Level of avoidance in crossing pedestrian flow

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Abstract

This study investigated pedestrians’ avoidance behaviors in crossing flow in order to obtain quantitative criteria for evaluating the difficulty of walking in a crowd. A new graphic illustration method, called the Short-Time Pedestrian Path Diagram, was developed and visually represents the state of a crowd. Under laboratory conditions, the results of our experiment suggest that pedestrians adjust their walking speed, walking route, and/or shoulder angle to avoid striking other people. Each of the pedestrian’s avoidance behaviors can be classified into three levels, whose thresholds are defined based on speed, angular velocity, or shoulder angle. It was also observed that the strength of avoidance behaviors is affected by the density of the crowd and the angle that the crossing pedestrian walked into the pedestrian flow.

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1. Introduction

As the demand increases for large-scale buildings and railway stations, it is becoming more important to control complex pedestrian flow. It is generally agreed that pedestrian crossing points cause congestion. By observing pedestrian flow, we discovered that they pass each other smoothly in flow intersections where density is relatively low. Thus, it is theorized under specific conditions, pedestrian flows can cross one another without substantial stagnation.

There are several recent experimental laboratory studies showing pedestrian flow models, for example, by Johansson et al. (2007), Steffen et al. (2009) or Rupprecht et al. (2011). Another significant study by D. Bauer (2010) demonstrates simulation models of pedestrian crossing that were calibrated using real data. However, the effects of walking difficulty and pedestrian behavior in such crossings have not yet been adequately clarified. Based on our previous studies and reviews, it is clear that the density of the flows and angle between the flows affects walking difficulty in such intersections.

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Walking difficulty in the pedestrian flow is also discussed in this study. Utilizing extra actions to avoid other people during walking could lead to additional stress for pedestrians. Thus, it can be inferred that reducing avoidance behavior enables pedestrians to walk more comfortably.

2. Methods

It makes sense to suppose that intersecting two pedestrian flows is a collection of crossings single pedestrian across a flow. Therefore, in this study, we examine how a single pedestrian crosses a steady one-way-flow.

2.1. Experiment

An experiment was conducted under laboratory conditions to obtain data about pedestrians’ spatial avoidance behavior when crossing pedestrian flows. Participants included a total of 30 male and female university students. In each experiment trial, one participant crossed a pedestrian flow that consisted of 15 or 18 participants (Fig. 1). Hereinafter, the pedestrians who cross the flow are referred to as “traversers” and the pedestrians that crowd the flow are referred to as “pedestrians in flow”.

| flow density | crossing angle |
|--------------|----------------|
| level        | density        | 180° | 135° | 90° | 45° |
| I            | 0.25 (pers/m²) | 3    | 3    | 2*  | 3   |
| II           | 1.00 (pers/m²) | 3    | 3    | 3   | 1*  |
| III          | 2.00 (pers/m²) | 3    | 3    | 3   | 3   |

* reduced due to technical problems

Table 1: Number of valid trials per condition

Fig. 1: A scene in the experiment (density II / 135°)

Fig. 2: left) Layout of the pedestrian flow group with density conditions, right) Participants’ layout in the experiment room
The experiment was conducted utilizing three different density levels at four different crossing angles. As shown in Fig. 2 (left), the pedestrian flow groups were lined up in three lines representing the different densities: 0.25, 1.0, or 2.0 person/m². The traversers walked through the flow with from one of four incidence angles: 45, 90, 135, or 180 degrees (Fig. 2 (right)). Trials for each condition combination of conditions were replicated three times. Unfortunately, the total three trials were not recorded due to technical problems in logging (Table 1). Prior to the trials, the traversers were instructed as follows: “Walk straight towards their destination and naturally avoid other pedestrians if they come too close.” Likewise, the participants in the pedestrian flow group were instructed as follows: “Walk straight towards their destination at a quick pace and naturally avoid the traverser if he or she comes too close.” After each trial, the traversers completed a questionnaire that asked the question: “How difficult was it to walk in that pedestrian flow?” Participants responded by choosing one of five options: “easy,” “rather easy,” “neutral,” “rather difficult,” and “difficult.” In addition, the participants’ head and shoulder coordinates were recorded with a motion capture system. The first 1.5 seconds after the beginning of trials were cut off from recorded data during analysis, because the pedestrians’ walking speeds first became steady after this point.

2.2. Short-Time Pedestrian Path Diagram

A new graphic illustration method called the Short-Time Pedestrian Path Diagram (STPP-Diagram) was newly developed to visually represent the state of a crowd. The STPP-Diagram depicts the distribution of pedestrians, as well as their head and shoulder positions. It also captures the walking distance and direction of each pedestrian until the next second. We developed the program in Python 3 and it requires the second interval pairs of x-y coordinates of the head and shoulders of every pedestrian to create the STPP-Diagram. In the diagram, each circle with an oval represents pedestrians’ heads and bodies, and the vector arrow drawn from these heads are line segments connecting the pedestrian’s positional coordinates of time \( t \) and one second after the time \( t + 1 \). The circles represent pedestrians’ head positions, the ovals under these circles represent pedestrians’ shoulder positions and the length and direction of the vector arrows represent the pedestrians’ walking speeds. The arrow is not drawn if the walking speed is under 0.2 m/s, because it is hard to determine walking direction from such small movements. Changing the color of the pedestrian symbols can provide additional status information about pedestrians.

In this study, STPP-Diagrams and other numerical values were calculated every 0.5 seconds using the pedestrian positional data that were recorded in the experiment. This series of STPP-Diagrams were turned into animated movies to better observe phenomena of interest (Fig. 3).

![Fig. 3: An STPP-Diagram sequence (135° / density II)](image)

2.3. Determination of the various avoidance levels

Analyzing sequences of the STPP-diagrams, we noted that pedestrians’ avoidance behaviors could be classified into three types: walking speed reduction, detouring, and shoulder twist. Furthermore, it was suggested that each of these behaviors has three intensity stages. These stages were divided into:

- Potential avoidance: an avoidance behavior that is not directly observed but appears in data.
- Weak avoidance: an avoidance behavior that can be observed.
- Strong avoidance: an avoidance behavior where the pedestrian is obviously hindered when walking by other pedestrians.
Potential avoidance could not give the physical load to behave but the pedestrians could avoid unconsciously avoid other people. As becoming the avoidance level from potential to strong, pedestrians have more physical load. From this, it can be inferred if there is a less strong avoidance behavior, a more smooth and comfortable pedestrian flow intersection is realized.

2.3.1. Levels of avoidance by walking speed reduction

The speed of a pedestrian at the time point \( t \) is defined as the moving distance from the time point \( t \) to the next time point \( t + 1 \) that is one second after the time point \( t \). To find appropriate thresholds, test movies of the STPP-Diagram in which the colors of pedestrian symbols are changed in walking speed 0.1 m/s each were generated. Then, actions that were identified as avoidance actions by multiple researchers were extracted and organized from these movies. The thresholds were determined utilizing them.

2.3.2. Levels of avoidance by detouring

The detouring angle of a pedestrian at time point \( t \) is defined as the absolute value of the angular difference in the walking direction from \( t - 1 \) to \( t \) and from \( t \) to \( t + 1 \).

Following the same process used in speed reduction level determination, the thresholds for detouring levels were determined. In this case, the colors of pedestrian symbols in the test movies of the STPP-Diagram were each changed by 3-degrees (= 1/60π rad.) to find accurate values rather than walking speed.

2.3.3. Levels of avoidance by shoulder twist

The twist angle of a pedestrian at the time point \( t \) is defined as the absolute value of the shoulder angle variation obtained in the following calculation process. To begin, the line segment connecting the head that coordinates one second before the time \( t \) (\( t - 1 \)) and one second after time \( t \) (\( t + 1 \)) is defined as the walking direction at the time \( t \). Since the perpendicular line of this line segment is the stable shoulder position when the pedestrian walks straight, the absolute value of the angular differences between this ideal shoulder direction and in the recorded shoulder direction can be defined as the twist angle (Fig. 4).

The same level valuation process used for determining the detour level was used to determine levels for shoulder twist.

2.4. Colorization of STPP movies with each avoidance level

The pedestrian symbols in the STPP-Diagram movies were colorized for each determined avoidance level. Observed avoidance behaviors where values were in the range but might not have occurred to avoid other pedestrian were manually excluded from following analysis and were not colorized.

2.5. Calculation of each pedestrian’s maximum avoidance level

The maximum avoidance strength levels of each pedestrian in an experimental trial were calculated, and then the occurrences of the maximum avoidance levels were integrated per experiment condition. Matrix tables for maximum avoidance levels were created corresponding to the experimental conditions for both traversers and pedestrians in flow. This matrix describes each maximum avoidance level as well as maximum avoidance level in each avoidance type: speed reduction, detouring, and shoulder twist.
3. Results

3.1. Walking difficulty from questionnaire

Table 2 shows the traversers’ averaged responses about the walking difficulty per each experiment condition. As scores become higher from 1 to 5, it means the traversers felt it was more difficult to walk.

Table 2: Averaged scores of traversers’ walking difficulty from questionnaire per condition

| density | crossing angle | 180° | 135° | 90° | 45° | Scores: |
|---------|----------------|------|------|-----|-----|----------|
| I       |                | 1.0  | 1.3  | 1.7 | 2.0 | 1. easy  |
| II      |                | 1.0  | 3.7  | 4.7 | 4.0 | 2. rather easy |
| III     |                | 4.7  | 4.7  | 4.0 | 4.0 | 3. neutral |

As demonstrated, crossing lower density pedestrian flow was easier. The easiest condition was the 180-degree crossing angle combined with densities I and II. However, the 180-degree crossing with density III was as difficult as other angles. In other crossing angles, a large difference exists between densities II and III.

3.2. Distributions and level ranges for three types of avoidance strength

Results confirmed that both traversers and pedestrians in flow utilized avoidance actions when the traverser entered in the pedestrian flow. These avoidance actions had three stages of strength (potential, weak, and strong). The thresholds for stages of each avoidance behavior type were determined using the method described above.

3.2.1. Walking speed reduction

The thresholds for walking speed reduction levels were determined as described in section 2.3.1. The walking speed range for the potential avoidance was 0.9 m/s to 1.0 m/s, for weak avoidance was 0.7 m/s to 0.9 m/s, and for strong avoidance was less than 0.7 m/s. From the histogram (Fig. 5), it was confirmed that these values are different enough from the steady walking speed. Overall, the average speed was 1.15 m/s and the standard deviation was 0.15.

Fig. 5: Histogram of walking speed from all trials
3.2.2. Detouring

The thresholds for detouring levels were determined as described in section 2.3.2. The detouring angle range for the potential avoidance was 12-degrees to 18-degrees, for the weak avoidance was 18-degrees to 24-degrees, and for strong avoidance was more than 24-degrees. From the histogram (Fig. 6), it was confirmed that these values are far enough out of the steady walking direction. Overall, the average angle was 3.30° and the standard deviation was 3.67.

![Fig. 6: Histogram of detouring angle from all trials](image)

3.2.3. Shoulder twist

The thresholds for shoulder twist levels were determined as described in section 2.3.3; The twist angle range for the potential avoidance was 12-degrees to 24-degrees, for the weak avoidance was 24-degrees to 36-degrees, and for strong avoidance was more than 36-degrees. From the histogram (Fig. 7), it was confirmed that these values are different enough from the steady shoulder angle. Overall, the average angle was 4.97° and the standard deviation was 6.68.

![Fig. 7: Histogram of shoulder twist angle from all trials](image)

3.3. Typical avoidance behaviors from the STPP movies

Some typical cases of pedestrian avoidance behaviors are shown in Fig. 8-10 as colorized STPP-Diagrams.
Fig. 8 is STPP-Diagrams from a trial with a crossing angle of 180-degrees and density level III. In this trial, the traverser walked straight to the goal but slightly reduced his/her speed and avoided others mostly primarily by controlling his/her shoulder angle to fit through narrow gaps. The pedestrians in flow also twisted their shoulders. Fig. 9 represents a trial with a crossing angle of 135-degree and density level III. From these diagrams, it can be seen that the traverser avoided others with strong speed reduction and strong detouring. Fig. 10 demonstrates a trial with a crossing angle of 90-degrees and density level II. The diagrams show that the traverser and a pedestrian in the flow ran into each other. Consequently, pedestrians in the flow avoided him/her using only speed reduction, since they did...
not have enough time to detour in advance. As a result, a “traffic jam” occurred in this trial. However, pedestrians in flow did not need to twist their shoulder since there was still enough margin space around them.

3.4. Summarized level of avoidance strength

In general, the results demonstrate that the higher the density the more frequently and strongly avoidance occurs. Both traversers and pedestrians in flow utilized avoidance actions. However, traversers have a tendency to avoid more actively than pedestrians in flow. The frequency of each avoidance behavior also differs with the crossing angles. Tables 3 and 4 show the strongest avoidance levels in each condition as well as each avoidance type.

Table 3: Maximum avoidance levels of traversers

| Density | Crossing Angle | 180° | 135° | 90° | 45° |
|---------|----------------|------|------|-----|-----|
|         | Max.           | Max. | Max. | Max. |     |
| I       |                |      |      |      |     |
| II      |                |      |      |      |     |
| III     |                |      |      |      |     |

| Avoidance Types: | Avoidance Levels: |
|------------------|-------------------|
| S Speed Reduction| P Potential       |
| D Detouring      | W Weak            |
| T Shoulder Twist | S Strong          |

Table 4: Maximum avoidance levels of pedestrian flows

| Density | Crossing Angle | 180° | 135° | 90° | 45° |
|---------|----------------|------|------|-----|-----|
|         | Max.           | Max. | Max. | Max. |     |
| I       |                |      |      |      |     |
| II      |                |      |      |      |     |
| III     |                |      |      |      |     |

| Avoidance Types: | Avoidance Levels: |
|------------------|-------------------|
| S Speed Reduction| P Potential       |
| D Detouring      | W Weak            |
| T Shoulder Twist | S Strong          |

In the trials with a 180-degree crossing angle, there were no avoidance actions used with low density. On the other hand, on density III, both traversers and pedestrians in flow strongly avoided others using shoulder twist. The traversers also used speed reduction on density III. On the 135-degree crossing angle, weak avoidance behavior began to appear on density I. In addition, on densities II and III, both traversers and pedestrians in flow had relatively strong avoidance behaviors in all speed reduction, detouring and shoulder twist. On the 90-degree crossing angle, no avoidance behaviors were observed on density I, but appeared on densities density II and III at a strong level. Avoidance behaviors were also observed with the 45-degree crossing angle. However, even on density III, their levels were not strong. Specifically, on the 45-degree crossing angle they primarily used speed reduction and only infrequently used shoulder twist avoidance.

3.5. Characteristic avoidance behaviors from STPP movies

By studying the STPP movies, the results in section 3.4 can be interpreted as follows.

Since pedestrians have enough adjustment space around themselves in density I, almost no observable avoidance behavior occurred. Results of the crossing angle 180-degrees clearly demonstrates that there was no avoidance behavior, as long as the gap width between pedestrians next to each other was substantial enough (densities I and II). When this gap width becomes smaller than their body width (density III), pedestrians twist their shoulders in order to make the body width which is perpendicular to the walking direction smaller. This avoidance behavior occurred among both traversers and pedestrians. In addition, it is particularly inefficient to detour at this crossing angle. On the other crossing angles (135-, 90- and 45-degrees), avoidance behaviors were observed on density II among both pedestrians and traversers. Specifically, in the 135-degree crossing angle traversers predominantly avoid pedestrians...
in flow. In the 90-degree crossing angle, both traversers and pedestrians in flow perform avoidance actions in equal amounts. Finally, in the 45-degree crossing angle, no strong avoidance behavior was observed. This result likely occurred because the relative walking speed between the traverser and pedestrians is lower than other conditions. Furthermore, it is hard for pedestrians in flow to take avoidance action since the traverser is out of their vision before they come across.

4. Discussion and perspective

Comparing the summary of the traversers’ avoidance levels (Table 3) with the participants’ responses to the questions in the walking difficulty questionnaires (Table 2) reveals certain trends. It is presumed that this physical avoidance strength levels corresponded to the pedestrian’s mental walking difficulty. Our analytic approach using STPP-Diagrams and avoidance levels requires only the sequential positional coordinates of each pedestrian for its data source. Thus, this method could also be able to apply to the simulation in order to measure pedestrians’ mental walking difficulty. In addition, it can also be easily compared with actual crowd data.

5. Conclusion

In this study we analysed pedestrians’ avoidance behaviors in crossing pedestrians in flow. The results of the experiment clearly suggest that pedestrians adjust their speed or body angle as well as detour around other people to avoid bumping into them. Using the new Short-Time Pedestrian Path Diagram, illustration method for crowds, the phenomena of pedestrians’ avoidance behaviors can be visually illustrated in great detail. Furthermore, the strength of these avoidance behaviors can be classified into three levels, each with a value range. Density of the pedestrian flow to cross and the crossing angle are both associated with these avoidance types and strength levels. Finally, the strength of these avoidance behaviors corresponded to pedestrians’ mental walking difficulty in the intersections condition.

The following trends were revealed in the study:

- Pedestrians took almost no avoidance action in density I (0.25 person/m²) but generally did so in densities II (1.00 person/m²) and III (2.00 person/m²).
- On the 180-degree crossing angle, no avoidance action was observed until density II. However, traversers and pedestrians in flow strongly twisted their shoulder and also reduced their walking speed on density III, since the gap space the traverser has to go through becomes more narrow than their body width.
- The following behaviors were observed on 135-, 90- and 45-degree crossing angles in the density II and III conditions:
  - 135-degree: Traversers were most likely to adjust and used avoidance behaviors.
  - 90-degree: Both traversers and pedestrians in flow used avoidance behaviors in equal amounts
  - 45-degree: No strong avoidance behavior was observed. This may have occurred since the relative walking speed between traversers and pedestrians in flow was low and pedestrians in flow could not see the traversers before they came across.

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