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A Virtual Reality Platform to Study Crowd Behaviors

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Abstract

Microscopic pedestrian simulation models are based on local interactions between agents. Many interactions occur between walkers, with many factors of influence. There is a need for observations of individuals facing interactions in crowds to better understand them and improve the level of realism of simulation algorithms. We explore Virtual Reality (VR) as an experimental tool to perform such observations with an accurate control of experimental conditions. However, the bias introduced in the collected data through the VR-system must be evaluated. We present the effort we have made in the last few years to evaluate such bias.

Keywords: virtual reality; validation; experiments; crowd; navigation.

1. Introduction

Crowd simulators have been designed through two different approaches. On one hand, the macroscopic approach considers the crowd as a whole, behaving such as a fluid. On the other hand, the microscopic approach considers that global crowd motion emerges from local interactions between agents. Crowd simulators have a wide range of application, from entertainment in movies and video games, to architecture in building analysis and emergency evacuation studies. Because of such important application fields, the community has put a lot of effort into developing more and more realistic crowd simulation algorithms, especially using microscopic approaches. In this context, we define realism as a match between simulated data and real data.

To provide realism to crowd simulated motion, there is a need to understand and model how humans move and behave during local interactions with their neighborhood in real conditions. Observation data is then required to define a 'gold standard' for comparisons. Building an observation database is however a difficult task. Indeed, to consider the complexity of human motion and interactions, we have to focus on various situations (several kinds of motion or interactions) and take into account multiple factors such as sociological or psychological ones. Data can be extracted from in situ situations (i.e., observing a crowd in a street) using video techniques or mobile phone information, but outdoor recordings generally suffer from lack of precision, uncertainties on people states and motivations, and involve

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uncontrolled factors. To solve these problems, data can be extracted from laboratory experiments using optoelectronic devices but these experiments are expensive to set up and focus on specific factors.

Virtual Reality (VR) is a powerful and complementary tool to acquire useful data on human motion and behaviors in crowds. It allows exposing participants to virtual crowds: only one participant is required to observe individual behavior in crowded situations, stimuli can be accurately controlled and repeated over several participants, individual data can be accurately measured, information can be manipulated to inspect the role of some specific factors, etc.: experimental design and achievement are eased in many ways. Such properties have made VR a common tool to perform experiments in socio-psychology, spatial-cognition, motion control, etc. VR is then a relevant tool to study how we navigate in crowds. However, we can wonder whether the data obtained in such conditions are still valid: are locomotion trajectories in VR similar to reality? Does the interaction loop in VR affect user behavior? Does the visual feedback in VR enable participants to make realistic navigation decisions? What is the bias induced by the use of locomotion interfaces?

This paper proposes an overview of our research which aims at analyzing human motion and interaction behaviors in VR. Our ultimate objective is to develop a relevant and powerful VR platform to design microscopic algorithms for realistic crowd simulation. The paper is organized as follows: section 2 presents previous researches on the design of realistic crowd simulation based on observation data as well as the use of VR to study human motion. Then, based on experimental observations, sections 3 and 4 introduce our work on the design of VR-experimental platform considering goal-directed trajectories and interaction with virtual walkers. Finally, we conclude on the ability of our VR platform to produce reliable motion data and we provide perspectives on the development and the use of such a platform.

2. Related work

A large part of recent developments in crowd simulation has been devoted to microscopic algorithms (Thalmann and Musse (2012)). A microscopic simulation model mathematically describes how agent motions are influenced by neighbors, such as boids (Reynolds (1987)). There can be various type of interactions (following, avoidance, grouping...) that can be modeled as attractive and repulsive forces (Helbing and Molnár (1995); Pelechano et al. (2007)). Designing a microscopic crowd simulator requires the understanding of how humans select neighbors (interaction filtering and ordering), how each interaction influences motion, and how interactions can be combined together (when several neighbors are simultaneously considered). Observations and analysis are both required to perform simulator calibration and assessment (Wolinski et al. (2014); Kapadia et al. (2011)). Today, human interaction selection and combination processes are not fully understood. Simulator progress is delayed by the lack of knowledge on these questions. Observations are required.

The development of more efficient and cheaper tracking systems makes the data on crowd motions increasingly available. On one hand, data can be recorded *in situ*. This ecological data sometimes suffers from uncertainty and lack of accuracy, but is relevant and useful to provide statistical observations as well as examples. In this context, Karamouzas and Overmars (2010) simulated group formations based on the observation of real groups of people (Moussaid et al. (2010)). On the other hand, data can be captured in laboratory conditions. This is more accurate and useful to elaborate simulation models. Work leveraging laboratory data include modeling realistic following interactions (Lemercier et al. (2012)), calibrating algorithms (Brogan and Johnson (2003)) or evaluating existing ones (Seyfried et al. (2007)). Guy et al. (2010) validated the Principle of Least Effort (PLE) based on studies performed on collision avoidance (Olivier et al. (2012, 2013)), which also inspired vision-based models (Ondřej et al. (2010)). Ecological and laboratory data is extremely useful to experiment on crowd behavior, but is expensive to acquire, or tainted with uncertainty. The present paper suggests exploring VR to generate data both to ease the experimental process and enable new kinds of experiments and analysis.

VR is a powerful tool for perception-action experiments (Loomis et al. (1999)). VR-based experimental platforms allow exposing a population to fully controlled stimuli that can be repeated from trial to trial with high accuracy. Factors can be isolated and objects manipulations (position, size, orientation, appearance, ..) are easy to perform. Stimuli can be interactive and adapted to participants' responses. Such interesting features allow researchers to use VR to perform experiments in sports (Bideau et al. (2010)), motion control (Fink et al. (2007)), perceptual control laws (Warren and Fajen (2004)), spatial cognition (Mallot et al. (1998); Mohler et al. (2006)), and in our special case of interest in crowd simulation. Small groups of people can share the same virtual space (Slater et al. (2013)). Immersive crowds were used to treat social anxieties (Kwon et al. (2009)). A set of experiments were performed in crowd simulation perception, to design for example realistic immersive crowds (McDonnell et al. (2009); Ennis and O'Sullivan (2012)). VR has also been used to evaluate simulation quality (Pelechano et al. (2008); Rojas and Yang (2013)). However, the interaction loop between users and their environment differs in virtual conditions in comparison with real conditions. Figure 1 illustrates the interaction loop between a human and his/her environment both in real and in virtual conditions.

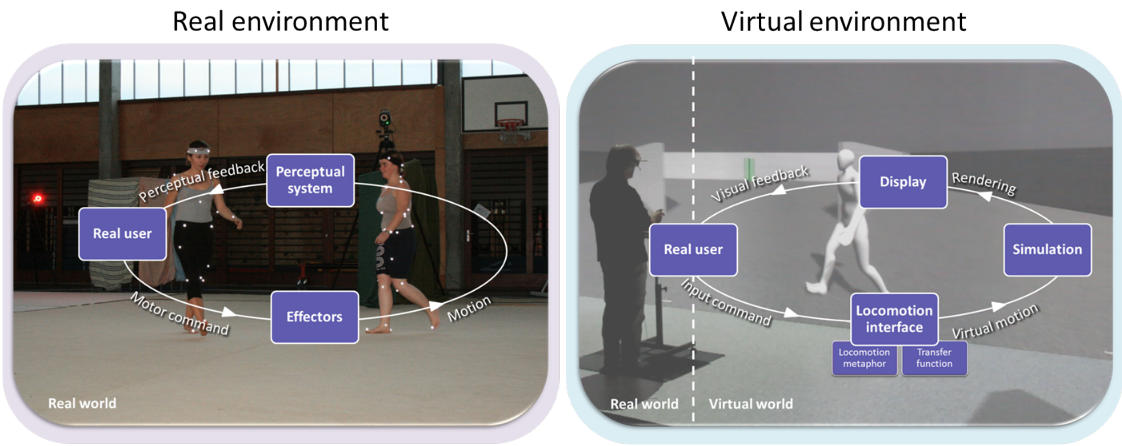

Fig. 1. Interaction loop between a human and his/her environment in real and virtual conditions.

In real conditions, a walker through motor commands to the effectors moves in an environment. While moving, the perceptual system (vision, proprioception,..) provides feedback about the walker's own motion and information about the surrounding environment. That allows the walker to adapt his/her trajectory to sudden changes in the environment and generate a safe and efficient motion. In virtual conditions, the interaction loop is more complex because it involves material aspects.

First, the virtual environment is perceived through a numerical display which could affect the available information and thus could potentially introduce a bias (Fink et al. (2007)). For example, studies observed a distance compression effect (Loomis and Knapp (2003); Willemsen et al. (2004); Renner et al. (2013)), partially explained by the use of Head Mounted Display with reduced field of view and exerting a weight and torques on the user's head. Similarly, the perceived velocity in a VR environment differs from the real locomotion velocity (Banton et al. (2005)), introducing an additional bias. Other factors, such as the image contrast (Hassan et al. (2007)) and the point of view (Mohler et al. (2010)), also influence navigation efficiency in VR.

The second point concerns the user's motion in the virtual world. The user can actually walk if the virtual room is big enough or if wearing a head mounted display. Even with a real motion, authors showed that walking speed is decreased (Fink et al. (2007)), personal space size is modified (Gérin-Lajoie et al. (2008)) and navigation in VR is performed with increased gait instability (Hollman et al. (2007)). Although natural walking is certainly the most ecological approach, the physical limited size of VR setups prevents from using it most of the time. Locomotion interfaces are therefore required. Locomotion interfaces are made up of two components, a locomotion metaphor (device) and a transfer function (software), that can also introduce bias in the generated motion. Indeed, the actuating movement of the locomotion metaphor can significantly differ from real walking and the simulated motion depends on the transfer function applied. Locomotion interfaces cannot usually preserve all the sensory channels involved in locomotion. Indeed, either they play on them (redirected walking (Razzaque et al. (2001))), or they sacrifice a part of them (equilibrioception: walk in place (Slater et al. (1995)), proprioception: joyman (Marchal et al. (2011)), kinesthetic channels: hand-held devices).

When studying human locomotor behavior in VR, the aforementioned factors in the interaction loop potentially introduce bias both in the perception and in the generation of locomotor trajectories. Validating the VR tool is then a mandatory step to be performed before using VR for capturing and analysing human motion. To evaluate these bias and also to try to reduce them, several studies were proposed. For example, it has been shown that distance compression is significantly reduced after five minutes of continuous visual feedback (Mohler et al. (2010)). In addition, locomotor behavior might not always be solely based on perceptual cues, but also on task-specific controls, unchanged in a VR context (Fink et al. (2007)). Researchers proposed various sets of metrics to compare real and virtual trajectories. Many studies on novel locomotion interfaces evaluate virtual trajectories using difference performance criteria (Cirio et al. (2012); Souman et al. (2008); Zanbaka et al. (2005)) (i.e., task completion time, traveled distance, collisions,...), empirical observations of the trajectory (Zanbaka et al. (2005)), as well as cognitive, presence and cybersickness questionnaires (Zanbaka et al. (2005); Whitton et al. (2005); Suma et al. (2010)). Although often sufficient in their context, these metrics cannot reliably evaluate the realism of a trajectory since they do not take into account its underlying shape and its kinematic aspects. Several studies have nevertheless used the mean point-by-point euclidean distance between trajectories (Pham et al. (2007); Brogan and Johnson (2003)) which takes into account the temporal aspect of the trajectory. Ruddle et al. (2013) also showed that speed profile is an important clue to evaluate user proficiency in the task. Fink et al. (2007) used a different set of metrics, namely the mean radius of curvature along the full path, the maximum euclidean distance from a straight line between the origin and the target, and the minimum euclidean distance between the path and the obstacles of the virtual environment. In addition, they leverage their least squares trajectory optimization approach as Fajen and Warren (2003) by using the mean fit values as a metric to account for the realism of the trajectories. Whitton et al. (2005) used Principal Component Analysis to study a set of VR trajectories, and found that for their specific constrained task velocity profiles were mostly defined by the maximum velocity, the percent of time to reach the maximum velocity, and the maximum deceleration.

In the first part of our work, we propose an evaluation of our VR platform using a comparison of reference trajectories with virtual trajectories formed during goal directed locomotion tasks, i.e., the basic level motor synergies involved in human navigation. Compared to previous kinematic-based studies, we benefit from recent results on locomotion stereotypy (Hicheur et al. (2007)) to avoid constraining locomotion paths (e.g., with walls): this enables us to introduce criteria about *the shape* of the path in combination with velocity profiles. Through the framework described in the next section, we expect a richer and more comprehensive set of trajectory evaluation criteria. In the second part, we search for the requirements of a VR platform to study human behavior in crowds. Previous studies focused particularly on human trajectories in VR but few of them consider the validation of the interaction between a user and virtual humans (Bailenson et al. (2003); Perrinet et al. (2013)). Here, we want to provide the conditions to study the behavior of a single individual (the real user) moving in a virtual crowd. We expect users to be able to move in a natural way through the VR crowd, as they would have done in real conditions.

3. Goal directed locomotion and VR

Our first effort to design a VR platform, which aims at studying crowd behaviors, was to focus on goal-directed locomotor tasks. Before considering the complex situation of interactions, it is indeed mandatory to assess whether humans perform the first basic level of motion, i.e. walking, in the same way in a virtual environment as in a real environment. For such a purpose, we designed a trajectography-based framework (Figure 2). Our VR platform is a 4-screen CAVE equipped with 13 projectors (15MPixels resolution), $9m$ large, $3m$ high and $3m$ deep. Active stereoscopy is achieved with Volfony ActiveEyes Pro Radiofrequency wearable glasses, tracked by an ART system. The framework as well as the results of the experiments are fully detailed in Cirio et al. (2013). The objective of this paper was to present a framework that is able to evaluate the effect of various virtual locomotion conditions by comparing virtual trajectories performed during goal-directed locomotion tasks with reference trajectories. Reference trajectories can be recorded through motion capture of a human moving in a real environment or can be generated through a numerical model of human locomotion still based on human motion analysis. We demonstrated our evaluation framework through virtual locomotion conditions that are classicaly used in VR studies. These conditions are obviously non exhaustive but the genericity of our framework allows to evaluate various required conditions. We then conducted a set of five experiments to evaluate the influence of the following virtual locomotion conditions:

- the input control device through the use of a *joystick* (baseline), a *keyboard* and a *gamepad*
- the input control law through a *linear rate control law* (baseline), an *inertial rate control law*, and the *Joyman control law* (Marchal et al. (2011))

- the viewpoint through the use of a *subjective camera* (baseline), a *third-person camera* and a *fixed camera*
- the field of view through values of *60°* (baseline), *45°* and *90°*
- the output display device through a *desktop screen* (baseline), a *head-monted display*, and an *immersive projection setup*

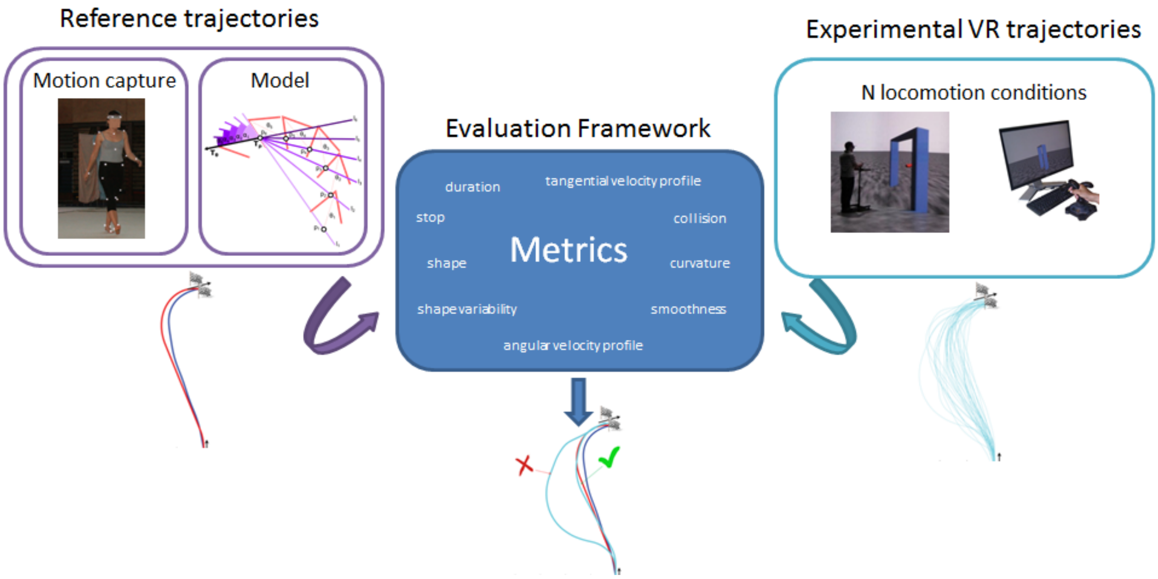

Fig. 2. General priniciple of our evaluation framework to compare trajectories performed in a virtual environment, through various locomotion interfaces, with reference trajectories either obtained from motion capture or generated using a model.

Twelve participants volunteered for these experiments. They gave written and informed consent and the study conformed to the declaration of Helsinki. We used nine kinematic metrics to evaluate the realism of a given set of virtual trajectories, defined as the conformity of the generated trajectories to their real counterpart. These metrics analyzed global properties of trajectories (e.g., trajectory duration, length), local characteristics (e.g., presence of stops, collisions with the target, etc.), as well as continuous variables (e.g., overall shape, speed profile, path curvature, etc.). We also introduced metrics about *the shape* of the path in combination with velocity profiles and a model to eventually get rid of the need for trajectories performed in real conditions.

The main result of this set of experiments showed that, whatever the virtual locomotion condition, users tried to generate trajectories that conform to real ones. This was achieved with varying degrees of success depending on the conditions. Virtual trajectories always exhibited some fundamental characteristics of real locomotion such as smooth and long curves, progressive reorientations, or an offset to one side (e.g. the right) even if the target is on the other side (e.g. the left) when large reorientations are required. This result was not obvious since we could have expected that trajectories generated while being seated with manual action would have been completely different from real trajectories generated through natural walking. Indeed, a manual and a bipedal tasks use different limbs, with different internal mechanics, different kinematic constraints, different inertias, etc. Some locomotion conditions among the ones considered maximized the conformity to real trajectories such as the use of a joystick (compared to a keyboard or a gamepad), a wide field of view or an immersive projection set up. These results are encouraging for the use of VR to study human locomotion and allow us to extend the analysis of VR to interaction with other people while navigating in a virtual environment.

4. Interactions in a crowd in VR

Our second effort to design the VR platform was to focus on the interaction between a real user and a virtual human. The question we wanted to answer was whether we were able to find the conditions that could enable participants to adapt their trajectories as they would have done in real conditions. In this case, we had not only to consider the metrics about the user's trajectory but also the metrics about the interaction to fully evaluate the conformity of virtual to real situations. We focused on a collision avoidance task. We proposed 4 successive experiments.

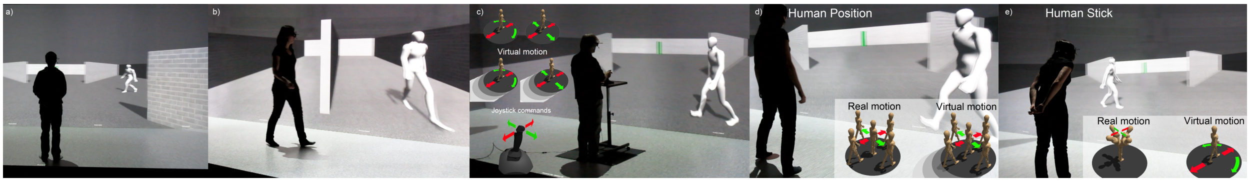

Fig. 3. Illustration of our experiments on the evaluation of the interaction between a real user and a virtual human.

The first experiment was a perception study to assess that the visual feedback provided to users enabled them to correctly perceive the virtual character motion (cf. Figure 3a). Users, who were virtually passively moved in the virtual environment, were asked, for different conditions of crossing distances, whether they think there would be a collision with the virtual human and whether they would have been first or second at the crossing. In experiments 2, 3 and 4, users were actively moving in the virtual environment and avoiding if necessary the virtual human. We recorded their trajectory in the virtual environment for the following locomotion interfaces:

- Natural walking interface: the user is able to really walk in the immersive environment (Figure 3b). The real position is directly transformed into the virtual one.
- Joystick based interfaces: the user moves by actionning a joystick (Figure 3c). We choose such an interface because they are commonly used and, as explained in the previous section, they were proved to generate realistic virtual locomotion trajectories. Nevertheless, the question of the transfer function (TF) remains. We propose evaluating 4 TF named R, S, A+R and A+S. Fot the TF R, the longitudinal axis of the joystick controls speed and the lateral axis controls angular rotation speed. For the S TF, the orientation is fixed, and the lateral axis of the joystick controls the lateral speed of motion (i.e., inducing strafe motion). A+R and A+S TFs combine R and S TF with an automatic forward motion set at comfortable speed (1.4m/s). This means that users perform actions on the joystick only to make adaptations to their trajectories.
- Whole body motion interfaces: they require physical whole body motions that are closer to real walking. We evaluated two interfaces. The first one is named human position (HP) and is based on an automatic forward motion combined with offset translations (Figure 3d). The second one is named human-stick (HS). User virtually moves by leaning in the desired direction of motion (Figure 3e).

The general principle of our evaluation framework is the same as the one illustrated in Figure 2. We compared virtual trajectories with reference ones. In that case, we based our comparison metrics on the results of previous studies which analysed collision avoidance between two real walkers having orthogonal trajectories (Olivier et al. (2012, 2013)). To this end, we designed a virtual environment which reproduced the same experimental set-up than in these real conditions. We used a neutral virtual human to interact with the user. 15 participants volunteered for this experiment. Our main comparison criteria were based on the *mpd* function analysis (*mpd* means minimum predicted distance) introduced in Olivier et al. (2012). *mpd* is a continuous function of time which computes the future distance of closest approach between two walkers based on their current position, orientation, and speed. Extrapolation of future trajectories assumes that walkers keep walking at the same orientation and speed. *mpd* is constant in time when walkers do not perform adaptations of their respective trajectories (i.e., changes in speed or orientation resulting into variations of *mpd*). *mpd* reveals the effect of adaptations on the future crossing distance as well as the temporal structure of collision avoidance. Collision avoidance behavior was described as a three-step process: first, the *observation period* where *mpd* is constant even though it is low; second, the *reaction period* where *mpd* increases due to the walkers' adaptations (Olivier et al. (2012)); third, the *regulation period* where *mpd* is constant but high enough to ensure a safe distance for collision avoidance. Moreover, the derivatives of the *mpd* reveal the strategies (i.e., adaptation of orientation or speed) set by walkers to perform collision avoidance (Olivier et al. (2013)). We then evaluated whether collision avoidance behaviors in VR match the following properties of real ones:

- **accurate estimation of collision risk**. In real interactions, adaptations (*mpd* variations) are observed if, and only if, a risk of future collision exists (*mpd* value is low at the beginning of interactions, $< 1m$). We check the perception of collision risk in Experiment 1, we also analyze the evolutions of *mpd* in the other experiments.
- **walkers anticipate collision avoidance**. In real interactions, having a *regulation period* (*mpd* constant with high enough value) before walkers reach the closest distance demonstrates that avoidance maneuvers are performed with anticipation.
- **walkers have combined and role-dependent avoidance strategies**. In real interactions, walkers combine turning and speed changes to avoid collision and the average combination depends on their roles (passing first, giving way).

Results of these experiments showed first that the information available in the virtual set-up enabled users to evaluate the situation of interaction. Users correctly perceived the situation of interaction with the virtual character but there were two limitations: information about collision was shortly delayed in comparison with reality, and the position in the virtual environment was perceived with a slight offset (around 10cm). Second, results showed that all the studied interfaces led to qualitatively realistic trajectories, with some quantitative differences in avoidance distances or strategies. Users slightly over-adapteded their trajectories, maybe due to different distance perception in VR (Loomis and Knapp (2003)). But our evaluation demonstrated that reliable results can be obtained for qualitative analysis, such as collision avoidance strategies, anticipation, and navigation decision. Some of the interfaces we evaluated were realistic but limited at the same time, because the user could not freely navigate. With the natural walking interface, the virtual reachable space was limited by the dimensions of the VR system, which can be problematic to deal with crowd studies in large space. Over all evaluated conditions, the joystick device combined with **A+R** TF matched best with human behavior observed in real conditions, which made it a good candidate for natural navigation and interaction with crowds.

To demonstrate our platform in action for crowd simulation applications, we studied individual strategies during group avoidance. We explored how the decision to avoid groups as a whole was taken. To this end, 13 people volunteered for this experiment. Their task was to go to a target, using the joystick-based interface associated with **A+R** TF, while avoiding a collision with a group of virtual people walking in the street (Figure4a).

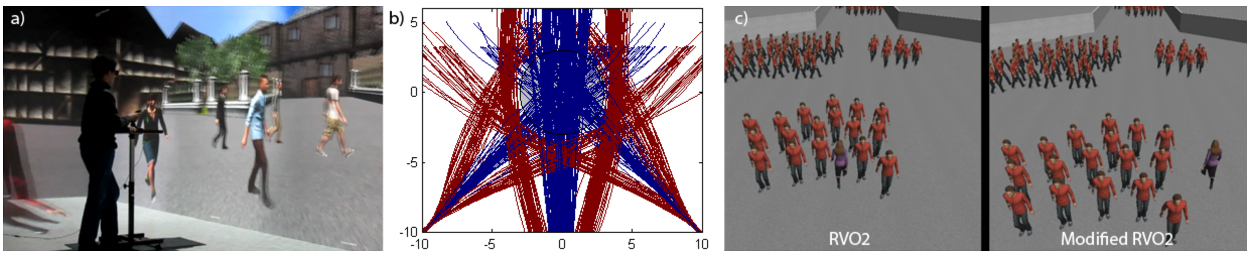

Fig. 4. a) A user interaction with a crowd. We recorded his trajectories in the virtual world (b) and analyse whether he goes around (red path) or through (blue path) the group of virtual humans. This decision ananlysis allows to adapt existing microscopic crowd simulation models to group avoidance (c).

We evaluated the influence of several aspects of the group of virtual walkers on the decision taken by the user to avoid it (density, visual appearance of the virtual characters, group direction of motion). We recorded participants trajectories in the virtual environment (Figure4b). The results of this experiment showed that group density was the most dominant factor in the decision for individuals to go through or around groups. This result was expected, and our experimental results provided quantitative evaluations of the switching threshold (when spacing between characters is between 1.7m and 2m). This result was used to adapt an existing microscopic crowd simulation model, i.e., the RVO2 model (Berg et al. (2011)), for group avoidance. An example of the decision taken by the women dressed in purple with the original RVO2 model and the RVO2 model adapted for group avoidance is illustrated on Figure4c.

5. Conclusion

We proposed an overview of our work which aims at evaluating and using VR to perform experiments on human motion and interactions. The underlying objective is to provide new data on individual motion behaviors in crowds for the development of realistic immersive crowds. Our contribution is an experimental evaluation of the ability of VR to provide reliable motion data both for goal-directed and collision avoidance trajectories. We proposed a framework able to compare the trajectories generated in a virtual environment with reference trajectories captured in real situations. We showed that the trajectories formed by participants were qualitatively similar to real ones in many aspects, but that quantitative differences exist. These differences were evaluated for various locomotion conditions, and the advantages and drawbacks of each can be defined. Our framework also enables to capture the navigation decisions of a user in a crowd. We demonstrated the strength of VR and showed its usefulness for improving crowd simulation algorithms. VR facilitates experiments in many ways (cost, preparation and realization) and even enables to study situations that would be impossible in real conditions (accurate repeatability, incongruencies). These results are promising and open several perspectives either to further evaluate the technical aspects of VR platforms (e.g., additional locomotion interfaces, sound or tactile feedback modalities) or to perform new experiments on user behaviors in virtual crowds. For example, a VR setup can fully control and record the visual flow of users. This is relevant to investigate how humans process visual information in their complex interaction with crowds. Simulations would then benefit from more realistic selection and filtering of interactions (agents' neighbors, interaction combinations, etc.).

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