

# The One-Man-Crowd: Single User Generation of Crowd Motions Using Virtual Reality – Supplementary material –

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## 1 INTRODUCTION

The aim of this supplementary material is twofold. First, in Section 2 we further detail results obtained in our experiments, by providing the complete set of trajectories for all the S2N and N2N datasets of the main material. Then, Section 3 provides some preliminary results on scenarios involving multilateral movement.

## 2 COMPLEMENTARY RESULTS

In this section, we provide the complete set of plots for all S2N and N2N datasets, compared with the real-world results of which we replicated the experiments.

### 2.1 Unidirectional Flow

Figure 1 presents the evolution of each pedestrian's position for the S2N (#1-#8) and N2N procedures of the Unidirectional Flow experiment, as well as example trajectories of real data [2], using the 1-dimensional description explained in our paper. We show the computed local maximum/minimum of speed and the result of their linear regression.

### 2.2 Bottleneck

Figure 2 presents trajectories generated by the S2N (#9-#16) and N2N procedures for the Bottleneck experiment, as well as example trajectories of real data [3]. The trajectories are coloured by the starting order of the pedestrians (dark blue for the first pedestrian, and bright yellow for the last). The real data does not contain information of neither starting position nor starting order.

### 2.3 Inflow Behaviour

Figure 3 presents the final position of each pedestrian as well as their order while entering the virtual lift, as generated by the S2N (#17-#25) and N2N procedures for the Inflow experiment, as well as real data for comparison [1]. We illustrate the personal space of each pedestrian at the end of each experience by the Voronoi cell based on their final positions. The personal zones are coloured by their area.

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Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: [reprints@ieee.org](mailto:reprints@ieee.org).  
Digital Object Identifier: xx.xxx/TVCG.201x.xxxxxx

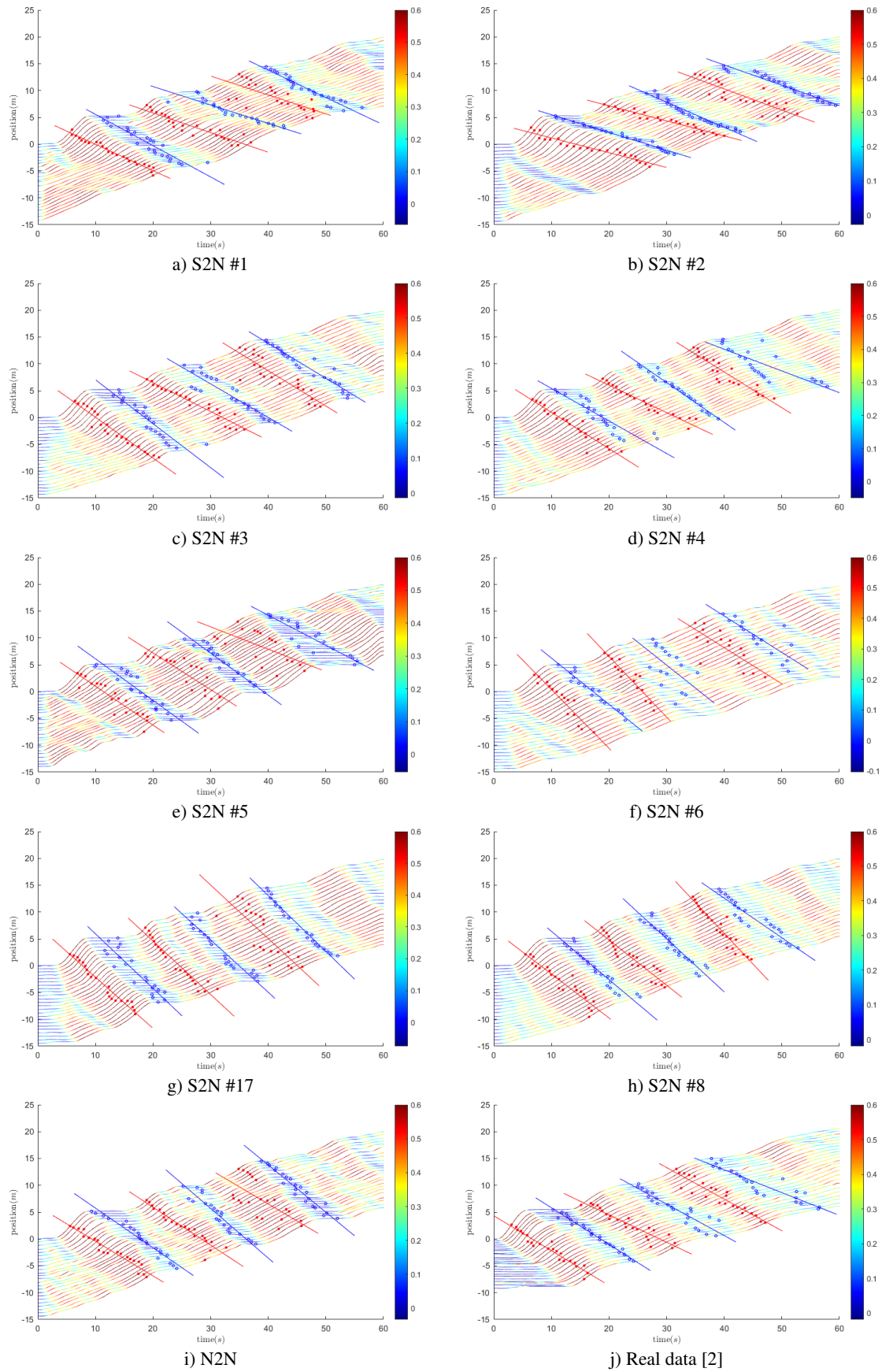


Fig. 1. Unidirectional flow scenario: evolution of pedestrians' position and the results of linear regression.

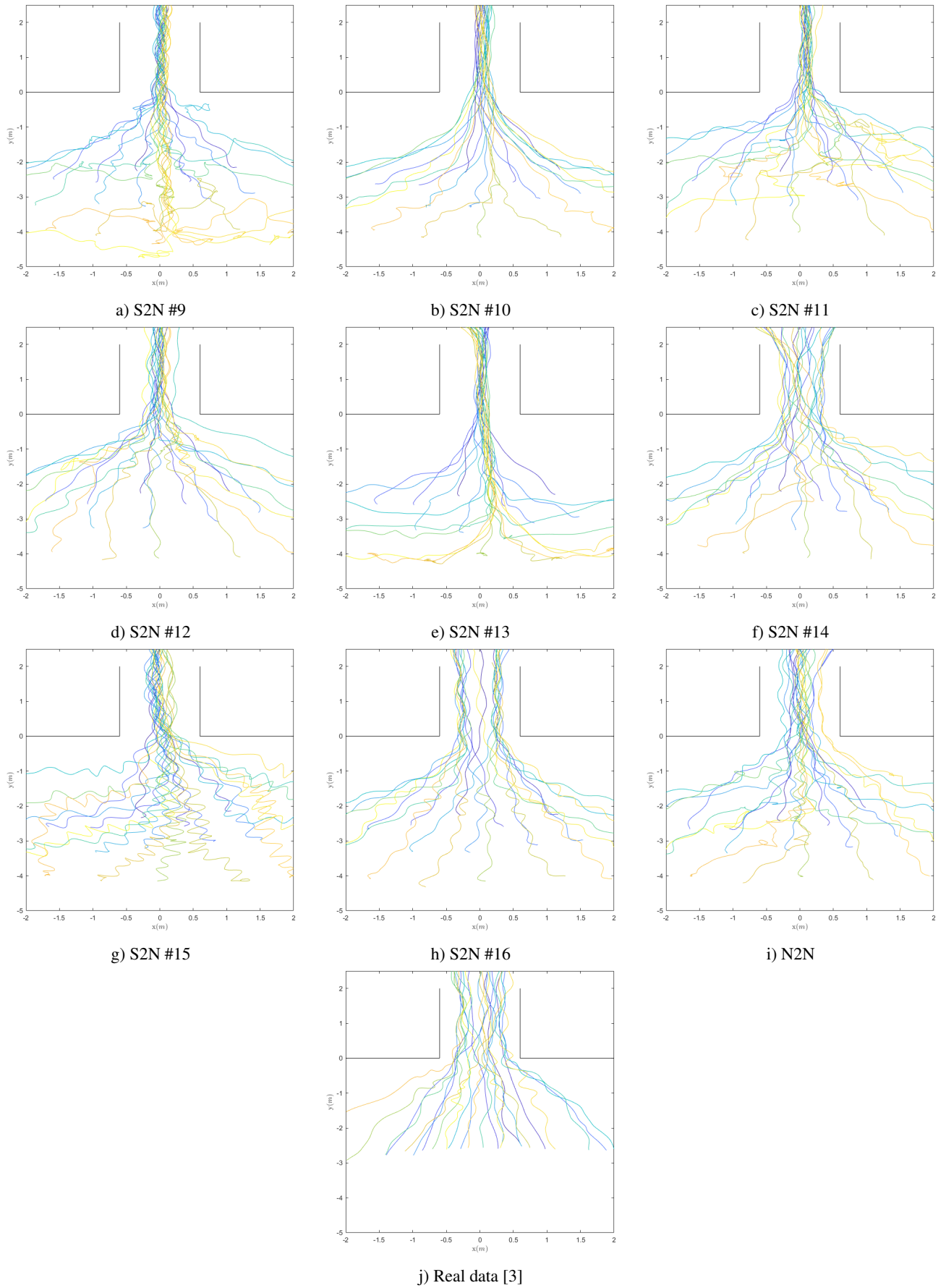


Fig. 2. Bottleneck scenario: trajectories of each (virtual) pedestrian.



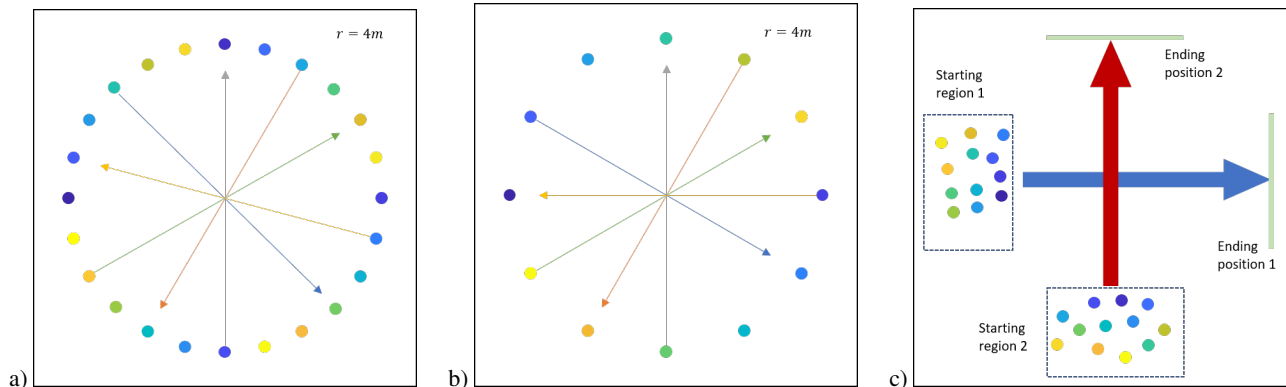


Fig. 4. Configuration of the preliminary experiments. Black squares delimit the  $10 m \times 10 m$  experimental ground. Each dot represents the initial position of a character, indicating the starting order. The first to start is coloured by dark blue, while the last is coloured by bright yellow. The arrows indicate the direction of each character. a) Configuration of Circle-24 and b) Circle-12, where participants are instructed to walk to the position diagonally opposite in the circle. c) Configuration of the crossing flow virtual experiment, the initial positions in each starting zone are generated by a Poisson distribution.

### 3 PRELIMINARY EXPERIMENT ON MULTILATERAL INTERACTIONS

In this work, we prioritised replicating unilateral interactions in an attempt to demonstrate the potentialities of OMC, while a failure to reproduce them would obviously have invalidated the paradigm, including cases of bilateral or multi-lateral interactions. In this document we present our preliminary attempts at exploring more complex multi-lateral scenarios, in order to draw preliminary insights about potential asynchrony biases due to the unilateral interaction inherent to the current OMC approach in such situations. We therefore designed 3 different scenarios which specifically involved multi-directional movements to plan the trajectories. The experimental setup was the same than the one of the experiments presented in the main paper. These preliminary results are however only reported for the S2N approach and with only 1 participant involved.

#### 3.1 Overview

##### 3.1.1 Tasks

We designed three virtual scenarios to explore the problem of multi-lateral crowd movements: one crossing flow situation and two circle crossing movements with different numbers of agents but 1 participant.

**Circle-24.** This scenario was designed to study multi-lateral interactions. In this scenario, 24 agents are uniformly spaced out on a circle (radius:  $4 m$  – see Figure 4-a). The goal of the participant is to reach the opposite side of the circle, without colliding with any other agent. Participants are asked to act all the 24 characters present on the circle, starting from the agent on the position  $(-4, 0)$ . Then, the participant always act the 6th neighbour on their right hand side, skipping it if it was already embodied.

**Circle-12.** This scenario was designed as a controlled experiment to Circle-24, to study the effect of density. The task is exactly the same than in the Circle-24 scenario, except that the number of virtual characters is reduced to 12 so that each virtual character can have more space for its movements (see Figure 4-b). The starting order is decided in the same way than Circle-24.

**Crossing Flow.** This scenario was designed to study the performance of OMC during crossing flows. In this scenario, 24 virtual characters are equally divided into 2 groups. The two flows cross around the centre of the virtual scene at a 90-degree angle (see Figure 4-c). The participant is asked to act alternatively one character of each group, until he has acted all 24 characters. The participant is instructed to traverse the virtual room and to reach the ending position, while avoiding any collision with the other virtual characters. The participant alternates

trials involving characters starting from a different starting region (i.e., from one of the two groups of characters). For each group, the starting positions were randomly generated by a Poisson distribution, and the virtual characters are acted by participants in the order of increasing initial distance towards the centre of the scene.

##### 3.1.2 Participant

As we were interested in preliminary insights about how OMC would behave with multi-lateral interactions, only one naive participant participated in this preliminary study, and performed the three scenarios. It is important to note that only one participant performed the experiment due to time constraints. Our main focus is to explore the nature and importance of artefacts we may encounter in multi-lateral interactions, in preparation for larger scale experiments. For the same reason, our analyses are not statistical.

##### 3.1.3 Preliminary Questions

As this experiment is only preliminary, our main goal is to study how the multi-lateral movements tend to influence the OMC paradigm. Our questions are thus related to the feasibility of complex crowd movements and local reactions of the participant.

- **Q1:** In the multi-lateral movements, the participant needs not only to react to the virtual characters in the front, but also to pay attention that virtual characters may come from his lateral direction, and even from behind. In this case, can the participant generally complete the creation of crowd scenario without colliding with virtual characters?
- **Q2:** During the experiment, as the participant successively embodies as different character, he will have to interact with more and more moving characters. Will this continuously increase the difficulty for the participant to perform collision avoidance? Will the participant have to gradually increase the complexity of his movement?
- **Q3:** The difficulty of generating multi-lateral crowd movement can be influenced by both the number of interactions and their directions. Do these two factors have equal level of impact to the generating procedure?

#### 3.2 Circle-24 & Circle-12

To maximize the use of collected data, we have adopted a cross-comparison method to extract as much information as possible from the experimental results. As Circle-12 is a simplification of Circle-24, we present their results together.



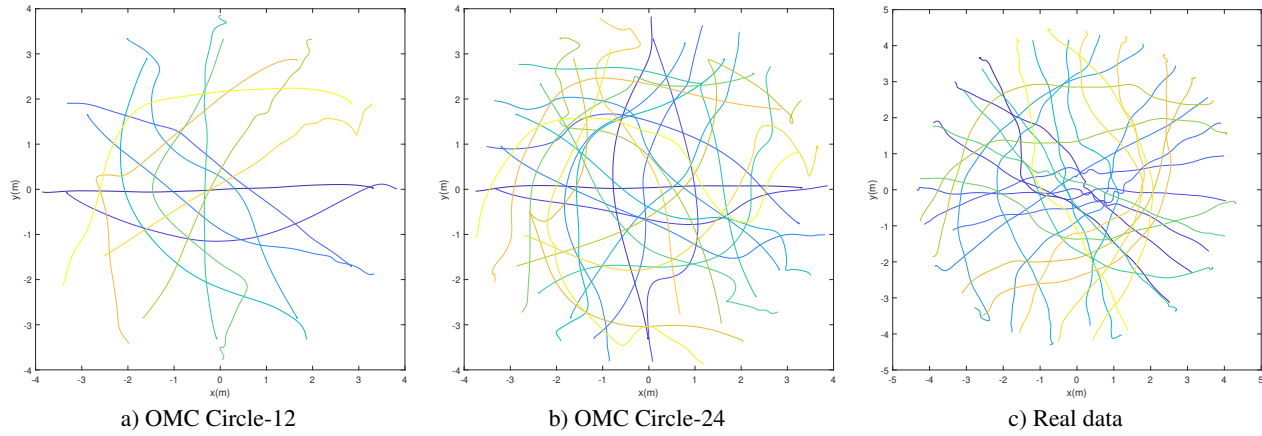


Fig. 5. The generated trajectories, coloured with respect to the starting order from dark blue (first to move) to bright yellow (last to move).

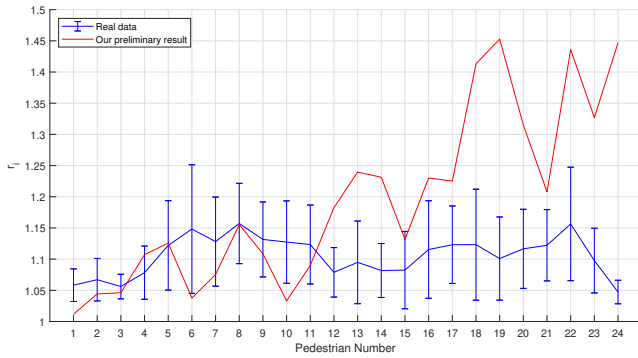


Fig. 6. Ratio between the distance that the participants walked and the distance between the starting and ending positions, depending on the trial number, compared to real-world result. The real-world result is averaged over 21 data. Note that in the real-world case, the pedestrians walked simultaneously, and their number are not order-dependent. In our preliminary, on the contrary, the pedestrian number is bind to the trial number.

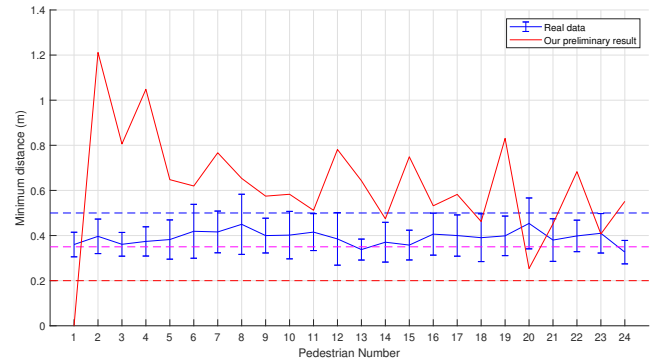


Fig. 7. The shortest distance to other that each pedestrian has had during the experiment. The real-world results is averaged over 21 data. The dashed lines highlight 3 important level of distance. The blue dashed line indicate the distance where 2 pedestrians are very close. The magenta dashed line indicates the emergence of slight touch. For the real condition, the red dashed line indicates collision, whereas in the virtual environment, this would indicate severe interpenetration between the participant's avatar and a virtual character

### 3.2.1 Trajectories

In Figure 5 we compare two sets of trajectories generated with OMC (Circle-12 and Circle-24), with data from real experiments.

**Circle-24.** From the trajectories displayed in Figure 5-b, it appears that the participant adopted two entire different strategies. More specifically, we can see that early trials use a strategy going through the centre of the circle, while in later trials he adopted longer trajectories, enabling him to circle around the centre and therefore to limit the quantity of interactions in this area. We hypothesise that the difference in strategies is due to the increase of collisions happening with the increase of characters moving in the scene in such a complex situation. However, it is also important to mention that both types of strategies were also observed in real experiments (Figure 5-c), where we can see that some agents (possibly moving faster) went almost directly to their destination through the centre of the circle, while others (possibly starting later) displayed more indirect trajectories.

**Circle-12 vs. Circle-24.** The Circle-24 scenario was supposed to be more difficult than the Circle-12 scenario with doubled density. We can see that the participant adopted similar trajectories for both scenarios, even though with less trajectories going around the center in the Circle-12 situation, as can be observed from Figures 5-a & -b.

### 3.2.2 Behavioural Complexity

As shown in Figure 6, the behavioural complexity continued to increase during the experiment. An important common phenomenon of the three experimental results is that the first pedestrian always walked directly towards his goal, leading to an almost straight first trajectory (dark blue horizontal trajectories). As the number of trials increases, the global shape of trajectories becomes more and more complex. We can estimate behavioural complexity of each trial  $i$ , through the distance ratio  $r_i$ :

$$r_i = d_i / \|\mathbf{p}_i\| \quad (1)$$

where  $d_i$  is the distance that the participant walked through during the trial  $i$ , and  $\mathbf{p}_i$  is the vector from the starting position and the ending position. We present the evolution of behavioural complexity in Figure 6. As the number of moving virtual pedestrians increases, the behavioural complexity presents a clear tendency of increasing, both for the Circle-12 and Circle-24 scenarios.

### 3.2.3 Collisions

We detected collisions between the participant and the virtual characters through post-processing of the generated data. Specifically, we calculated the shortest distance between the participant and every moving characters during the trial time. As shown in Figure 7, the participant was generally successful to keep relative large distance to all the moving characters and only had slight touch with them during the trial 20,

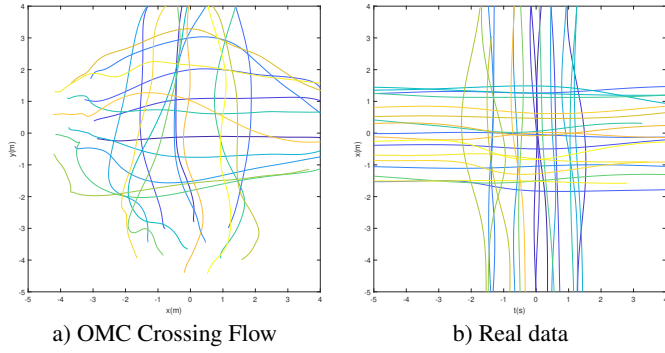


Fig. 8. Generated trajectories for the Crossing Flow scenario, coloured with respect to the starting order from dark blue (first to move) to bright yellow (last to move). a) Results generated by the participant using OMC. b) Real-world result.

where he needed to react to 19 moving characters. Severe interpenetration was not observed (geometries did not fully interpenetrated).

### 3.2.4 Discussion

Through this preliminary experiment, our goal was to further explore 1) if participants can successfully achieve the task without colliding with agents, 2) how increasing complexity of the scene might influence the participant's strategies, and 3) how the complexity of the scenario might influence the participant's behaviour as well. Even though we cannot draw any decisive conclusion due to the preliminary nature of the experiment, the trajectories captured with OMC highlight interesting features and tendencies which are consistent with real observations. We observed that the participant adopted both direct (i.e., going through the centre) and indirect (larger curved trajectories, avoiding the centre) for both Circle-12 and Circle-24. Of course, this choice of strategies might be relative to participants' individual preferences. In terms of the behavioural complexity, we observe that the participant made more and more complex behaviours during the procedure. A naive explanation of the situation is that, as more and more virtual pedestrians moved in the scene, he needed to make more and more effort to avoid colliding with pedestrians from each direction. Meanwhile, the occlusion among the characters made it more difficult to predict which character was going to be where. Surprisingly, even with such difficulties, the participant accomplished the experiment without barely colliding with any virtual character. Although more participants would be required to conclude whether the answer to **Q1** can be positive, this preliminary result suggests that the OMC paradigm can handle scenarios of multi-lateral movement, including complex ones **Q3**. The observation of Figure 6 is likely to lead us to a confirmatory response of **Q2**.

## 3.3 Crossing Flow

Similarly to the Circle-12 and Circle-24 scenarios, we analyse the trajectories and behavioural complexity.

### 3.3.1 Trajectories

Figure 8 shows the trajectories generated by the participant. Different from real-world situation, the participant has shown a strong preference on the strategy of detouring the centre of the virtual scene (i.e. the friction zone) by adopting large curved trajectories going through the edges of the scene. We can observe that in the real-world experiment, the shapes of the two flows were basically consistent during the whole crossing. Although the large motion strategy in our result can also be observed in the real case, its emergence is less frequent and the motion is less amplified.

### 3.3.2 Behavioural Complexity

As previously, we estimated the participant's behavioural complexity during each trial using Equation 1. The results are presented in Figure 9, and show that the behavioural complexity stayed at a low level for the

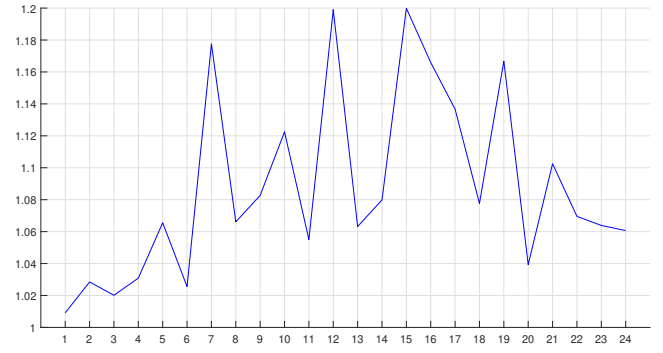


Fig. 9. Ratio between the distance that the participants walked and the distance between the starting and ending positions, depending on the trial number, for the Crossing Flow scenario.

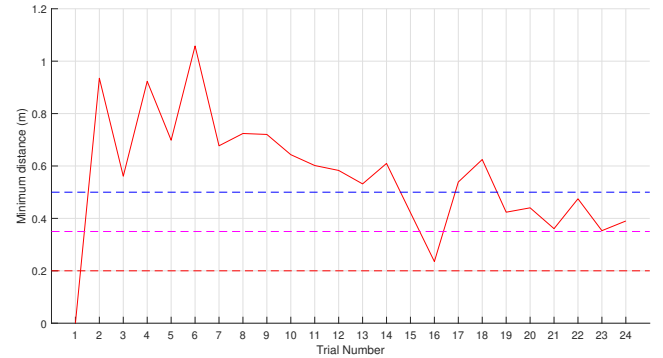


Fig. 10. The shortest distance to other that each pedestrian has had during the experiment. The dashed lines highlight 3 important level of distance. The blue dashed line indicate the distance where 2 pedestrians are very close. The the magenta dashed line indicates the emergence of slight touch. For the real condition, the red dashed line indicates collision, whereas in the virtual environment, this would indicate severe interpenetration between the participant's avatar and a virtual character

first four trials. Afterwards, it evolved in a peak-valley manner, while slowly increasing on average.

### 3.3.3 Collision

Again, we calculated the shortest distance between the participant and any moving characters during each trial. A close touch has been detected during the trial 16 (Figure 10) where the participant needed to react to 15 characters (8 characters coming from lateral side, as well as 7 characters moving in the front). This might be a chained reaction after the slight touch happened during the trial 15, where we observe a peak of behavioural complexity (Figure 9). Interestingly, no other collision happened during the following trials.

### 3.3.4 Discussion

In the crossing flow scenario, multiple agents walk through the centre of a virtual scene from two fixed direction, at a 90° angle. The participant therefore need to react to the movement of the agents in front of them, as well as to those coming from their lateral side. As the participant's moving speeds are limited by the agents in front of him, different agents will arrive at the crossing zone at different time and will there need to perform local collision avoidance. This might explain the shape of the participant's behavioural complexity plot shown in Figure 9. Meanwhile, the difficulty of collision avoidance increased during the generation of more agents' movements. One light collision happened during the experiment, but its influence remained to be local. Although the strategy of large trajectories and detouring the friction zone through the edge of the virtual room, the participant's performance gave out a positive response for **Q1**. For **Q2**, the difficult of collision avoidance

did increase, but the participant still managed to finish the experiment without barely no collision. The complexity of his behaviour, however, did not continuously increase.

### 3.4 Conclusion

In this preliminary experiment, we explored three scenarios to give us insights about the ability of OMC to handle complex situations that involve dense, multi-lateral, interactions. The scenarios can be classified as two category:

- 1) Crowd scenario with multiple directions (Circle).
- 2) Crowd scenario with two main directions (Crossing).

Our experimental results show that even the introduction of multi-lateral interactions make the participant's task more difficult, it is still possible to create such crowd movements using the One-Man-Crowd paradigm. In both of the cases, the participant finished the scenario without interpenetrating (or in a very light way) with virtual agents. This leads us to a positive answer to question **Q1**. In addition, in both of the scenarios, we observed that the difficulty of keeping large distance to all of the moving characters continuously increased. In terms of the behavioural complexity, we have however observed that, in the scenario of *Crossing Flows*, the behavioural complexity of the participant seems to be limited in an specific region. This resulted in a positive answer to **Q2**, with a nuance about the progressive increasing of behavioural complexity. Meanwhile, this might imply that the number of directions and the number of interactions do not have the same impact to the generating procedure: the number of direction has shown to have more impact (**Q3**).

In terms of the behavioural variety which has been a major focus of the principle material, we have different observations between the *Crossing Circle* and the *Crossing Flow* scenarios. In the *Crossing Circle* scenario, the participant has generated a set of trajectories with various different movements, which can also be observed in real cases. In the *Crossing Flow* scenario, the lack of behavioural variety has led to a individual-specific result, which is unrealistic. It is thus interesting to evaluate the use of local adjustments for the movements that have already been recorded, to improve the interactivity of the generated crowds, and reduce the frequency of generating individual-specific trajectories. More explorations need to be conducted in this direction.

There are several things that we need to improve before conducting further formal researches. First, we have observed that our participant walks directly to the target position during the first trial, which is relevant since the movement of other agents is not there yet. This may raise the need to generate some initial agents' motion before the participant embody them, based on a simulation technique for example. Second, the real-world multi-lateral flow experiments are usually carried out in large space to enable a large number of pedestrian to walk. Our current experimental setup only covers a  $10\text{ m} \times 10\text{ m}$  space, which may be insufficient to replicate any real-world experiment. To carry out further experiments, we might need to perform technical improvements to resolve the physical restrictions.

### REFERENCES

- [1] T. Ezaki, K. Ohtsuka, M. Chraibi, M. Boltes, D. Yanagisawa, A. Seyfried, A. Schadschneider, and K. Nishinari. Inflow process of pedestrians to a confined space. *Collective Dynamics*, 1:1–18, 2016. doi: 10.17815/CD.2016.4
- [2] S. Lemerrier, A. Jelic, R. Kulpa, J. Hua, J. Fehrenbach, P. Degond, C. Appert-Rolland, S. Donikian, and J. Pettré. Realistic following behaviors for crowd simulation. *COMPUTER GRAPHICS FORUM*, 31:489–498, 2012. doi: 10.1111/j.1467-8659.2012.03028.x
- [3] J. Liddle, A. Seyfried, W. Klingsch, T. Rupperecht, A. Schadschneider, and A. Winkens. An experimental study of pedestrian congestions: influence of bottleneck width and length. *arXiv preprint arXiv:0911.4350*, 2009.