ANALYZING VARIATIONS IN SHOULDER ROTATION BEHAVIOR WITH RESPECT TO MACROSCOPIC CROWD CHARACTERISTICS:

INSIGHTS FROM CROWD LIMITS

FINAL REPORT

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Abstract

In crowded pedestrian environments, individuals often resort to rotating their bodies as a strategy to avoid collisions. Surprisingly, this rotational behavior, despite its significant implications for crowd capacity, has received relatively little attention in research. This study seeks to fill this gap by diving into the complicated world of pedestrian rotation behavior, particularly in the context of high-density bidirectional and crossing flows.

Drawing upon data gathered from the CrowdLimits experiments, we start the exploration of how various factors impact the rotation behavior of pedestrians. Our investigation covers crowd density, the fundamental movement scenarios (bidirectional and crossing flows), flow ratio, and the influence of disturbances within the crowd under different scenarios.

Our key findings reveal that all these factors play a role in shaping the frequency of rotations within a crowd. However, the extent and precise conditions under which these factors influence this subject demand further in-depth research and exploration.

In essence, this study addresses the fundamental question: How does shoulder rotation behavior vary concerning macroscopic crowd characteristics, including crowd density, flow ratio, and movement patterns like bidirectional and crossing flows? Through this research, we hope to highlight the complex interplay between these factors and the rotational strategies operated by pedestrians, ultimately enhancing our understanding of crowd dynamics.

1 Introduction and Research Questions

The study focuses on shoulder rotation behavior and its relation to macroscopic characteristics in crowded areas such as public transportation hubs, stadiums, and shopping centers this study will also provide an overview of the main issues, and target clients.

Rotation behavior refers to the strategy employed by pedestrians to rotate their bodies in order to avoid collisions with other individuals or obstacles in a crowded environment. Instead of solely relying on changes in speed or direction, pedestrians utilize body rotation as an additional means of collision avoidance. This behavior involves individuals adjusting their orientation or turning their bodies to navigate through congested areas, allowing them to find a path that minimizes the risk of collisions. By studying rotation behavior, researchers aim to understand its impact on pedestrian flow dynamics, capacity, and overall safety in different scenarios. Understanding and accurately representing this behavior in models is crucial for accurately simulating and predicting pedestrian movements *[11]*.

Furthermore, the focus on pedestrian behavior in urban areas has a significant impact on traffic engineering and policy-making. Understanding pedestrian behavior is crucial for designing effective infrastructure, improving traffic flow, and reducing accidents involving pedestrians *[13]*.

Daamen, W., & Hoogendoorn, S. P. *[12]* emphasize the importance of gaining insights into both the microscopic (individual pedestrian behavior) and macroscopic (pedestrian flow) characteristics. They state that most previous research has relied on video data to describe and study pedestrians, which limits the ability to influence independent variables. By conducting controlled experiments, the researchers can deliberately change experimental variables and observe their effects on response variables. This approach allows for a deeper understanding of pedestrian behavior and the factors that influence it *[12]*.

Numerous studies have utilized field investigations, controlled experiments, or numerical simulations to analyze the macroscopic, microscopic behaviors and mechanisms of pedestrian rotation behavior.

Helbing et al. *[1]* developed a pedestrian motion model by investigating the formation of trail systems in public areas, which has been used to predict pedestrian traveling paths by evaluating typical parameter values. In a study by Yu and Song *[2]*, it was found that pedestrians tend to prefer walking on one side based on their cultural background, as evidenced by investigations and counterflow models of Chinese and Japanese pedestrians.

Recent research has treated pedestrian behavior as a complex system, where individual route choices shape the crowds and are affected by them in turn. This highlights the importance of understanding pedestrian rotation behavior and its relationship to macroscopic characteristics in crowded areas. In addition, it has been demonstrated that even in public spaces that fully meet design standards, a crowd incident can be triggered by competition or avoidance behavior at certain spots *[3]*. Thus, pedestrian rotation behavior research and analysis can contribute to the development of better crowd management strategies and design principles for public spaces.

Numerous studies have delved into the complex nature of pedestrian behavior. On one hand, social research suggests pedestrians act independently and interact thoughtfully while pursuing their goals. On the other hand, practical observations draw parallels between pedestrian behavior and the flow of particles in highly crowded spaces *[4]*. As a result, there's been a split in modeling approaches. Some prioritize individual pedestrian traits and local interactions, while others focus solely on pedestrian flow. For example, Seyfried et al. *[3]* conducted a study using real-world data and modeling methods to examine how pedestrians rotate in bottleneck situations. Their findings indicate that rotations often happen in response to disruptions in the flow, like obstacles or slow-moving pedestrians.

In one study conducted by Johansson et al. *[4]*, they closely observed how pedestrians behave when navigating a corridor intersection. Their findings revealed that rotation behaviors are shaped by a combination of factors, including the corridor's width and individual characteristics like walking speed and distance to their destination. On the other hand, Helbing et al. *[5]* took a different approach. They crafted a model for pedestrian movement aimed at predicting travel paths. This model relied on standard parameter values and the creation of trail systems in public spaces. While such modeling has its advantages, it may be less directly applicable to understanding real-world pedestrian behavior compared to the empirical observations made by Johansson et al. Meanwhile, Yu and Song *[2]* analyzed pedestrian walking behavior in Chinese and Japanese crowds using investigations and counterflow models, revealing that pedestrians tend to stay on one side of the walkway. Furthermore, the macroscopic characteristics of pedestrian flows have also been investigated to understand rotation behavior. Field investigations, controlled experiments, and numerical simulations have been successfully used to analyze microscopic behaviors and mechanisms at pedestrian intersections *[1]*. Moreover, a study by Shi, Xiaomeng, et al. *[10]* conducted controlled laboratory experiments to examine the impact of merging angle and flow direction on the outflow and safety of pedestrian crowds. They found that both macroscopic and microscopic properties of crowd dynamics are critical factors that can have safety implications for merging crowds. The study highlights the need for considering both microscopic and macroscopic parameters in developing mathematical models intended to simulate merging crowd behavior.

Additionally, a study by Sparnaaij, M., Duives, D. C., & Hoogendoorn, S. P. *[11]* showed that shoulder rotation is a significant aspect of overall body rotation behavior. By specifically examining shoulder rotation, we can gain insights into the precise movements and adjustments pedestrians make to avoid collisions. This level of detail allows for a more accurate representation of real-world pedestrian behavior in models and simulations. Secondly, shoulder rotation behavior provides valuable information about the intentions and decision-making processes of pedestrians. By analyzing the rotation of the shoulders, we can infer the direction in which pedestrians are planning to move or the direction they are trying to avoid. This understanding can be crucial for predicting and managing pedestrian flows in complex and crowded environments. Lastly, investigating shoulder rotation behavior allows for a more comprehensive understanding of the factors that influence pedestrian movements. By examining how density, flow ratio, disturbances, and other macroscopic characteristics impact shoulder rotation, we can identify patterns and relationships that can inform the development of effective crowd management strategies and pedestrian flow optimization techniques. However, the study does not have enough power to determine to what degree these factors influence the number of rotations and in which cases they exactly influence the number of rotations.

Overall, these studies suggest that pedestrian rotation behavior is a complex phenomenon influenced by individual characteristics and environmental factors.

In recent years, pedestrian behavior has been recognized as a critical factor in ensuring public space safety. Various crowd disasters have highlighted the importance of understanding and predicting pedestrian behavior to prevent incidents. For instance, even public spaces that fully meet design standards can experience crowd incidents due to competition or avoidance behavior at a certain spot *[3]*.

Despite the progress made, there is still a need to investigate the complex dynamics of pedestrian rotation behavior and its implications for crowd management strategies and public space design *[6][7]*.

In addition, pedestrian rotation behavior presents several key issues that warrant investigation. Firstly, it directly affects the overall movement efficiency and flow dynamics within crowded areas *[8]*. By studying the patterns and mechanisms of rotation behavior, researchers can gain insights into optimizing space utilization, reducing congestion, and improving pedestrian safety. Secondly, the relation between pedestrian rotation and macroscopic, microscopic characteristics such as crowd density, flow rate, walking speed and distance to destination, and environmental layout is a crucial aspect to consider *[9][10]*. Analyzing this relationship can lead to a better understanding of how these characteristics influence and are influenced by pedestrian rotation behavior.

Macroscopic characteristics, such as density, movement base case, flow ratio, and disturbances, play a significant role in determining the overall behavior and efficiency of pedestrian flows. By studying the impact of these factors on rotation behavior, we can gain valuable insights into how to optimize pedestrian flow management and design more efficient and safe pedestrian environments. Compared to other characteristics, macroscopic characteristics have a broader impact on the overall flow dynamics and capacity. By investigating the relationship between rotation behavior and these macroscopic characteristics, we can better understand how to manage and control pedestrian flows in various scenarios, such as high-density bidirectional and crossing flows *[11]*.

Further supports the focus on macroscopic characteristics by discussing the distinction between primary and secondary factors in the research. While primary factors were influenced during the experiments, secondary factors are specific to different pedestrians. This suggests that understanding the macroscopic characteristics of pedestrian flows, such as density, composition, and mean speed, is crucial for gaining insights into overall pedestrian behavior *[12]*.

Moreover, the macroscopic characteristic of pedestrian behavior is essential because it provides a broader perspective on the overall patterns and trends of pedestrian movement. The macroscopic analysis allows for a better understanding of the collective behavior of pedestrians, such as their route choices and crossing decisions, which can have a substantial impact on traffic flow and congestion.

While other characteristics of pedestrian behavior, such as individual preferences and psychological factors, are also important, the macroscopic characteristic provides a more comprehensive understanding of pedestrian behavior on a larger scale. By investigating the macroscopic characteristics, researchers can identify common trends and patterns that can be used to develop more accurate and reliable models for predicting pedestrian behavior and designing pedestrian-friendly urban environments *[13]*.

Based on the understanding gained from the literature review, the gaps mentioned earlier, and arguments on why we should fulfill these gaps a hypothesis will be formulated based on the the scope of this research to create a feasible research question to fulfill the gaps.

Scope: Our focus in this study is to investigate the complicated connections between shoulder rotation behavior and a range of macroscopic traffic variables across various scenarios. We aim to understand how these variables impact shoulder rotation patterns. Specifically, we explore the relationship between shoulder rotation behavior and crowd density, using the data from the CrowdLimits experiment considering different scenarios (24 scenarios). Additionally, we dive into the influence of flow ratio (e.g. 50/50, 80/20, and 70/30) on shoulder rotation behavior across diverse contexts.

Disturbances within crowds also capture our attention, and we seek to uncover their effects on shoulder rotation patterns across various scenarios by applying different assignments (A-normal, B-cross, and C-fast walking). To gain a comprehensive understanding, we analyze how shoulder rotation behavior varies within different movement base cases, Including bidirectional flows and crossing flows.

We aim to identify and characterize various crowd behaviors and types of crowds within our study. Our focus is on diverse scenarios, but we also prioritize specific assignments based on their relevance and potential to shed light on shoulder rotation behavior in real-world pedestrian dynamics.

Hypothesis: There is a significant correlation between macroscopic characteristics and the frequency and extent of shoulder rotation behavior. Density, Movement Base Case, Flow Ratio, and Disturbances will have an impact on the number of rotations in a flow.

Previous studies have indicated that macroscopic characteristics influence pedestrian behavior, including rotation. Investigating the relationship between macroscopic characteristics and shoulder rotation behavior can provide insights into crowd dynamics and aid in optimizing crowd management strategies and public space design.

The literature review highlights the potential of understanding shoulder rotation behavior to enhance crowd management strategies and design principles. Investigating this relationship further can provide evidence-based recommendations for professionals involved in urban planning, transportation management, and public space design.

Research Questions:

Main Question:

What are the relationships between shoulder rotation behavior and various macroscopic traffic variables?

Sub-questions:

- What insights can existing literature provide regarding the relationships between shoulder rotation behavior and macroscopic traffic variables?
- How was the CrowdLimits experiment designed and conducted to investigate shoulder rotation behavior?
- What methodologies were employed to extract shoulder rotation data from video data?
- What are the quantitative findings regarding the relationship between crowd density and shoulder rotation behavior in different scenarios?
- How does shoulder rotation behavior relate to crowd density in different scenarios?
- What is the impact of flow ratio on shoulder rotation behavior across different contexts?
- How do disturbances influence shoulder rotation patterns in various scenarios?
- In the context of different movement base cases (bidirectional flows and crossing flows), how does shoulder rotation behavior vary?

2 Research methodology

2.1 Central Theory and Theoretical Framework

The central theory underlying the research methodology is that analyzing pedestrian shoulder rotation behavior can provide insights into crowd dynamics and contribute to the development of improved crowd management strategies and design principles. The theoretical framework draws upon previous studies that have explored the relationship between rotation behavior and macroscopic characteristics *[8][9][10].* Macroscopic characteristics, such as density, movement base case, flow ratio, and disturbances, influence the frequency and extent of shoulder rotation behavior in pedestrian flows. These characteristics are considered independent variables that have an impact on the dependent variable, which is rotation behavior *[11]*. The theoretical framework would include concepts such as geometrical features, crowd dynamics, individual preferences, and the influence of macroscopic characteristics on pedestrian behavior.

- Macroscopic Characteristics: The framework incorporates macroscopic characteristics, including crowd density, flow ratio, effective walking speed, and movement base case. These factors are known to influence pedestrian behavior and are often used to describe the overall dynamics of crowds in various settings *[3][11]*.
- Individual Preferences: The framework acknowledges that pedestrians have individual preferences and cultural backgrounds that influence their behavior. Studies by Yu and Song *[2]* have shown that pedestrians tend to exhibit cultural preferences in terms of walking on one side of walkways. These individual characteristics and preferences are considered influential factors in the theoretical framework.
- Geometrical Features: Geometrical features of the environment, such as the width of passages and corridor intersections, also play a role in pedestrian rotation behavior. Johansson et al. *[4]* investigated the influence of geometrical features on pedestrian rotation behaviors and found that passage widths and individual characteristics, such as walking speed and distance to destination, impact the rotational patterns.
- Crowd Dynamics (self-organization behavior): Theoretical principles from crowd dynamics provide insights into the collective behaviors of pedestrians. Concepts such as self-organization, emergent patterns, and the impact of perturbations on crowd flow are considered within the framework *[5]*. These concepts help us understand how individual pedestrian behaviors collectively shape the overall crowd dynamics.

By integrating these concepts and theories, the theoretical framework provides a comprehensive understanding of shoulder rotation behavior and its relationship to macroscopic characteristics.

Figure 1 illustrates the conceptual framework outlining all relevant factors and their relationships to shoulder rotation behavior.

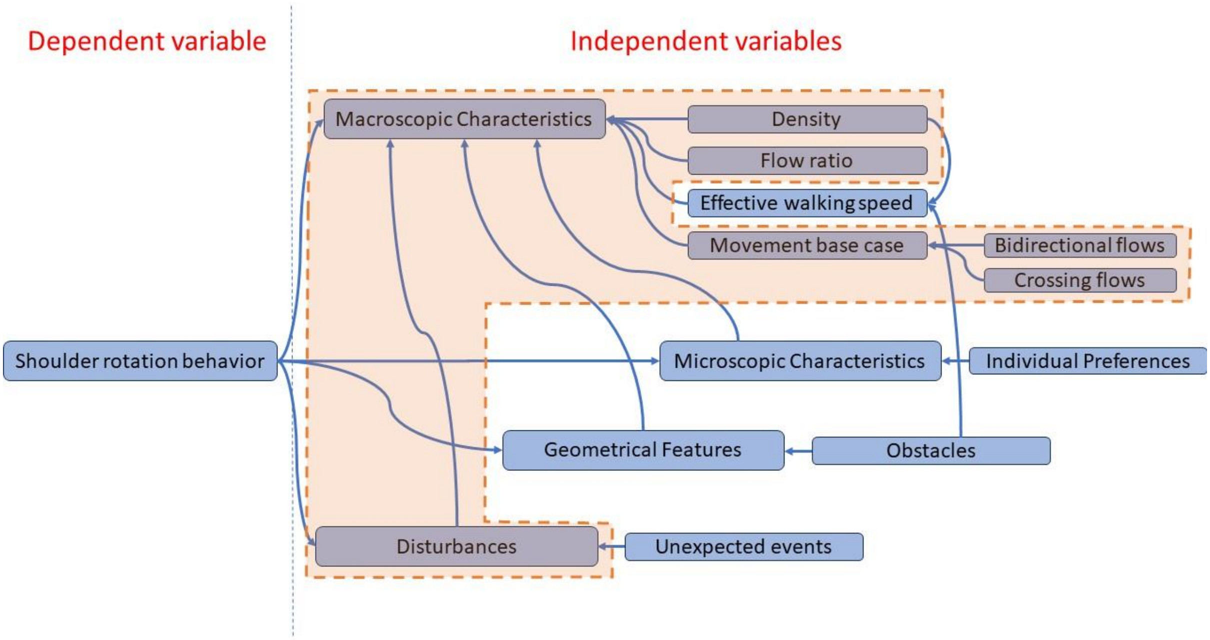

Figure 1: Conceptual Framework

The conceptual framework suggests that Crowd Dynamics plays a crucial role in understanding shoulder rotation behavior. Changes in crowd density levels can significantly impact the frequency and occurrence of shoulder rotation as pedestrians navigate through crowded spaces. Higher densities may lead to a higher likelihood of shoulder rotation behavior as individuals strive to avoid collisions and maintain personal space. Conversely, lower densities may reduce the need for shoulder rotation as there is more room for pedestrians to move freely without obstruction.

The Movement Base Case is another factor considered in the conceptual framework. The configuration of pedestrian flows, whether bidirectional flows or crossing flows, is expected to influence the patterns and strategies of shoulder rotation behavior. In bidirectional flows, where pedestrians move in opposing directions, the need for shoulder rotation may be more prevalent to avoid head-on collisions. On the other hand, in crossing flows, where pedestrians intersect or cross paths, shoulder rotation behavior may occur at specific points of interaction or when navigating through congested areas.

Additionally, the Flow Ratio, which represents the proportion of pedestrians moving in different directions, is hypothesized to impact the distribution and frequency of shoulder rotation behavior. Varying flow ratios, such as imbalanced or skewed flows, can create situations where the need for shoulder rotation is more pronounced. For instance, when the number of pedestrians moving in one direction significantly outweighs those in the opposite direction, shoulder rotation behavior may increase as pedestrians adjust their movements to accommodate the dominant flow direction.

In addition to the factors discussed above, the conceptual framework recognizes the influence of Effective Walking Speed on shoulder rotation behavior. Effective walking speed refers to the speed at which individuals cross a given space, considering various factors such as crowd density and obstacles. It is an important aspect to consider as it can impact the decision-making process of pedestrians when determining the need for shoulder rotation.

Furthermore, the conceptual framework acknowledges that geometrical features and disturbances, such as obstacles or unexpected events, can disrupt pedestrian flows and influence rotation behavior.

These disturbances may trigger more frequent or more extensive rotation behavior as pedestrians adjust their movements to navigate around obstacles or respond to unexpected situations.

Microscopic Characteristics also play a significant role in shoulder rotation behavior. Individual Preferences, as highlighted in the framework, indicate that pedestrians may exhibit cultural or individual tendencies regarding their preferred side of walking. These individual characteristics and preferences can influence shoulder rotation behavior, particularly in scenarios where pedestrians from diverse backgrounds coexist within a shared space.

By considering Crowd Dynamics, Microscopic and Macroscopic Characteristics (including Individual Preferences), and the influence of Disturbances and Geometrical Features, the conceptual framework provides a comprehensive understanding of the factors that shape shoulder rotation behavior. It emphasizes the interplay between environmental factors, individual characteristics, and collective dynamics, ultimately contributing to the design of more efficient and safe pedestrian spaces. As mentioned earlier, this study only focuses on macroscopic characteristics(crowd density, flow ratio), Disturbances, and movement base case as shown in the orange shape in Figure 1.

2.2 Experimental Methods for Data Collection

The central theory underlying this study is that shoulder rotation behavior is influenced by the macroscopic characteristics of pedestrians. To investigate this relationship, a mixed-methods approach will be employed, combining controlled experiments, and data analysis.

2.2.1- Controlled experiments

Controlled experiments were conducted using an overhead camera to analyze pedestrian trajectories. By manipulating macroscopic characteristics such as crowd density and layout, the experiments will allow for a more controlled examination of the relationship between these factors and shoulder rotation behavior.

The primary method for data collection involves analyzing trajectories based on video data collected from the CrowdLimits experiment (more specific details about the experiment can be found in **Paragraph 3**) to analyze the rotation behavior of pedestrians. The video data is analyzed using computer vision techniques to extract rotation behavior data. This method allows for the precise tracking of pedestrian movement and rotation within a controlled experimental setting ***[11]***.

Pros:

- Provides accurate and detailed trajectory data, allowing for a comprehensive analysis of shoulder rotation behavior.
- Enables the collection of data in real-time, capturing the dynamic nature of the pedestrian movement.
- Allows for the examination of multiple variables simultaneously, such as crowd density, flow rate, and environmental layout.

Cons:

- Requires careful calibration and positioning of the overhead camera to ensure accurate tracking and minimize occlusions.
- Relies on clear visibility and lighting conditions to obtain high-quality camera images.
- May be limited in capturing fine-grained details of individual characteristics and interactions.

2.2.2 Data Analysis

The research methodology used in this study involves a combination of quantitative and qualitative methods. The study utilizes video data collected from the CrowdLimits experiment (more specific details about the experiment can be found in **Paragraph 4**) to analyze the shoulder rotation behavior of pedestrians in bidirectional and crossing flows. The data is analyzed using statistical methods to identify patterns and relationships between macroscopic characteristics and shoulder rotation behavior. Additionally, qualitative analysis is used to gain insights into the decision-making processes and spatial awareness of pedestrians ***[8][9][11]***.

Pros:

- Provides objective and quantitative insights into the relationship between shoulder rotation behavior and macroscopic characteristics.
- Enables the identification of statistical associations and trends.
- Allows for comparisons and generalizations across different scenarios and conditions.

Cons:

- May not capture the full complexity and context-specific factors influencing shoulder rotation behavior.
- Relies on assumptions and simplifications in modeling the relationship between variables.

2.3 Expected Results

The research expects to uncover the relationship between shoulder rotation behavior and macroscopic characteristics, providing insights into the factors influencing rotation patterns. The analysis is anticipated to reveal correlations between crowd density, flow ratio, disturbances, and movement base case with the frequency and extent of shoulder rotation behavior. The results will contribute to the development of empirical models and recommendations for optimizing crowd management strategies and public space design.

Overall, the research methodology combines the analysis of trajectory data using an overhead camera with quantitative and qualitative analysis techniques. This approach enables the investigation of shoulder rotation behavior in relation to macroscopic characteristics, aligning with the central theory and theoretical framework. By employing these methods, the study aims to provide valuable insights into crowd dynamics and contribute to the field of crowd management research.

3 CrowdLimits Experiment

In June 2018, Delft University of Technology conducted comprehensive pedestrian experiments known as the CrowdLimits experiments *[11][14]*. The primary objective was to delve into pedestrian behavior within high-density bidirectional and crossing flows. However, the experiment's setup allowed for the exploration of pedestrian rotation behavior in specific flow scenarios. For a more comprehensive understanding, a brief overview of the experimental setup is provided here.

These experiments spanned two evenings. The first evening replicated bidirectional flow, while the second evening simulated a two-way crossing flow. Each evening comprised 12 runs, involving two distinct flow ratios and three unique movement assignments, as outlined in Table 1.

Flow distribution over the entrances was manipulated in each run, with options for an even 50-50 split or a split favoring a major flow (80% and 70%) and a minor flow (20% and 30%). The selection of these scenarios was based on previous research illustrating their impact on capacity.

During each run, which lasted approximately 5 minutes, inflow increased gradually every minute. Queuing areas with lanes and stop-go lights controlled the inflow into the experimental infrastructure. Participants were instructed to enter either the corridor or crossing, proceed to the other side, and walk as they normally would before rejoining the queue Assignment A. Notably, Assignment C and Assignment B introduced an interesting element by asking about 10% of participants to simulate walking faster than usual and to cross the crowd diagonally and leave the corridor from the other side, introducing an element of disruption.

Participants with assignment A (approximately 80% of participants) consistently adhered to their assignments, while those with assignments B and C (each comprising 10% of participants) only followed their assignments when signaled. Participants were repeatedly reminded to adhere to their assignments within the construction, given that these assignments often deviated from their natural behavior. The experiments took place in a big indoor hall, constructed using L-shaped wooden elements, and in the case of the corridor, additional 2-meter-wide panels. These elements were 2.4 meters high to create a sense of enclosure. The detailed layout and dimensions can be found in Figure 2.

Table 1: Distribution of scenarios over the two experimental days

Run no.	Day 1				Day 2		
	Movement base case	Flow ratio	Assignment	Corridor width	Movement base case	Flow ratio	Assignment
1	Bidirectional	50/50	['A'] no assignment	big	Intersecting	50/50	['A'] no assignment
2	Bidirectional	50/50	['A'] no assignment	big	Intersecting	50/50	['A'] no assignment
3	Bidirectional	50/50	['A'] no assignment	big	Intersecting	50/50	['B'] Crossing
4	Bidirectional	50/50	['B'] Crossing	big	Intersecting	50/50	['C'] 10% Fast walk
5	Bidirectional	50/50	['C'] 10% Fast walk	big	Intersecting	50/50	['B'] Crossing
6	Bidirectional	50/50	['B'] Crossing	big	Intersecting	50/50	['C'] 10% Fast walk
7	Bidirectional	50/50	['C'] 10% Fast walk	big	Intersecting	70/30	['A'] no assignment
8	Bidirectional	80/20	['A'] no assignment	small	Intersecting	70/30	['A'] no assignment
9	Bidirectional	80/20	['B'] Crossing	small	Intersecting	70/30	['B'] Crossing
10	Bidirectional	80/20	['C'] 10% Fast walk	small	Intersecting	70/30	['C'] 10% Fast walk
11	Bidirectional	80/20	['B'] Crossing	small	Intersecting	70/30	['B'] Crossing
12	Bidirectional	80/20	['C'] 10% Fast walk	small	Intersecting	70/30	['C'] 10% Fast walk

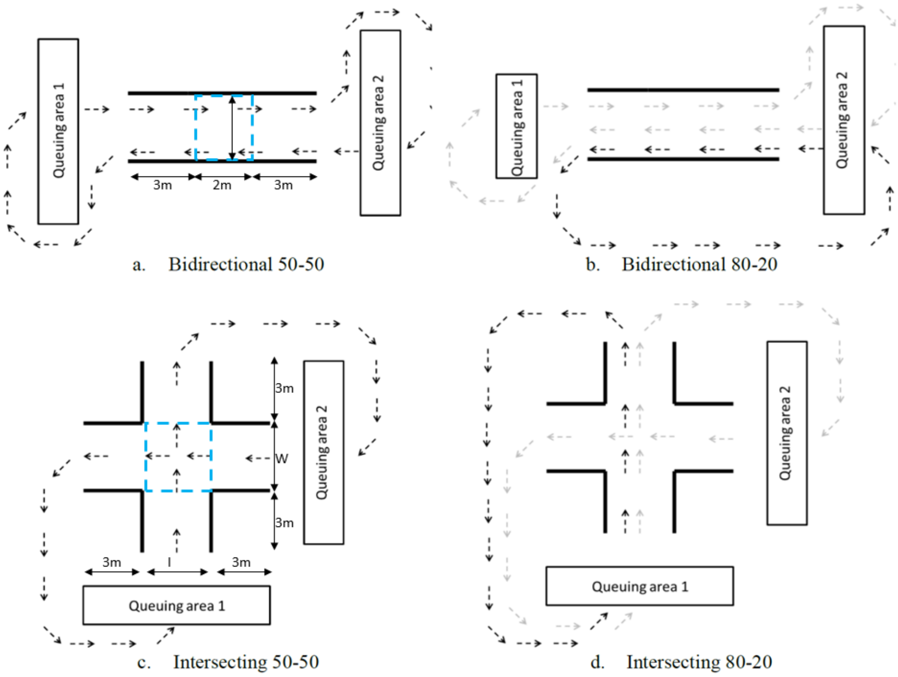

Figure 2 Layout of the scenarios including the dimensions, the areas of interest, and the movement scenarios for the first day (a & b) and the second day (c & d), where the black arrows indicate the movement direction of the major flow and the grey arrows of the minor flow.

Each evening witnessed the participation of approximately 130 individuals, forming a diverse group with 55% males and 45% females, spanning ages from 18 to 70 and with an average height of 1.76 meters. Among the participants, 74% were Dutch, with the remaining comprising various nationalities.

To track participant movements, multiple cameras captured the action from above. Participants were identifiable by their red caps and white t-shirts decorated with blue dots marking their shoulder points, aiding in tracking, as illustrated in Figure 3.

Over two days, all combinations of movement base cases, flow ratios, and assignments were tested twice, resulting in 24 experiments.

The CrowdLimits experiments, designed with meticulous attention to detail, aimed to offer valuable insights into pedestrian behavior under high-density conditions, presenting an opportunity to better understand crowd dynamics and safety considerations in various scenarios.

4 Extracting the Rotations from the Video Data

Following the experiments, we started an accurate process to extract rotation and density data from the recorded videos. This section outlines the three-step methodology employed for this purpose.

Step One: Defining the Area of Interest

In the initial step, we specified a specific area of interest within which we would measure rotations and density. This area was carefully selected to capture rotations related to the specific movement base cases. Notably, it excluded rotations occurring in bi-directional flows leading to or from the crossing and those at the boundaries of the infrastructure. Figure 2 illustrates this designated area of interest for both experimental scenarios.

Step Two: Shoulder Annotation

The second phase involved the annotation of participants' shoulders. To achieve this, we manually annotated the shoulders of each person located within the area of interest. It's worth noting that we performed this annotation for one frame per second, as opposed to every frame. Figure 3 shows this annotation process, with the left shoulder marked by a red dot and the right shoulder by a green dot.

Step Three: Density and Rotation Calculation

The final step was dedicated to the calculation of both density and rotations based on the annotated shoulders and the designated area of interest. Density, defined as the number of pedestrians within the area of interest to its size, was determined for each frame. In parallel, we computed the rotations of all participants within this area. The rotation angle was calculated by measuring the angle between the assumed direction of movement (horizontally or vertically depending on the scenario) and the line segment formed by connecting the left and right shoulder points.

It's important to note that our methodology employed assumed directions of movement (as Figure 3 shows) rather than actual movement trajectories, primarily due to the unavailability of trajectory data.

A Matlab code created by ***Mr. Martijn Sparnaaij*** was used in this step to annotate the shoulders and the area of interest. The code provides the shoulders, and area of interest coordination based on two groups of movement. We used this raw data to conduct our analysis by creating Python code to help us perform quantitative analysis (using statistical methods such as mean, standard deviation, minimum, maximum, and median), and qualitative analysis (by systematically examining and interpreting different types of charts such as CDF charts, etc.).

Employing this systematic approach, we processed videos from all 24 experiments, resulting in 24 distinct datasets. These datasets comprehensively captured all rotations observed in the respective experiment videos. The subsequent section goes deep into the valuable insights derived from these datasets.

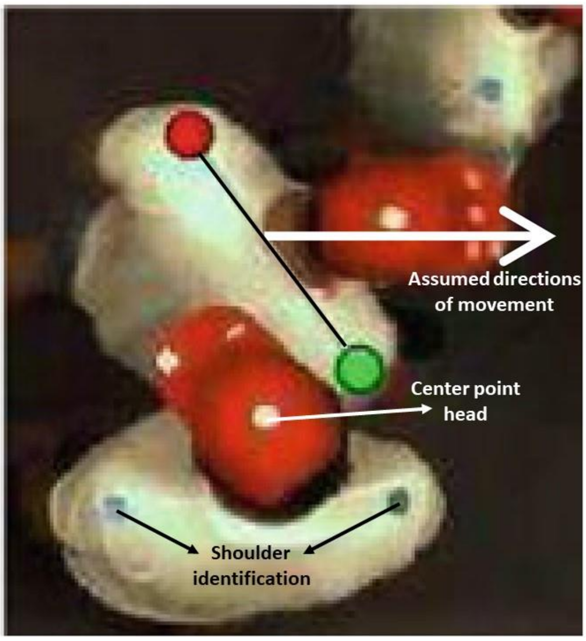

Figure 3 Annotation of shoulders

5 Results (Quantitative and Qualitative analysis)

In this chapter, we take a deep dive into the analysis of shoulder rotation behavior across various scenarios. We cover several critical aspects:

- Scenario Parameters (Figure 4, Table 2- appendix): We start by examining the parameters of different scenarios to understand how they affect shoulder rotation behavior.
- Graphical Analysis (Figure 5): Figure 5 plays a crucial role in our analysis. We use Cumulative Distribution Function (CDF) and Proportions of Rotations vs. Density plots to uncover patterns and relationships within our data. These visual representations help us draw meaningful conclusions about how pedestrian characteristics relate to rotation behavior.
- Local Density (Figure 6): Figure 6 offers a comprehensive view of rotation behavior concerning local density.

Following we will touch on all of the previous points one by one to give more insight into our results

Figure 4 and Table 2- appendix shows different parameters for different scenarios which we will use to perform the statistical analysis.

We can clearly see in the 4a graph large differences in the min average value of the rotation angles in the case of 50/50 bi-directional movement between the two opposite directions compared to the case of the flow ratio of 80/20. This can be justified by the fact that the large difference in the number of people facing each other will lead to the group with the smaller number being forced to maintain large rotation angles compared to the larger group to be able to avoid collisions. This is something that we cannot see in the case of 50/50, as the homogeneity of crowd movement has led to the homogeneity of rotations.

What supports this assumption is the clear difference in the average mean in the 4c graph in the cases of 80/20, as the group with the smaller number had to make bigger rotations compared to the larger group, with some exceptions when assignments B and c were applied, which led to creating a state of disturbance, as the participants must enter from a place and departing from an opposite place by performing a cross path or move faster the normal situation, which led to the formation of a special situation that forced the two groups to perform almost equal size of rotation angles.

In general, the absence of a significant difference between the mean and the median in the 4e graph indicates that there are not many extreme outliers, and we can support this assumption by looking at the standard deviation, which can be classified as moderate. This indicates that there is some difference in the data, but it is not extreme. In any case, we can point out that in general, the average mean is greater than the average median, which indicates that the big rotations are dominant, Although to a small extent, and this is normal because we aim to reach a state of congestion.

We find similar results in the case of the cross movement in the 4d and 4d graphs, but it must be pointed out that in general the difference in the rotation angles between the two directions is considered bigger than in the bi-directional movement. This is considered evidence that the type of movement has an effect on the rotation behavior and could be explained by the fact that the bi-directional system gives comfort to the participants in not executing many big rotations to avoid collisions because they have the ability to just follow each other and create a fixed path.

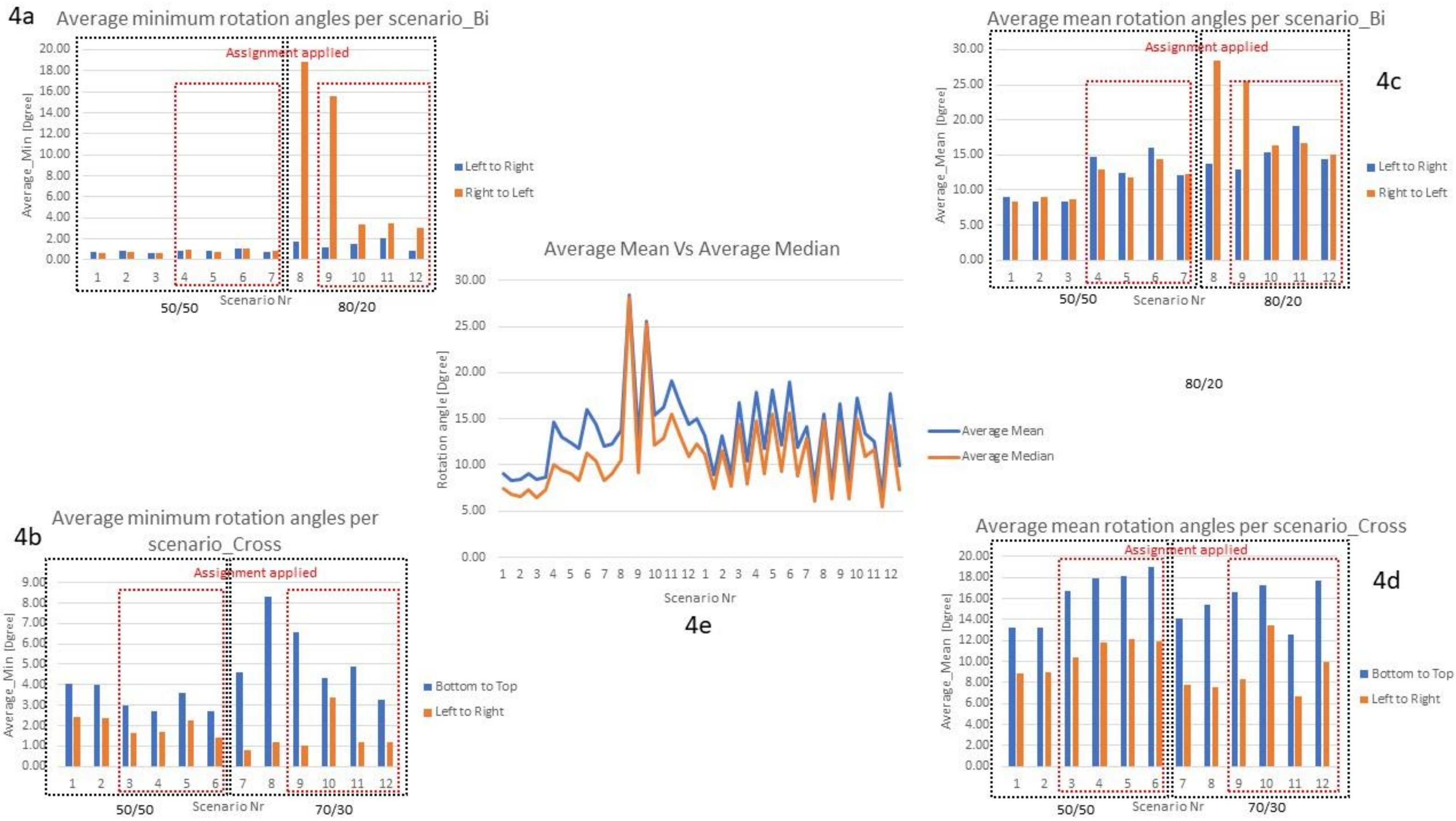

Figure 4: Statistical summary of rotation angles across scenarios whereby graphs a and b show the average min of the rotations per scenario, graphs c and d the average mean of rotations per scenario, and c compares the average mean with the average median per scenario

Figure 5 provides a comprehensive view of the findings across all scenarios we studied. In particular, the CDF and Proportions of Rotations vs. Density plots which serve as analytical tools to uncover patterns and relationships within the data, helping us draw meaningful conclusions about how shoulder rotation behavior relates to various pedestrian characteristics. let's dive into the details revealed by the graphs in this figure.

Graphs 5a and 5b showcase the distribution of rotations across these cases. Although the general shape of the distribution is quite similar, there are noteworthy distinctions among them. Particularly, we can observe that if we draw a verticle line from a 20-degree point on the x-axis the proportions of the angle below or equal to 20 degrees is between 70 and 90 percent of all measured angles for all scenarios which indicates that the majority of rotations are smaller than 20 degrees. As indicated by previous research, these small rotations likely do not stem from interactions with other pedestrians. Confirming this, annotations of pedestrians' shoulders in free-flow conditions show that rotations smaller than 20 degrees are probably not due to interactions with others *[11]*. Consequently, only rotations exceeding 20 degrees are considered in the subsequent analysis.

However, we can notice from Graph 5a that the probability of small angles is greater in the case of homogeneous flows 50/50 in the case of bi-directional movement than the ratio 80/20 (the blue, orange, and green lines have bigger proportions for smaller angles than the rest of the scenarios). This indicates that in homogeneous flows 50/50 there is no need for the some of participants to make many rotations to avoid collisions because the participants usually form fixed patterns of crossing forcing them to determine a general path for the crowd, which in turn leads to reducing the number of turns, which is difficult to form in the case of heterogeneous 80/20 flows due to the mass difference between the two groups. In contrast and from Graph 5b, in cross-movement, the probability of small angles is less in the case of homogeneous flows 50/50 than the probability of 70/30, and this explains that it might be difficult to form stable paths for crowds due to the cross-movement system in the case of homogeneous crowds 50/50, which prompts participants to make a lot of bigger rotations to avoid collisions, while the probability of this small angles increases when there becomes a clear difference in the flow 70/30 due to the possibility of a small number of people that the participants from the bigger group will encounter in a certain direction of movement or simply fewer people crossing a major flow, while in the 50/50 case, both groups are equally distributed.

It is also interesting that in the bi-directional movement, we can notice that the probability of small rotation angles increases when comparing Assignment C to Assignment B, regardless of the flow ratio. Based on this, we can say that increasing speed (Assignment C) leads to an increase in the probability of small rotations compared to random movements (Assignment B) within the crowd. It is natural that people who are speeding will generally tend to follow the shorter route, which will save them from changing their path of movement a lot and help them to create a fixed path by trying to follow each other. However, in cross-movement, the probability of small angles will be a bit close to each other in the case of 70/30 flows regarding Assignment C to Assignment B, which means that changing the type of task does not affect much in this case, but in the case of 50/50 flows, increasing the speed will reduce the probability of small rotations, and this may be a result of the Inability to create fixed paths.

In general, this suggests that while the fundamental pattern remains consistent, the way rotations are spread varies across scenarios.

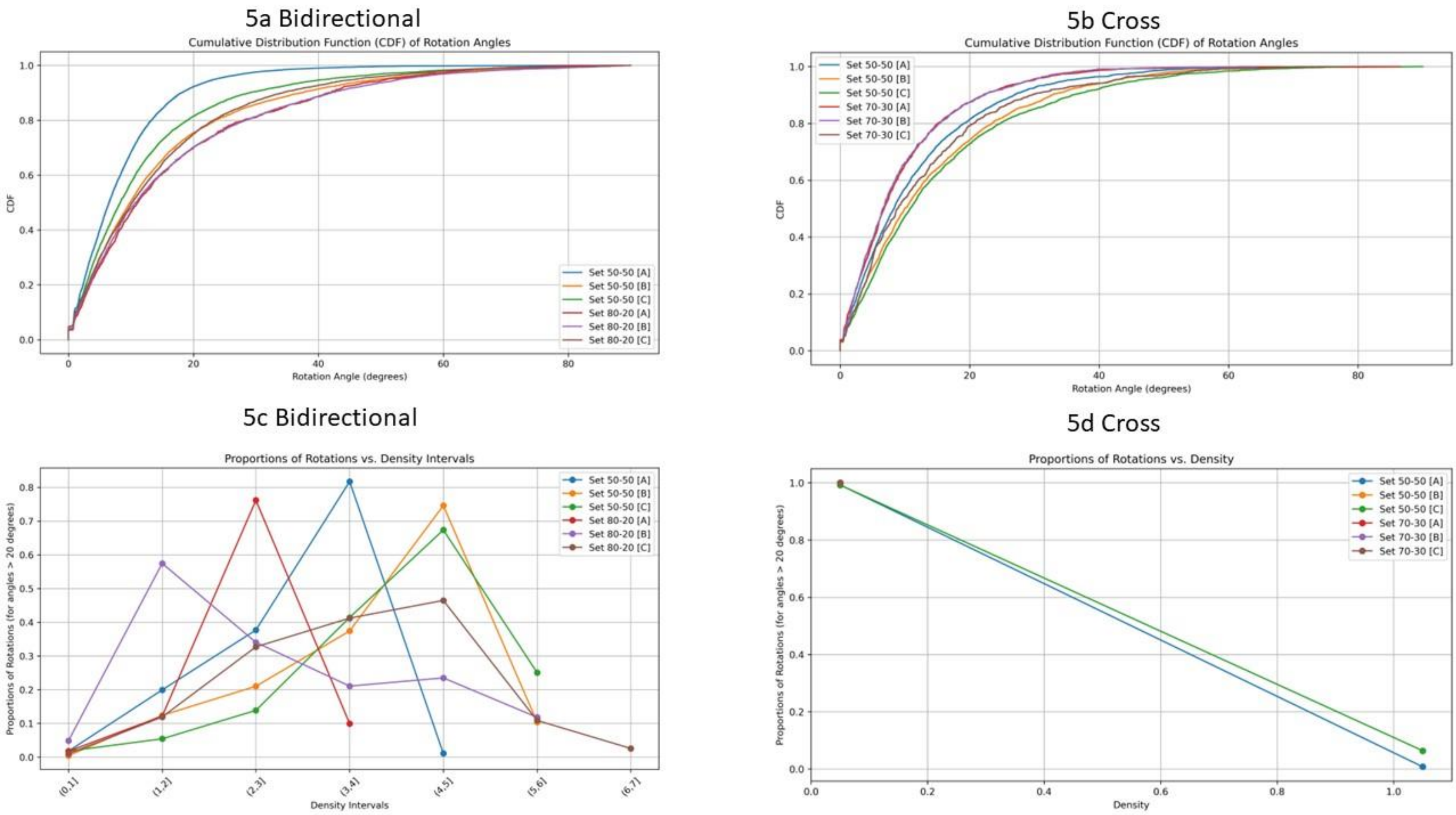

Figure 5: The results whereby graphs a and b show the cumulative distribution of the rotations per case and graphs c the proportion of rotations per density

Graphs 5c and 5d illustrate how the proportion of rotations exceeding 20 degrees correlates with global density. In the context of bidirectional movement, Graph 5c highlights variations across the scenarios. These differences appear in the relationship between rotations and density.

Both the 80-20 [A] scenario and the 80-20 [B] scenario show a minimal correlation between density and the frequency of rotations. However, it's evident that more individuals engage in rotations in the 80-20 [B] scenario. In contrast, the rest of the scenarios demonstrate some correlation with density, where the frequency of rotations increases with rising density. The strength of this correlation and the extent of rotations involved differ between these cases. in addition, we can clearly see that for all scenarios the proportions of rotation angles decrease when we start moving toward the congested case, and this is reasonable because in congested situations, people tend to not move or rotate much but instead just follow each other.

In summary, there are clear indications that in the bidirectional context, the assignment and the movement case significantly influence how often people rotate and how this relates to density.

In contrast, the disparities between the scenarios involving cross movement, as Graph 4d shows, are relatively minor.

In general, the number of rotations tends to decrease with higher density. Moreover, the distinctions among the cases are relatively small. The primary distinction lies in the range of densities observed, with the 50-50 [A] and 50-50 [C] scenarios having wider ranges compared to the other cases. This suggests that assignments may not have a clear impact on rotation behavior.

When comparing Charts 5c and 5d, it becomes evident that the underlying movement context significantly influences rotation behavior. For instance, both the frequency of rotations and the correlation of rotations with density show clear differences between the 50-50 [A] scenarios in cross-movement and bidirectional movement.

Figure 6 offers a comprehensive view of the findings across all scenarios, particularly regarding local density, also known as Voronoi density. Local density is a measure of how crowded or congested a specific area within the crowd is. It's calculated based on the division of the crowd into Voronoi cells, which are essentially individual spaces allocated to each person in the crowd. These cells adapt to the distribution of individuals, so dense areas have smaller cells.

Now, when we examine the data, we notice an interesting pattern, especially when comparing scenarios with bidirectional and cross flows. In the case of bidirectional flows, where people move in two opposite directions, we often observe much higher densities compared to the cross flows. This phenomenon can be explained by the nature of the movement. In bidirectional flows, individuals face each other while moving, leading to a higher likelihood of being in close proximity. This proximity means smaller personal spaces within the Voronoi cells, resulting in higher local densities. People are essentially navigating through a corridor, and as they move in opposite directions, they tend to occupy the available space more densely.

In contrast, in intersecting flows, individuals are often moving in different directions, and there might be more space between them. This leads to larger Voronoi cells and lower local densities since each person has a bit more personal space.

In general, the distribution of the points for all scenarios is scattered randomly without a clear pattern, so we can say that there is no clear or strong relationship between the rotation angle and the local density. But we can try to look at somewhat small or non-general patterns since we can say that in all the scenarios when the rotation angles start to exceed 20 degrees, the points start to be scattered more randomly than when the rotation angles are less than 20 degrees. This can tell us that when we have a high local density, meaning smaller personal spaces, people then tend to rotate less.

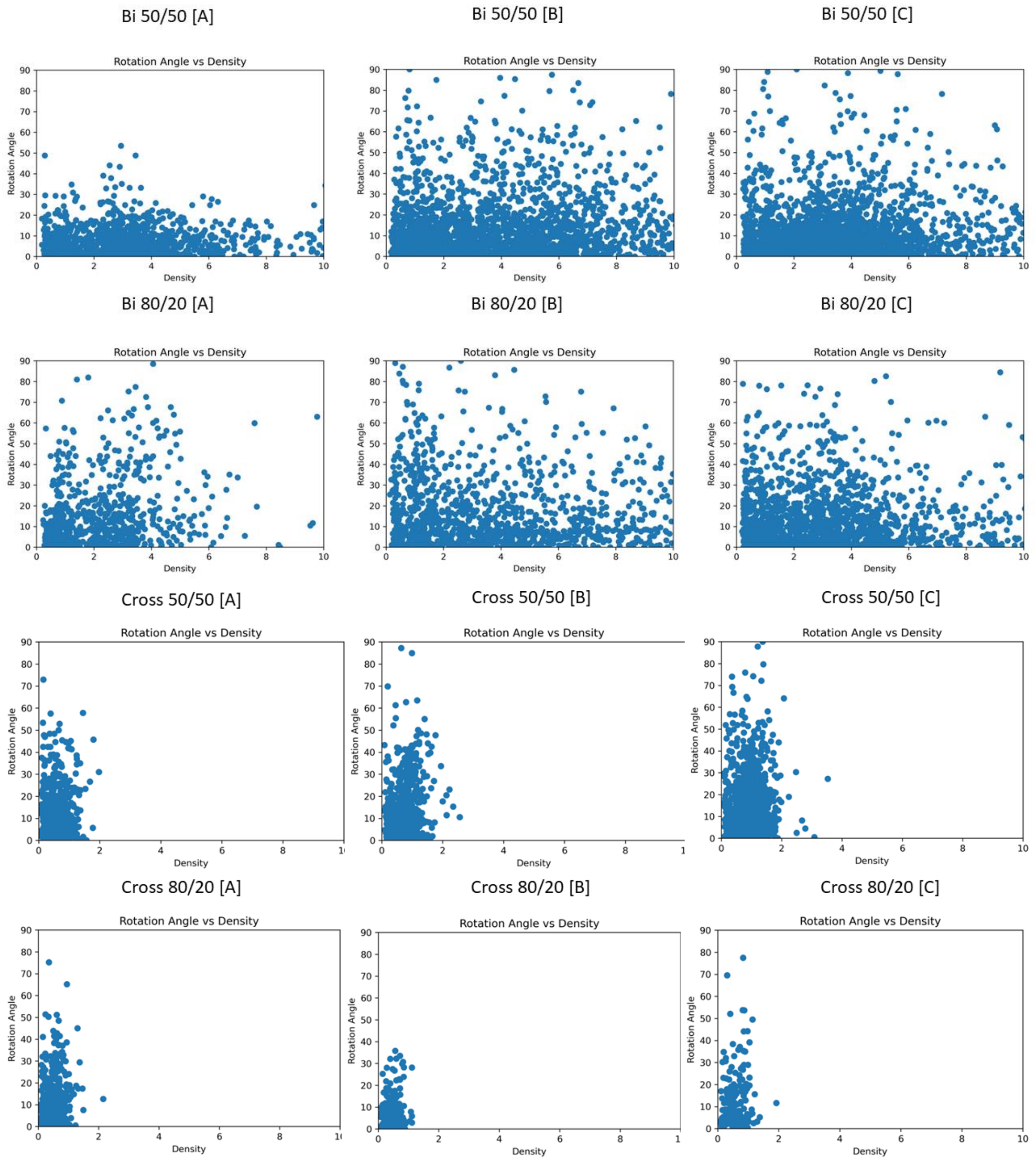

Figure 6 Comprehensive view of the findings across all scenarios regarding the local density

6 Conclusions

The findings from the CrowdLimits experiment provide significant insights into the dynamics of crowd behavior. This research dived into key factors: density, movement base case, flow ratio, disturbances, and assignments, highlighting their influence on the tendency of individuals to rotate their bodies when encountering conflicts within a crowd. However, it's crucial to acknowledge the study's limitations, which offer valuable directions for future research.

The results can be summarized as follows:

- The difference in Rotation Angles: A significant difference is observed in the minimum average rotation angles between the two scenarios: 50/50 bi-directional movement and 80/20 flow ratio. In 50/50 scenarios, rotations tend to be smaller, suggesting participants form fixed patterns and require fewer rotations to avoid collisions.
- Rotation Behavior and Flow Ratio: The results indicate that flow ratio plays a crucial role in rotation behavior. In the 80/20 scenario, where one group is significantly smaller, the larger group tends to make smaller rotations, except in Assignment B, which creates disturbances and forces both groups to perform similar rotations.
- Bi-Directional vs. Cross Movement: In bi-directional movement, participants show a greater probability of small angles in homogeneous 50/50 flows compared to 80/20 flows. In cross-movement, this trend reverses, indicating the difficulty of forming stable paths in homogeneous 50/50 flows.
- Assignment and Rotation Angles: In bi-directional movement, increasing speed (Assignment C) leads to more small rotations compared to random movements (Assignment B). In cross-movement, the type of task change has a minor effect.
- Correlation with Density: The relationship between rotation frequency and density varies across scenarios. In bidirectional movement, certain scenarios show minimal correlation, while others show a stronger correlation between rotations and rising density. In congested situations, rotations decrease as people tend to follow each other instead of rotating.
  The differences between scenarios involving cross-movement are relatively minor compared to bidirectional movement. The primary difference lies in the range of densities observed, suggesting that assignments may not have a clear impact on rotation behavior in cross-movement.
- Local Density: Generally, there is no clear or strong relationship between rotation angle and local density. However, when rotation angles exceed 20 degrees, points scatter more randomly, suggesting that in high local density situations with smaller personal spaces, people tend to rotate less. However, the differences in local densities between bidirectional and intersecting flows can be attributed to how individuals interact and move in these scenarios. Bidirectional flows often result in higher densities due to face-to-face movement, while intersecting flows allow for more spatial dispersion, leading to lower local densities.

While the study provides valuable insights, the limitation regarding assumed walking directions paves the way for future investigations aimed at refining our understanding of crowd dynamics. Incorporating real-time data on walking directions promises to yield even more comprehensive and accurate insights into human behavior in crowded environments.

Our key findings reveal that all these factors play a role in shaping the frequency of rotations within a crowd. However, the extent and precise conditions under which these factors influence this subject demand further in-depth research and exploration. Here are some specific suggestions for further study or experiments:

- Investigate whether different crowd types (e.g., concert audiences vs. commuters) react differently to varying densities.
- Analyze whether rotation behavior is influenced by the direction of pedestrian movement (e.g., clockwise vs. counterclockwise).
- Assess whether there are specific zones within these scenarios where rotations are more likely to occur.
- Examine whether changes in flow ratio over time impact rotation behavior dynamically.
- Explore the nature of disturbances that trigger rotations (e.g., sudden stops, collisions, or disruptive behavior).
- Investigate whether specific crowd management strategies, like crowd marshals or signage, influence rotation responses in disturbance scenarios.
- Assess how individual differences (e.g., age, gender, or familiarity with the environment) might moderate the impact of these factors.
- Investigate if there are daily or seasonal patterns in rotation behavior in real-world scenarios.
- Conduct comparative studies in various real-world settings (e.g., transportation hubs, sports events, or shopping malls) to generalize findings.
- Compare pedestrian rotation behavior in controlled experiments with observations in uncontrolled, naturalistic settings.

In conclusion, the CrowdLimits experiment highlights the multifaceted nature of crowd behavior. It emphasizes the importance of density, movement base case, flow ratio, and assignments as influential factors in shaping how individuals respond to conflicts within crowds.

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Appendix

Table 2: Statistical summary of rotation angles across scenarios

	Video Number	Movement Direction	Assignment	Average_Min	Average_Max	Average_Mean	Average_Median	Average_Std_Dev
BI 50/50	1	Left to Right	['A']	0.74	26.22	9.07	7.40	7.57
	1	Right to Left	['A']	0.62	27.51	8.33	6.83	7.01
	2	Left to Right	['A']	0.82	26.46	8.40	6.54	7.46
	2	Right to Left	['A']	0.77	27.07	9.00	7.27	7.67
	3	Left to Right	['A']	0.63	26.47	8.41	6.48	7.44
	3	Right to Left	['A']	0.69	25.80	8.64	7.29	7.30
	4	Left to Right	['B']	0.89	51.49	14.68	10.10	14.66
	4	Right to Left	['B']	0.94	44.09	12.97	9.48	11.99
	5	Left to Right	['C']	0.87	39.13	12.37	9.12	11.33
	5	Right to Left	['C']	0.72	42.16	11.76	8.36	11.36
	6	Left to Right	['B']	1.03	52.95	16.00	11.35	15.32
	6	Right to Left	['B']	1.11	48.76	14.44	10.44	13.50
	7	Left to Right	['C']	0.78	43.73	12.07	8.33	12.35
	7	Right to Left	['C']	0.91	43.34	12.29	9.02	12.20
BI 80/20	8	Left to Right	['A']	1.69	36.57	13.80	10.52	12.27
	8	Right to Left	['A']	18.83	38.41	28.40	28.16	14.71
	9	Left to Right	['B']	1.15	40.59	12.91	9.22	12.40
	9	Right to Left	['B']	15.58	36.29	25.52	25.37	14.66
	10	Left to Right	['C']	1.53	42.72	15.45	12.21	13.48
	10	Right to Left	['C']	3.37	43.33	16.28	12.94	13.52
	11	Left to Right	['B']	2.05	52.22	19.07	15.55	15.81
	11	Right to Left	['B']	3.47	43.84	16.70	13.34	13.49
	12	Left to Right	['C']	0.83	43.31	14.40	10.97	13.49
	12	Right to Left	['C']	3.08	41.31	15.04	12.31	12.60
Cross 50/50	1	Bottom to Top	['A']	4.06	27.14	13.19	11.14	10.71
	1	Left to Right	['A']	2.40	19.58	8.89	7.39	7.52
	2	Bottom to Top	['A']	3.99	26.63	13.21	11.57	10.05
	2	Left to Right	['A']	2.38	18.79	8.93	7.74	6.80
	3	Bottom to Top	['B']	2.96	36.56	16.75	14.44	13.07
	3	Left to Right	['B']	1.61	26.27	10.42	7.93	9.32
	4	Bottom to Top	['C']	2.70	42.75	17.92	14.73	14.69
	4	Left to Right	['C']	1.70	32.72	11.79	9.07	10.33
	5	Bottom to Top	['B']	3.58	40.99	18.11	15.56	13.96
	5	Left to Right	['B']	2.27	32.10	12.11	9.27	10.67
	6	Bottom to Top	['C']	2.72	45.54	19.04	15.62	15.73
	6	Left to Right	['C']	1.42	33.04	11.94	8.85	10.57
Cross 70/30	7	Bottom to Top	['A']	4.59	26.42	14.14	12.95	10.38
	7	Left to Right	['A']	0.80	21.93	7.81	6.08	6.98
	8	Bottom to Top	['A']	8.29	23.62	15.45	14.83	10.25

	8	Left to Right	['A']	1.17	17.76	7.55	6.38	5.93
	9	Bottom to Top	['B']	6.55	29.89	16.57	14.65	12.36
	9	Left to Right	['B']	1.01	23.56	8.35	6.37	7.51
	10	Bottom to Top	['C']	4.35	36.25	17.22	15.04	14.29
	10	Left to Right	['C']	3.35	34.20	13.39	10.88	10.57
	11	Bottom to Top	['B']	4.88	21.20	12.58	11.67	9.61
	11	Left to Right	['B']	1.16	16.73	6.68	5.49	5.33
	12	Bottom to Top	['C']	3.28	38.78	17.74	14.33	14.54
	12	Left to Right	['C']	1.18	30.41	9.89	7.32	9.38