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K. Ramachandra Rao
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Traffic and Granular Flow '22

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Traffic and Granular Flow '22

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Preface

The fourteenth edition of the Traffic and Granular Flow (TGF) Conference was held for the first time in South Asia, India during 15-17 October 2022. IIT Delhi is honoured to host this edition of the prestigious conference series. Like before, we hope to continue the rich tradition of TGF, which has grown over the years as a confluence and intersection of various disciplines of traffic low—vehicles and pedestrians, and granular media. These are the proceedings of this edition.

Due to the challenges imposed by the COVID-19 pandemic, this conference was held in a hybrid mode. The conference had around 120 high-quality presentations from 20 different countries in podium and poster sessions both in person and online. There are 62 full articles included in this edition of the Proceedings in the three broad areas of, a) Cities, vehicular traffic and other transportation, b) Pedestrian dynamics, c) Granular and active matter.

This conference would not have been possible without the unwavering trust and faith imposed by the TGF Scientific Committee on us. We are grateful to the local organising committee and the advisory committee for making this conference a reality. Notable mention for those of our colleagues, Geetam Tiwari, Rajib Basu Mallick, A.K. Swamy, Manoj M., and Nezamuddin. Special thanks goes out to Sai Chand and Mohit Kumar Singh for their unwavering, tireless, and continuing support till date on all the aspects of the conference. We missed the presence of Dinesh Mohan, our philosopher, mentor, friend, and well-wisher, who is no more. The active support of the PhD students of Transportation at IIT Delhi, with their effervescence and high energy levels, has helped us all through. The following deserve a special mention: Krishnan K.N., Mehraab Nazir, Tarapada Mandal, Debashis Ray Sarkar, Yawar Ali, Abhishek Bansal, Najib Karimi, Mustansir Farooq, Avaratanu Roy, Piyush Lalwani, Deotima Mukherjee, Priyanshu Aman, Poonam Adusule and Vamsi Krishna. The logistics support of Diya Walia (Conference Manager) and Mahesh Gaur is highly appreciated. The Springer Nature office of Delhi, particularly Priya Vyas and her colleagues, have helped us with the publishing aspects. We are grateful to Springer Nature for continuing their support to bring out the proceedings of TGF22 as in the past several editions. We eagerly look forward to the next edition (fifteenth) of the Traffic and Granular Flow conference series returning to Europe. This will be

organised by Nicolas Bain, Angelo Furno, Alexandre Nicolas and Osvanny Ramos in Lyon, France, in 2024.

New Delhi, India — K. Ramachandra Rao
Jülich, Germany — Armin Seyfried
Cologne, Germany — Andreas Schadschneider

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Part I
Pedestrian Dynamics

Collective traffic of agents that remember

Danny Raj M and Arvind Nayak

Abstract Traffic and pedestrian systems consist of human collectives where agents are intelligent and capable of processing available information, to perform tactical manoeuvres that can potentially increase their movement efficiency. In this study, we introduce a social force model for agents that possess *memory*. Information of the agent's past affects the agent's instantaneous movement in order to swiftly take the agent towards its desired state. We show how the presence of memory is akin to an agent performing a proportional–integral control to achieve its desired state. The longer the agent remembers and the more impact the memory has on its motion, better is the movement of an isolated agent in terms of achieving its desired state. However, when in a collective, the interactions between the agents lead to non-monotonic effect of memory on the traffic dynamics. A group of agents with memory exiting through a narrow door exhibit more clogging with memory than without it. We also show that a very large amount of memory results in variation in the memory force experienced by agents in the system at any time, which reduces the propensity to form clogs and leads to efficient movement.

Keywords: Memory, Agent based models, Jamming behaviour, Faster is slower effect, Collective motion

1 Introduction

The ability to think is a key distinction between agents in human collectives, like vehicular and pedestrian traffic flows [1, 2, 3, 4], and granular collectives [5, 6], which are made up of grains that respond and move only to external forcing. Therefore, when one writes down a set of governing equations either in the form of rules of

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interaction or social forces, it is important to specify those that distinguish a living agent from one that is non-living. It would be an interesting problem to explore how this distinction manifests in the dynamics of the collective. Since a comprehensive model for human cognition (or thinking) is incredibly hard to formulate, we adopt a bottom-up approach where we investigate how a certain facet of intelligence affects the collective dynamics.

One of the key characteristics of a living agent is its ability to assimilate information, process it and alter the agent's decisions based on it. A critical aspect in this process is the agent's memory. An agent can remember its past actions and change its current actions accordingly to achieve better performance. Memory of an agent can affect the dynamics across several time scales: from learning route-specific rules over several days and months, to remembering its recent trajectory and reacting to immediate changes in the environment/jams. Here, we concentrate on the latter. We develop a social force model for the memory of an agent based on its past movement. Remembering how it moved in the recent past, the agent evaluates how well it has achieved its desired velocity and takes a tactical decision—to make up for the sub-optimal past movement.

In this article, we introduce a social force model for agents that exhibit memory. Memory is characterised by two parameters: *i*) how long the agent remembers and, *ii*) impact of memory on the movement. We first analyse the model equations to understand the impact of memory on the dynamics of an isolated agent. Then, we proceed to test the effect of memory on the collective. We simulate agents attempting to exit via narrow door where agents are known to exhibit clogging behaviour near the exits. Our objective is to understand how memory aids in the collective motion: Does the presence of memory always guarantee efficient movement? How does it impact the propensity to form or displace agents in a clog?

2 Model for traffic dynamics

2.1 Agents with memory

The motion of agents is modelled using a social force model, similar to Helbing et al [7, 8, 9]. The velocity of an agent evolves in time based on Eq 1, where: *i*) the first term in the RHS is the restitution force that restores the agent to its desired direction and speed $\mathbf{v}_0$, *ii*) the second term is the force due to the effect of the memory of an agent and, *iii*) the third term $\mathbf{I}^i_{j,b}$ is the net social interaction of the agent to avoid collision with other agents and the boundary.

$$m\frac{d\mathbf{v}_i}{dt} = \frac{m}{\tau}(\mathbf{v}_0 - \mathbf{v}_i) + \tilde{\beta}\mathbf{M}_i + I^i_{j,b} \tag{1}$$

Here, the memory $\mathbf{M}_i(t)$ of an agent i at time t, is defined as the total deviation of the velocity of the agent from its desired velocity $\mathbf{v}_0$ in the time window $[t-T, t]$ of the agent's recent past (see Eq 2).

$$\mathbf{M}_i = \int_{t-T}^{t} \left(\mathbf{v}_0 - \mathbf{v}_i(t')\right) dt' \tag{2}$$

When the agent is unable to travel at its desired speed and direction, the memory term takes a positive value and offers an additional force to help restore the agent's motion sooner.

$$I^i_{j,b} = \sum_{\forall j \in \mathcal{N}_i} \left[\mathbf{F}^n_{i,j} + \mathbf{F}^t_{i,j}\right] + \mathbf{F}^n_b + \mathbf{F}^t_b \tag{3}$$

The term $\mathbf{I}^i_{j,b}$ can take different forms depending on the context of the traffic problem. For pedestrian dynamics [8], Helbing and co-workers considered interaction forces similar to that used in granular flows: a sum of the total normal and tangential (frictional) forces due to contact. However, $\mathbf{I}^i_{j,b}$ can also include small-ranged forces that prevent collisions [9], which are more suitable for traffic flow problems. The qualitative results shown in the paper do not depend on the exact choice of the models for interactions.

2.2 Connections to control theory

If one were to imagine $\mathbf{v}_0$ as the set-point for a given agent, *i.e.*, the desired *state* that the agent wants to achieve, then the restitution force and the memory term in Eqs 1 and 2, exactly resemble a proportional and an integral parts of a controller (PI), respectively. Presence of an integral component can result in overshoots and oscillations before the agent reaches its set-point. In the absence of memory and when there are continuous collisions with obstacles as agents move, we can expect the dynamics of the agent to show an offset (not reach $||\mathbf{v}_0||$)—since, it is well known that a proportional controller cannot take the system exactly to its set-point. Addition of memory could guarantee reaching the set-point, even in the presence of obstacles.

One could also conceive a dynamics resembling a PID controller. This modification does not qualitatively change the dynamics of the system. Since, adding a derivative term for the deviation $\mathbf{v}_0 - \mathbf{v}_i$, gets absorbed into the inertia (LHS term of Eq 1). In other words, the derivative term acts like an effective *mass* term that slows the response of the agent to any social force.

2.3 Memory as a state of the agent.

The memory term in Eq 2 is computed within a time window of $[t - T, t]$. Any information from outside the time window is not used and all the information within are equally weighted. A simpler and more elegant formulation can be arrived at, if we weight the information with an exponential weighting as shown in Eq 4.

$$\mathbf{M}_i = \int_0^t e^{\frac{t'-t}{\tilde{\alpha}}} \left(\mathbf{v}_0 - \mathbf{v}_i(t')\right) dt' \tag{4}$$

An exponential weighting prioritises information close to the current time instant than from a distant past. This allows us to move away from a discontinuous time window set by T and towards a time scale $\tilde{\alpha}$. Then, we can differentiate Eq 4 with time, using the Leibniz rule for differentiating under the integral sign to get Eq 5.

$$\frac{d\mathbf{M}_i}{dt} = \mathbf{v}_0 - \mathbf{v}_i - \frac{\mathbf{M}_i}{\tilde{\alpha}} \tag{5}$$

This allows us to convert the memory term, which was previously an integral, into a dynamic state of the agent. Eq 5 describes the evolution of this memory-state of the agent: $\mathbf{v}_0 - \mathbf{v}_i$ serves as the instantaneous source for the memory while $-\frac{\mathbf{M}_i}{\tilde{\alpha}}$ is the rate at which memory decays.

3 Results and Discussion

3.1 Dynamics of a single agent

The equations for the dynamics of an isolated agent, far away from the boundary, can be written compactly as in Eq 6. This is after: *i*) the governing equations in Eq 1 are scaled (t with τ, $||\mathbf{v}||$ with $||\mathbf{v}_0||$, $||\mathbf{M}||$ with $||\mathbf{v}_0||/\tau$), *ii*) the interaction terms are dropped and, *iii*) the scaled memory parameters become $\alpha = \tilde{\alpha}/\tau$ and $\beta = \tilde{\beta}/m$.

$$\frac{d}{dt}\begin{pmatrix} v_x \\ v_y \\ M_x \\ M_y \end{pmatrix} = \begin{pmatrix} -1 & 0 & \beta & 0 \\ 0 & -1 & 0 & \beta \\ -1 & 0 & -\frac{1}{\alpha} & 0 \\ 0 & -1 & 0 & -\frac{1}{\alpha} \end{pmatrix} \times \begin{pmatrix} v_x \\ v_y \\ M_x \\ M_y \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} \tag{6}$$

To understand the effect of memory (α and β) on the movement characteristics of a single agent, it is enough to look at the eigen values of the matrix in Eq 6. The eigen values are $\frac{1}{2\alpha} \times \left[-(\alpha + 1) \pm \sqrt{-4\alpha^2\beta + \alpha^2 - 2\alpha + 1} \right]$, repeated twice. Analysing the eigen values helps us partition the $\beta - \alpha$ space into four regions (see Fig 1, *i*).

Stability: When $\beta > 0$, the memory term aids in restoring the agent to its desired state at steady state (see Fig 1, *ii*). And when $\beta < 0$, memory opposes the agent's attempt to reach its desired state. However, since the restitution force $(\mathbf{v}_0 - \mathbf{v}_i)$ always

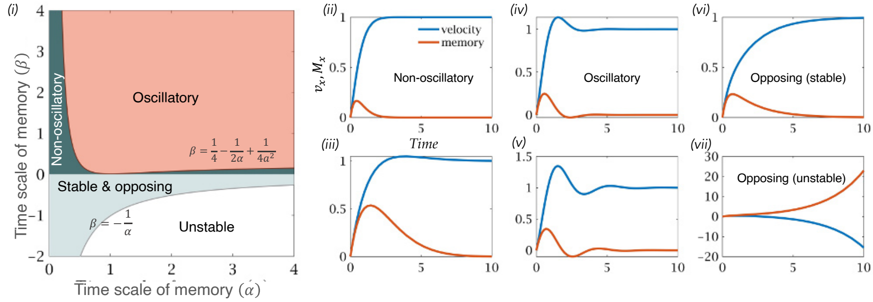

Fig. 1 *(i)* Regions with qualitatively different dynamics in the $\beta - \alpha$ parameter space. Coloured (shaded) regions exhibit stable dynamics, which can be oscillatory, non-oscillatory and opposing (negative β). The unshaded region marks the unstable region, which is found only when β takes a sufficiently large negative value. *(ii)-(vii)* Time evolution of the x components of velocity and memory of the isolated agent for different memory parameters. *(ii)* $\alpha = 0.3; \beta = 2$, *(iii)* $\alpha = 3; \beta = 0.2$, *(iv)* $\alpha = 0.75; \beta = 3$, *(v)* $\alpha = 3; \beta = 3$, *(vi)* $\alpha = 0.4; \beta = -1$, *(vii)* $\alpha = 3; \beta = -1$.

acts to restore the agent's dynamics, a small negative β memory does not immediately destabilise the dynamics and only increases the time taken to reach steady state (see Fig 1, *vi*). However, when $\beta < -\frac{1}{\alpha}$, the eigen values begin to have a positive real part and the memory term overpowers the restitution force leading to unstable dynamics (see Fig 1, *vii*).

Overshoots & oscillations: When $\beta > \frac{1}{4} - \frac{1}{2\alpha} + \frac{1}{4\alpha^2}$, the eigen values become complex conjugates and the dynamics become under-damped which results in oscillations in both the memory and the velocity of the agent (Fig 1, *iv* and *v*). Also, when $\alpha = 1$, any β greater than 0 results in oscillations. This divides the region exhibiting non-oscillatory dynamics into two. The high-α part of this region exhibits dynamics where we observe overshoots; *i.e.* the velocity takes a larger value before asymptotically tapering to the desired, steady state value (see Fig 1, *ii* and *iii* to compare the dynamics in the low-α and high-α regions).

3.2 Collective escape through a narrow exit

To understand the effect of memory on the dynamics of the collective, we consider a well known system: agents exiting a room via a narrow door (See inset of figure 2 *i*). We use the conditions similar to that in ref [8]. The governing equations in Eq 1 and 5 are simulated where every agent has a $\mathbf{v}_0$, directed along the line joining the agent centre and the mid-point of the exit of the door. The inter-agent interactions lead to collisions between agents as they crowd near the exit, slowing them down and giving rise to temporary clogging. Now as agents slow down, memory force increases since the source for the memory is $\mathbf{v}_0 - \mathbf{v}_i$. This makes the agents push harder as they attempt to exit the room. To understand how these forces experienced by the agents lead to the collective escape of these agents, we introduce an order parameter C that characterises the clogging propensity. Here, C is simply the fraction of the total time when the agent-number in the room remains a constant. With this definition, a high value of C would correspond to the prevalence of a large number of clogging events during which agent number in the room remains unchanged.

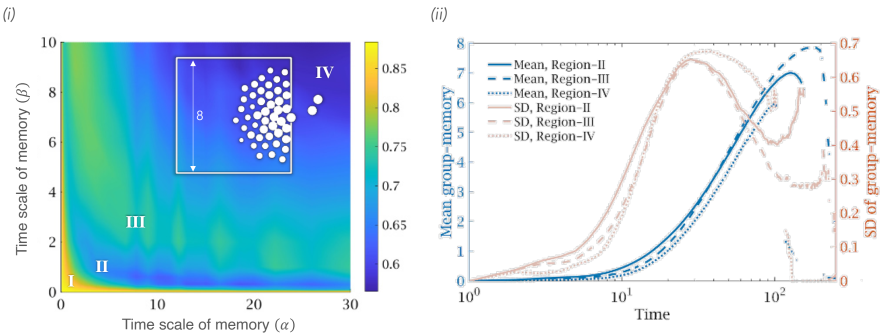

Fig. 2 *(i)* - Heat map of the clogging order parameter C, averaged over 75 independent realisations, plotted for the memory parameters $\beta \in [0, 10]$ and $\alpha \in [0.1, 30]$. INSET: a snapshot of agents exiting a room through a narrow exit. *(ii)* - Time evolution of the mean and the standard deviation of the memory of agents within the room, averaged over 75 independent realisations. This is plotted for three different memory configurations one from each of the regions II, III and IV. Parameters considered are $\alpha = 22.2$ and $\beta = 0.3$ for region II, $\alpha = 22.2$ and $\beta = 2$ for region III and $\alpha = 22.2$ and $\beta = 10$ for region IV.

Figure 2 *i*, shows the heat map of C in the $\beta - \alpha$ space. We find the landscape of C to be non-monotonic with respect to both the principle axes: *i.e.*, an increase in the memory does not necessarily reduce the propensity to form clogs. This observation is similar to the so-called faster-is-slower effect (FIS), reported by Helbing et al [8, 10, 11], where agents trying harder do not necessarily lead to more efficient escape. In addition, we find that the observed non-monotonic effect is more pronounced in certain regions of the $\alpha - \beta$ space. For instance, when either α or β are high (see figure 2 *i*), the non-monotonicity with respect to the other parameter is well pronounced in comparison to when they are low. We believe this feature arises due to the intrinsic dependence of the memory force on the parameters α and β as seen in figure 1. When an agent remembers only its recent past, *i.e.* when α is small, a high value of β is required to produce a force of a similar magnitude to transition from non-oscillatory to oscillatory behaviour and vice versa.

We partition the $\alpha - \beta$ space in figure 2 *i* into four regions while preserving the $\alpha - \beta$ relationship discussed previously. Region I is monotonic with respect to C and completely covers and extends over the region in the $\alpha - \beta$ space corresponding to non-oscillatory behaviour at the agent-level (compare with figure 1). Region II corresponds to the ideal amount of memory that agents can possess to efficiently escape through the exit. Region III corresponds to the FIS phenomenon and it is sandwiched between regions II and IV which exhibit efficient collective escape.

To understand how memory affects the escape dynamics and the formation of clogs, we look at the averaged dynamics of the memory term for the agents within the room. Figure 2 *ii* shows the time evolution of the mean and standard deviation of the memory $\|M_i(t)\|$ in system, averaged over all the independent realisations of the escape dynamics. The initial transient dynamics show that the effect of memory is more pronounced for the agents with lesser strength of memory (*i.e.*, regions $II > III > IV$). This is because memory increases when the agents begin to slow down and agents with a higher strength of memory reach their desired state faster. This trend disappears as the agents clog near the entrance: both the mean and standard deviation of memory of the agents within the room increases rapidly in time. The dynamics of agents with memory in region III begin to have a higher overall memory with smaller variation between the agents within the room in comparison to II and IV. In other words, the strength and time scale of memory is such that all the agents try hard to exit by a similar amount which favours the formation of clogs and gives rise to a high value of C. However, the higher variation and the lower mean memory of agents with memory in region IV implies that the some agents have more memory than the rest, which favours a more efficient exit strategy giving rise to lower values for C.

4 Conclusion

A key feature of the traffic characteristics of living collectives is the ability of individual agents to assimilate dynamic information and alter their movement appropriately. In this article, we introduce *memory*, a facet of intelligence where an agent remembers its trajectory from its recent past and quantifies how well it was able to achieve its desired velocity. The agent makes up for any non-optimal movement in its recent past with a social force proportional to the memory. We show that an agent's memory has an effect akin to a Proportional–Integral controller. Depending on the memory parameters α and β, the agent dynamics can be stable or unstable, and give rise to overshoots and oscillations. The eigen values of the system shed light on the boundaries that partition the different regions in the $\beta - \alpha$ space that show qualitatively different dynamics.

While the effect of memory on the dynamics of the agent is monotonic when only a single agent is considered, it is not the case when agents are in a crowd. We study the effect of memory on the dynamics of agents exiting a room through a narrow door. We find that the presence of memory does not always improve the movement of the agents: the clogging order parameter C has a non-monotonic landscape in the $\beta - \alpha$ space resulting in a behaviour similar to the well known faster-is-slower effect. This allows us to partition the $\beta - \alpha$ space into four regions based on a order parameter that quantifies clogging propensity. We find the eigen values corresponding to the motion of individual agents, in the non-monotonic region of the $\beta - \alpha$ space, to be complex. In other words, the observed FIS effect is a result of the under-damped response of agents arising due to the integral component of the memory force term.

The time dynamics of the mean and standard deviation of the memory of agents within the room, reveal why some regions in the $\beta - \alpha$ space favour the formation of clogs giving rise to non-monotonicity.

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“Nudging” crowds: When it works, when it doesn’t and why

Claudio Feliciani, Sakurako Tanida, Masahiro Furukawa, Hisashi Murakami, Xiaolu Jia, Dražen Brščić, and Katsuhiro Nishinari

Abstract In recent years, there has been a substantial technological improvement in pedestrian detection and numerical modeling. Yet, crowd steering is still based on constructional changes or on-site guidance with little automation. In this work, we investigate the possibility of using environmental stimuli to modify (collective) behavior or people. Three different scenarios are considered where steering method, interaction time (with the surrounding environment) and crowd density are changed. Results show that simple changes in land- and soundscape are not sufficient to modify human route choice in a familiar environment such when entering an office building. However, using supervised experiments we showed that when crowd density is sufficiently high, interaction time long enough and the context “neutral”, it is possible to “nudge” people into a more efficient motion. The outcomes of this work may help in the development of steering systems to be used in sparse crowds with minimal constructional intervention at the scope to reduce congestion and delay the occurrence of dangerous situations.

Keywords: crowd steering, nudging, collective interactions, crowd control, guidance

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1 Introduction

In recent years, considerable advances have been made in the detection, analysis and modeling of crowd dynamics and behavior [8]. Images obtained from cameras are now commonly analyzed using machine learning and computer vision techniques to extract information such as the number of people, but also trajectories and, in some cases, even their identities [1]. In addition, mobility data can be collected by exploiting the connectivity of mobile phones over multiple scales, ranging from the building level (BLE or WiFi may be used for this purpose) up to a city level (carriers know the total number of devices connected to a specific antenna). Similarly, crowd simulation has improved both in accuracy and performance. Pedestrian models are getting overly accurate and can reproduce with sufficient detail an increasing number of supervised experiments [14, 16]. Also, commercial simulators are being increasingly used by practitioners and their computing speed is increasing due to better algorithms and more powerful computers.

However, attempts aimed at influencing crowd motion are still mostly focused on constructional modifications or staff guidance. But constructional changes are costly and generally intended for final fixed layouts. Hence, such an approach is suitable in case crowd motion is consistently judged as risky in a specific area or there are enough resources to proceed with this strategy. On the other hand, staff guidance relies on the capability of the people and the organization involved in it and, ultimately, whether it is implemented or not. Whenever there is an organization managing a facility or organizing an event usually guidance is provided and effective. However, public spaces having no clearly-defined supervising authority are often left unguided, putting crowds at risk should an unexpected situation occur.

Considering the technological means available nowadays and the limitations in current steering practices, it would be therefore necessary to develop methods to steer crowds dynamically by making use of (real-time) collected data. This is already done by using automated audio messaging adapting to crowd conditions, but, in this work, we wish to focus on a non-invasive approach potentially influencing collective behavior without substantial intervention. Clearly, such an approach will not work in critical conditions (specifically for very dense crowds) where enforced instructions can only work, but it can nonetheless be effective in smoothing pedestrian motion in low-density situations, thus preventing or delaying the occurrence of congestion.

Specifically, we will study whether a modification of the environment may trigger a change in human behavior and under which conditions it can achieve the highest efficacy.

[1] Obtaining the *personal* identity is typically restricted by privacy regulations, but an *anonymous* identity may be used, for example, to track a person continuously through multiple cameras.

2 Related works

Although research on non-invasive crowd steering is an emerging topic and only few studies can be found in the literature, there are nonetheless existing attempts to tackle the subject and some related works are worth being reviewed.

Light has been known to affect people’s behavior in public spaces. Ingi et al. [11] note that people’s route choice during daytime is different from nighttime. Also, human mobility is affected by lighting conditions, in particular walking speed, gait characteristics and use of the walkway space. Corbetta et al. [2] employed an “arrow-like stimulus” to affect route choice of pedestrians combining light and visual information. They found that people are more likely to walk in the direction indicated by an arrow, even when there is no specific instruction in doing so.

In our previous works, we also studied how people’s decision making can be affected by information provided in different forms and depending on the degree of compliance [9, 5]. However, our investigation was performed through supervised experiments or using simulation, making contextualization of the outcomes limited to laboratory conditions.

Sound has been also commonly employed to influence walking behavior of pedestrians. Yanagisawa et al. [15] showed that rhythm can help increase walking speed under crowded conditions, although their experiment was limited to single file movement and performed in a supervised setting. The effect of music was investigated in an ecological context by Meng et al. [12] showing that people walk faster when no music is played. Finally, sound was actively used by Senan et al. [13] to influence the motion of people. The authors observed that people prefer to walk in quiet areas moving away from sounds which the authors used in an attempt to steer pedestrians.

In contrast to light and sound, the effect of color is however little or not investigated in the frame of crowd and pedestrian motion. Nonetheless, the work by Costa et al. [3] may help understand about the role it plays on humans over long time periods. The authors compared the perception of people living in a facility with rooms of different colors. They found that students living in a blue environment found it easier to study, especially compared to those living in a red environment. Green and yellow achieved similar and intermediate performance in regard to study activity. Costa et al. also found that people would eventually adapt to the environment thus minimizing potential effects on their perception.

Finally, Furukawa et al. [10] employed an “optical illusion” to influence walking direction of individuals. When walking over the “optical sheet” developed by the authors, as one moves forward, stripes appear to be moving from left to right thus influencing people to steer right. In their study, Furukawa et al. showed that people indeed tend to move toward the right helping to reduce frontal collisions that would occur without the use of their optical sheet. However, the sheet was only tested using individuals in low-density conditions, making it questionable whether the same effect could be achieved in denser crowds when visibility of the floor is drastically reduced.

3 Experiments and results

To study how the environment affects people's behavior and whether it can be used to steer them, three different experiments are considered. Below, each experiment is described and results briefly presented. In the following section(s), the three experiments will be compared to discuss potential and limitations of the non-invasive steering approach studied here.

3.1 Transit door

In the first experiment, we tried to steer people toward a particular door in a building where two are available to enter/leave, as illustrated in Fig. 1. Different combinations of ground colors were changed, particular sounds were played upon entrance/exit using directional speakers, light intensity was modified in one location and LED displays were employed to guide people toward a particular door.

LiDAR sensors were installed to count the number of people transiting through both doors in and out. Baseline condition (without steering) was collected over 53 days. Experiments using color, sound, light and LED display were performed for a duration of 32, 41, 37 and 39 days respectively [2].

Results (presented in Fig. 2) indicate that no solution was particularly effective in changing people's behavior in regard to door selection (or use). This could be explained considering that people are routine users of the facility (a university

Fig. 1 Location used to test the effect of environmental changes in regard to entrance selection. The picture was taken when the LED display was tested trying to move people to the right door. When testing colors, mat color was changed from the default green seen in the picture to black (left) and red (right). For acoustic steering, directional speakers (one seen on top-right) were used to play a sound when people transited through the left door (a different sound was used for entry and exit). Lighting intensity was increased on the right side to test the effect of illumination. Intuitively all methods should steer people to the right (with the possible exception of color).

[2] Data were collected during working days since doors are locked on holidays and entrance is only possible on the right using an identification card.

building). According to the “place script” theory [4] people follow a specific script, i.e., coded behavioral rules associated with a specific place which are hard to change (even in case of disasters). Thus, changing behavior of individuals in a familiar context is a very difficult task.

3.2 Crosswalk-type motion

In the second type of experiment, we observed two groups of 27 people passing in a mock-up corridor from opposite directions (a situation similar to a crosswalk). Starting density for each group was slightly less than 1 person per m^2 (thus the density reached in the middle would be around 2 people/m^2). To influence people’s behavior, a special optical sheet was set on the ground (see Fig. 3).

When walking over the sheet, as one moves forward, stripes appear to be moving from left to right, potentially nudging both groups to move to the right and help in the formation of lanes. The experiment was repeated five times and collective motion of the crowd was compared with the baseline condition without an optical sheet. Several quantities helpful in the analysis of bidirectional flows were used [7], but the preliminary analysis showed no clear steering efficacy when using the optical sheet. This result can be explained considering the short interaction time (less than 10 seconds), limiting the capability to influence overall behavior.

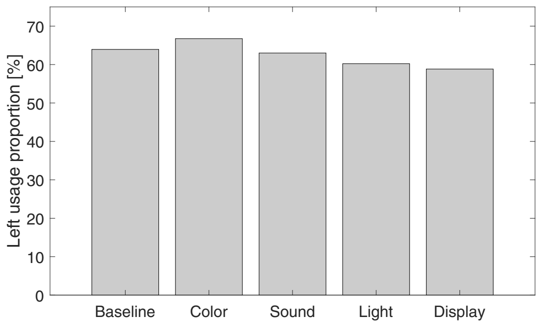

Fig. 2 Percentage of people using the left entrance depending on the steering method. Methods are provided in order of execution, showing a slowly decreasing trend. As a term of comparison, it should be noted that even without steering stimuli, the usage ratio fluctuates by around 5–10% over one month (the period of data collection).

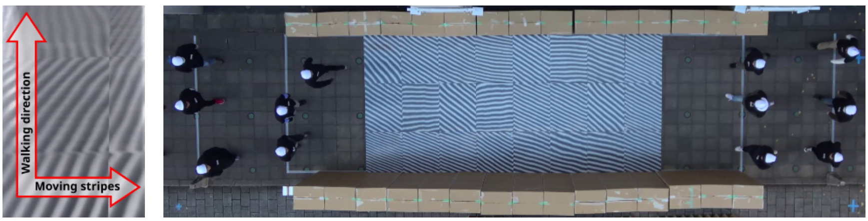

Fig. 3 Left: Working principle of the optical sheet, aiming to induce a turn to the right side. Right: Experimental setup used to check capabilities of the optical sheet in improving the smoothness in a bidirectional flow.

3.3 Continuous bidirectional motion

The third experiment is conceptually similar to what presented earlier but lasted longer in time, thus allowing us to verify whether time is indeed a limitation as speculated above. Specifically, an oval course which included two straight sections was created so that people could continuously walk in a bidirectional configuration (see Fig. 4). The straight sections, 9 m in length, were designed to allow people moving horizontally and minimizing the turning effect. The optical sheet was evenly divided into both straight sections, thus creating a "steering" area of around 4 m on each side.

Half of the people had to walk in the clockwise direction and half in the opposite sense. Each trial lasted about two minutes and three repetitions were performed for the condition with and without an optical sheet (the latter representing the baseline). The analysis focused on the straight sections where speed and density were computed. This time, the optical sheet was found effective in making the crowd faster and facilitating self-organization. More importantly, as shown in Fig. 4, the effect was stronger at higher densities, showing the importance of collective interactions.

4 Summary and discussion

In this section, we would like to compare the results from the experiments presented above and discuss the implications in regard to crowd steering. Table 1 briefly summarizes experimental conditions, steering methods and efficacy in modifying the (collective) behavior of people.

As already discussed, only the experiments in which people moved under medium densities for a comparatively long time were effective in achieving a steering effect. Similar results were also found in experiments with animals, somehow confirming the importance of in-swarm (in-group) interactions in strengthening the effect of external stimuli [6]. In this sense, we should stress on the non-linear nature of collective behavior, i.e. the capability to affect crowds is not linear with their size.

Fig. 4 Left: Configuration used to test the steering efficacy on the bidirectional flow over "long" time periods. Right: Change in average speed against the baseline condition (without optical sheet) for different densities. Only the straight sections are considered in this analysis. Each dot is computed for a density bin of 0.05 m^{-2}.