM uses letters A through F to denote the level of service: LOS A stands for the best and LOS F represents the worst quality of service. To assess the impact of walking configurations, walking speeds in the middle density ranges (i.e., LOS C and LOS D) with the majority of the data were used for comparing individual walking speeds. Therefore, only the mean speed values for LOS C and LOS D corresponding to the density values from 0.27 to 0.71 p/m^2 and from 0.63 to 1.35 p/m^2 were computed for the circuit and stair experiments, respectively. Speed analysis for different groups is summarized in Table 3 and indicates that all groups had the highest walking speed in the passageway facility, and people with motorized wheelchairs had the lowest mean speed in all facilities except in the right angle and stair facilities, where they were not observed. All types of individuals with disabilities had their minimum speed in the bottleneck and right angle facilities, suggesting that turning movements and space unavailability could make it difficult for these individuals to maneuver. For the stair experiment, the obtained values were comparable to the findings in Boyce et al. (1999a). The study indicates that the walking speed for individuals with disabilities is considerably lower than individuals without disabilities.

Table 3 also shows the level of significance for a pairwise ANOVA comparison of mean walking speed. For example, the statistical test for mean walking speed in the passageway facility compared with all other facilities indicates that the speed reduction was statistically significant (P-value < 0.05) across all pedestrian groups except for people with motorized wheelchair. It indicates that the physical configurations of the walking environment had a significant impact on walking speed for all pedestrian groups.

Table 3. Hypothesis Test of Walking Speeds for Different Pedestrian Groups

Type	Facility	Mean speed (m/s)	SD	N	P-value				
					Passageway	Oblique	Right	Bottleneck	Stair
Visual	Passageway	0.83	0.20	110	—	<0.01	<0.01	<0.01	<0.01
	Oblique	0.76	0.20	81	<0.01	—	<0.01	0.03	<0.01
	Right angle	0.67	0.20	67	<0.01	<0.01	—	0.3	<0.01
	Bottleneck	0.69	0.21	46	<0.01	0.03	0.3	—	<0.01
	Stair	0.39	0.16	296	<0.01	<0.01	<0.01	<0.01	—
Nonmotorized	Passageway	0.83	0.19	51	—	0.04	<0.01	<0.01	<0.01
	Oblique	0.76	0.22	49	0.04	—	<0.01	0.11	<0.01
	Right angle	0.64	0.18	38	<0.01	<0.01	—	0.1	<0.01
	Bottleneck	0.70	0.21	31	<0.01	0.11	0.1	—	<0.01
	Stair	0.43	0.20	6,320	<0.01	<0.01	<0.01	<0.01	—
Motorized wheelchair	Passageway	0.69	0.21	32	—	0.34	0.18	0.02	—
	Oblique	0.67	0.18	34	0.34	—	0.3	0.03	—
	Right angle	0.65	0.14	30	0.18	0.3	—	0.053	—
	Bottleneck	0.56	0.31	39	0.02	0.03	0.053	—	—
Individuals without disabilities	Passageway	0.94	0.21	467	—	<0.01	<0.01	<0.01	<0.01
	Oblique	0.86	0.21	478	<0.01	—	<0.01	<0.01	<0.01
	Right angle	0.77	0.19	541	<0.01	<0.01	—	<0.01	<0.01
	Bottleneck	0.73	0.19	391	<0.01	<0.01	<0.01	—	<0.01
	Stair	0.48	0.19	4,978	<0.01	<0.01	<0.01	<0.01	—

Note: N = number of observations; SD = standard deviation.

Table 4. Hypothesis Testing for Comparing Walking Speeds of Different Pedestrian Groups

Comparison groups		H_n^1 (5% significance level)				
		Passageway	Oblique	Right angle	Bottleneck	Stair
Visual	Nonmotorized	No reject	No reject	No reject	No reject	Reject
	Motorized wheelchair	Reject	Reject	No reject	Reject	—
	Without disabilities	Reject	Reject	Reject	No reject	Reject
Nonmotorized	Visual	No reject	No reject	No reject	No reject	Reject
	Motorized wheelchair	Reject	Reject	No reject	Reject	—
	Without disabilities	Reject	Reject	Reject	No reject	Reject
Motorized wheelchair	Visual	Reject	Reject	No reject	Reject	—
	Nonmotorized	Reject	Reject	No reject	Reject	—
	Without disabilities	Reject	Reject	Reject	Reject	—
Without disabilities	Visual	Reject	Reject	Reject	No reject	Reject
	Nonmotorized	Reject	Reject	Reject	No reject	Reject
	Motorized wheelchair	Reject	Reject	Reject	Reject	—

These findings are consistent with the study by Clark-Carter et al. (1986), who found that the walking speed of participants was significantly reduced by the complexity of the built environment.

Table 3 could also be used to compare different conditions. For instance, switching from an oblique angle to a right angle leads to a considerable speed reduction from 0.76 (2.49) to 0.67 m/s (2.20 ft/s) for individuals with a visual impairment (a 12% reduction) and from 0.76 (2.49) to 0.64 m/s (2.10 ft/s) for nonmotorized ambulatory device users (a 16% reduction). This change is marginal for individuals using motorized wheelchairs. This finding may be attributable to the lower speed of motorized wheelchair users, which enables them to control and maintain their speeds in more complex walking environments. An interesting similarity between all groups of people with disabilities was the insignificance of the difference between their mean walking speeds in the right angle facility versus their speed at the bottleneck. Although both turning movement and space unavailability significantly reduced the speed of individuals with disabilities, the magnitude of their impacts is not statistically different. However, this result is true only for individuals with disabilities. Individuals without disabilities walked slower in a narrow area (bottleneck) than in a facility requiring a turning maneuver (right angle). This is likely the result of individuals with disabilities' increased need for advanced movement planning in a complex environment.

Table 4 presents the results of statistical tests for comparing walking speeds of different pedestrian groups. Similar to the previous hypothesis, ANOVA was used to identify differences in walking speed among different groups. The results indicate that the mean walking speed of people without disabilities was higher than all types of people with disabilities in all facilities except the bottleneck facility. There was no statistical difference between the walking speed of people with a visual impairment and people who used nonmotorized ambulatory devices for walking in normal walking environments. People who used motorized wheelchairs, however, were slower than both people with visual impairments and people with nonmotorized ambulatory devices, with the exception at the right angle facility. This finding might be attributed to the speed constraints of the motorized wheelchair itself. Video records showed that these people were more conservative in keeping a safe distance from other participants, especially in situations with limited space, which might have also affected their speed. The comparisons also show that speeds of people with nonmotorized devices are higher than visually impaired people in stair experiments. This fact implies that visual constraints are more restrictive on walking speed than mobility impairments.

Table 5. Regression Results of Walking Environment, Disability Type, and Age on Walking Speed

Variable type	Variable name	β	t-stat	P-value	R^2
Constant	—	0.736	35.92	<0.01	0.73
Walking environment	Oblique angle	−0.076	−2.10	0.05	
	Right angle	−0.153	−4.22	<0.01	
	Bottleneck	−0.153	−4.31	<0.01	
Individual type	Nonmotorized	0.086	2.64	0.02	
	Visual impairment	0.086	2.64	0.02	
Age	Higher than 50 years old	−0.098	−3.02	0.01	

Quantification of Walking Environment, Disability Type, and Age on Walking Speed

To quantify and assess the magnitude of different factors on walking movement of individuals with disabilities, a regression model was calibrated based on aggregated speed data. Speed was treated as the dependent variable, whereas other factors were treated as binary independent variables. Different factors, including walking environment, disability type, and age, were considered in the model. Because of the large differences in the walking behaviors, only normal walking facilities were considered in the model. The calibration results, including the estimated coefficients (β), standard error (SE), t-statistics, level of significance, and coefficient of determination (R^2), are summarized in Table 5. The model reveals to what extent mean walking speed of groups of individuals with disabilities is affected by different parameters. In the model, people with motorized wheelchairs in a passageway facility was treated as the reference group. The regression model could be used as a proxy for comparing with previous results because the constant term of the model represents the mean speed of the reference group. The constant value in Table 5 was 0.73 m/s (2.39 ft/s), indicating that the mean speed of individuals with wheelchairs in the passageway was comparable to the statistical findings in Table 3.

From the regression analysis, approximately 70% of variation in the data was explained by the model, and all coefficients were statistically and significantly different from zero (P-value < 0.05). Coefficients related to walking facilities were negative, indicating that all facilities had a negative impact on the mean speed of all types of individuals compared to the mean speed in the passageway (i.e., the reference facility). Using the coefficient of a particular dependent variable, one could also compare the impact magnitude of dependent variable with respect to the reference group. For instance, the model revealed that the mean speeds of visually impaired individuals and individuals with nonmotorized walking devices were approximately 0.086 m/s (0.282 ft/s) higher than the people with motorized wheelchairs in the passageway facility. Further, the bottleneck and right angle facilities had the highest negative impact on the mean speeds for all disability types. These facilities had almost the same negative impact on the movements of all disabled groups (i.e., the magnitude of coefficients were similar). Results also showed that age can be an important factor affecting walking speed of individuals with disabilities. The walking speed of individuals older than 50 was approximately 0.1 m/s (0.32 ft/s) slower than younger individuals. Age variable had a more negative impact on mean walking speed than oblique angle. However, it had a less negative impact than right angle and bottleneck facilities.

Summary and Future Research

Pedestrian walking behaviors have been extensively explored for planning and designing more effective transport infrastructures (Ma and Yarlagadda 2014). However, the majority of past studies only considered homogeneous pedestrian stream and overlooked the heterogeneity in pedestrian population. There is limited research on walking speeds of individuals with different type of disabilities, and almost none examined the speed in crowd conditions. The purpose of this research was to explore the effect individuals with disabilities have on crowd walking speed in different walking environments and compare and analyze walking speeds of different individual types in various walking facilities. To this end, the walking speed of different types of pedestrians was studied through controlled experiments. More than 300 people, including individuals without disabilities and individuals with mobility and visual impairments took part in the experiments conducted in a constructed circuit with different walking facilities (passageway, oblique angle, right angle, and bottleneck) and on a stairway. Participants were tracked using an advanced tracking system, and their individual speeds were calculated using the resulting trajectory data. Statistical analysis of this data suggested the following key findings:

- The inclusion of individuals with disabilities had a considerable reduction of the mean speed of a heterogeneous population in all types of walking facilities. This effect was more pronounced for the stair facility.
- All pedestrian groups reached their maximum speed in the passageway. Considering this speed as their typical walking speed, all other facilities had a slowing effect. Facilities with more complex configurations (e.g., stair, bottleneck, and right angle) had the greatest slowing effect.
- Individuals without disabilities had a considerably higher speed than individuals with disabilities in all studied facilities except right angle. People who use motorized wheelchairs had the lowest mean speed among all groups in all facilities. This finding might be attributed to the speed constraints of the motorized wheelchair itself.
- No statistical difference in the mean speed of people with visual impairments and people with nonmotorized ambulatory devices was found in plain walking facilities.
- People with nonmotorized ambulatory devices had a considerably higher speed than individuals with visual impairment in the stair facility. This finding indicates that visual constraints are more restrictive than mobility impairments in this facility.
- Although both the right angle and bottleneck had a significant negative impact on the speed of individuals with disabilities, the magnitude of their impacts was not statistically different.
- Unlike individuals with disabilities, the walking speed of individuals without disabilities was considerably higher in the right angle compared to the bottleneck.
- Mean walking speed of visually impaired people, individuals with nonmotorized ambulatory devices, and people who use motorized wheelchairs were 12, 12, and 26% lower than the people without disabilities in a passageway.

This study suggested many possibilities for future research. One possible extension would be to study other properties of crowd dynamics such as the capacity of facilities with the inclusion of individuals with disabilities. The majority of existing studies explored properties of a homogeneous pedestrian stream in different walking environments (Lam et al. 2002, 2003; Wong et al. 2010; Xie et al. 2013). These studies could be reexamined using heterogeneous pedestrian stream data. Examining the relationships between the basic traffic flow variables while considering individuals with disabilities could also be meaningful. Finally, developing fundamental diagrams for heterogeneous populations and comparing those with homogenous populations would provide valuable information to improve the planning and design of walking facilities.

Acknowledgments

This research is supported by a National Institute on Disability and Rehabilitation Research (NIDRR) grant, under ED Grant No. H133G110242. The authors would also like to thank all who helped in building the circuit and aiding on tests and experiments. The project website is http://laep.usu.edu/htm/research/evacuation-behavior.

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