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Intelligent Modeling of Human Movement Behavior during Virtual Crowd Interaction in Immersive Virtual Environments

PhD Thesis

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Chapter 1

Introduction

1.1 Motivation

In our daily life we interact with other people on a number of different occasions, like when going to work or shopping, walking or meeting with friends, crossing roads, etc. With the use of modern display technologies and game engines, such daily activities can be recreated in a virtual space providing people the ability to observe such behaviors and characteristics of human crowds in virtual environments. In general a virtual crowd consists of individual groups with similar or not behaviors and characteristics. The necessity for designing immersive virtual environments populated with realistically simulated virtual humans, specifically in their behavior and navigation aspects, motivates the research in this specific field that will greatly improve the sense of presence of the immersed user in virtual environments.

Users in an immersive virtual reality system have the capability to interact while being immersed in a surrounding and realistic virtual environment [1]. Immersion in virtual reality attempts to create a fascinating experience while placing the user in a virtual environment, where he can be a part of the virtual world. The level of immersion of the user can be measured separately (based on his/her experience in general) and is considered as an objective attribute.

An essential task is to persuade the immersed user in a virtual environment with virtual humans, to feel, act and participate in this virtual experience naturally as he would in a similar real environment [2], but always within the limitation of the current system. The user must be able to interact with the environment and the virtual people. In addition, virtual humans' movement behavior and interaction must be realistic and convincing to improve the experience of the user. Populating virtual environments with virtual people and synthesizing their navigation and behavior to "feel" realistic could be a very challenging task.

The virtual reality community has been interested in human-virtual characters interaction the past few decades [10], [11], [12]. To investigate and understand the interactions with the virtual characters, researchers use various types of sensors (e.g. electroencephalograms, electrodermal sensors, eye-tracking sensors, and motion capture sensors) to collect objective data or subjective data through questionnaires. The results from such experiments (human-virtual characters interactions) show that these methods can capture data efficiently to analyze and understand such interactions [13], [14]. Furthermore, objective and subjective data collected during interactions with virtual humans tend to match data collected between humans' interactions in the real world [15], [16]. In addition previous studies show that humans' avoidance behavior is qualitatively similar in virtual and real conditions [17]. Those findings clearly indicate that studies around the subject of human-virtual crowd interactions can provide valuable information that are applicable not only in virtual reality scenarios (e.g. video-games, training, virtual experiments, etc.) but also to the research of real-world human behavior and interactions between people.

Overall the main purpose of such research is the creation of specific experiments and the decomposition of the behavior and possible responses of the immersed user, in order to understand the main elements that influence his/her experience, inside a virtual crowd.

1.2 Scope

Virtual crowds consist of a significant amount of virtual people that have similar or different behavior. In addition, virtual people that are part of a virtual crowd might have similar or totally different appearances. Finally, they might walk individually, follow a leader, and walk in couples or groups.

In order to create a successful and realistic simulation of a virtual crowd in an immersive virtual environment, there are several components that must be taken under consideration (Figure 1). More specifically, virtual humans should have different characteristics (e.g. color, height, gender, etc.), to create a realistic crowd [161]. In addition, it is necessary to investigate and analyze how virtual humans should be animated from simple, low-level (simple animation of limps), to more advanced, high-level (walking style, walking models, etc.).

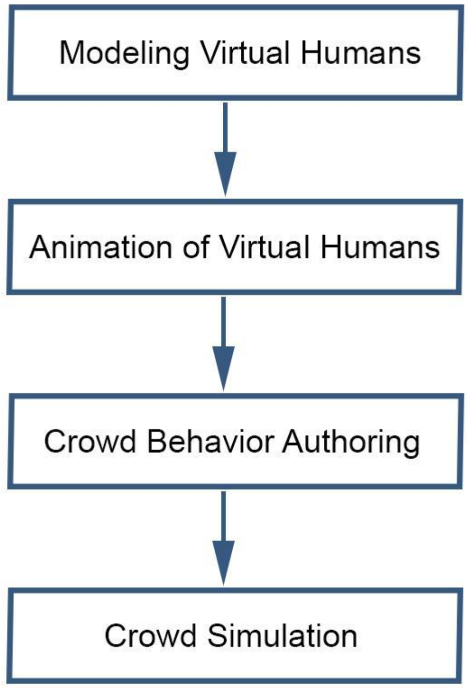


Figure 1. Modeling and synthesis pipeline of a virtual crowd

Similarly, in animation, the behavior of the virtual population could be divided to low and high-level style. The low-level behavior of the crowd investigates and collects data for the navigation and steering of the virtual people, how they follow a specific navigation path and avoid obstacles. The high-level behavior though investigates the overall task completion, path planning, decision talking, needs, etc. The addition of simulated virtual crowds in a virtual environment while configuring the virtual characters to act realistically, the interaction with other virtual and/or real people, collision avoidance, the walking in specific areas and act naturally as humans overall in an environment, with a huge amount of elements and constraints could be a challenging task.

In this thesis there are some significant issues relative to the immersive virtual environments and the crowd simulation. One issue is related to crowd navigation. More specifically, while creating navigation paths for each virtual human to define their route and collision avoidance, the main aim is to create realistic human-like steering behavior of the virtual humans. This issue can be divided in two sections: a) the design of realistic behavioral and navigation simulation models, which is a challenging, time consuming task and b) the definition of realistic simulation of movements (animations) of each virtual human. Overall, the latter is related to crowd behavior and navigation movements to look realistic and believable.

Several methods have been proposed in the literature to solve such crowd navigation issues. Those methods are either macroscopic or microscopic. In macroscopic methods the researchers simulate the crowd as a whole, while in the microscopic methods each virtual agent's behavior is simulated individually.

During the last few years some new techniques have been developed and assessed in crowd simulation models. These new methods follow data-driven techniques that aim to produce simulation models by combining behaviors which were extracted from videos captured in real environments. A great advantage of data-driven methods is that they can handle a huge amount of variations and behaviors that in a rule based system would be a massive time consuming task. Furthermore, these techniques do not require the subjective configuration of rules from an expert and by just changing the data different types and situations may be produced.

Another issue that this thesis addresses is relative to the crowd behavior in immersive virtual reality environments and the elements that have influence on the participants' experience. An immersive virtual reality system in order to be successful, it must offer a feeling of presence to the participant who is immersed. More specifically, if the immersive virtual environment is populated with a virtual crowd, it's a necessity to investigate and consider the behavior of virtual humans in relation to the user and their behavior to another virtual human. Thus, the user will have a more powerful feeling of immersion in the virtual environment and will be stimulated to act similarly to a real environment.

There are three conditions that must be fulfilled to accomplish such immersion for the user:

1. Low latency and consistent sensorimotor loop between sensory data and proprioception.
2. Statistical plausibility. The images and sensation presented in a Virtual Environment must be believable and realistic.

3. Behavior-response relations. There must be proper relations between user's behavior and the Virtual Environment that includes the virtual agents.

The second and third conditions are studied in this thesis, investigating how a user behaves while immersed in a virtual environment, surrounded by a virtual crowd while the crowd behaves and acts realistically. This thesis aims to understand the main factors that construct a realistic and convincing crowd that motivate the immersed user to move, behave and overall feel as he/she would feel in a real environment.

1.3 Contributions

We are commonly surrounded and walk alongside with other people in our daily routines, coordinating our movement behaviors based on people that surround us (e.g. while playing sports, walking on sidewalks, dancing etc.). According to several studies [3], [4], when two or more people perform an action with other people, one person's actions mutually influence the other people's actions. Moreover, people manage unconsciously to coordinate and synchronize their movements when walking together [5], [6].

In recent years there has been an increase in the use of virtual reality devices and interfaces. Users can experience and immerse themselves in virtual environments completely different from the place where they are located. While immersed in a virtual reality environment, aural, haptic, proprioceptive, and vestibular systems can and should be engaged to achieve a more complete and fascinating experience.

This thesis investigates the effects of virtual crowds on participants within an immersive virtual environment. More specifically, three different experimental studies have been conducted to investigate the impact of virtual crowds on users' behavior and additionally to gather valid answers to the following four research questions (RQs):

- *RQ1:* How human movement is or is not affected by a moving virtual crowd population in terms of speed, direction, and traveled distance? (Study 1)

- *RQ2:* How do humans coordinate their movement during immersive crowd interactions? (Study 2)
- *RQ3:* Did the tactile feedback affect the movement behavior of participants across the experimental conditions? (Study 3)
- *RQ4:* Were there differences in participants' self-reported ratings across the experimental conditions? (Study 4)

In the first experimental study (Study 1) [7], three parameters that specify a moving virtual crowd were explored, namely density speed and direction. More specifically, a virtual metropolitan city was designed where the participants were instructed to walk toward the opposite sidewalk (road-crossing scenario). Three parameters (density, speed and direction) were assigned to the virtual crowd, while on the participants, the parameters of speed, deviation and trajectory length were assessed. The results obtained from this experiment indicate that the high density, low speed and diagonal direction conditions of the virtual crowd have the most significant effects on participants' movement behavior. Especially on their speed, deviation and trajectory lengths, while they were immersed and walking in a virtual environment and at the same time surrounded by a moving virtual crowd.

The second study (Study 2) [8], investigated how participants coordinate their movement behavior while surrounded by a virtual crowd, when immersed in a virtual environment. A virtual metropolitan city scenario was designed for the respective experiment. The participants were instructed to perform a road-crossing task, to reach the opposite sidewalk. They were informed that they would perform the task ten times while the virtual crowd around them was scripted to walk in the same direction. Several measurements during the experiment were captured to evaluate the movement behavior of the participants. Time and direction data of the participants were also captured and used to initialize the parameters of the simulated characters that composed the virtual crowd. After analyzing the data obtained from the measurements significant differences between the movement behavior of participants and simulated virtual characters were found.

In the third study (Study 3) [9], it was investigated whether different tactile feedback conditions could affect the behavior of immersed participants in a virtual reality environment, while instructed to walk surrounded by a virtual crowd of people. A virtual metropolitan city was again designed where the participants performed a road-crossing task (reach the opposite sidewalk) wearing a tactile vest. Several tactile feedback conditions were developed (No Tactile, Side Tactile, Back Tactile, Front Tactile, Accurate Tactile, and Random Tactile) and generated individually (one condition per task) for each road-crossing task. The measurements' data from participants' movement behavior was captured, to explore the impact of tactile feedback on their movement. Furthermore, additional data was captured through questionnaires to obtain self-reported ratings of the experimental conditions. The analysis of the results indicate that participants' movement behavior was significantly affected by the tactile feedback conditions. More specifically, the results indicated that the participants became more sensitive to tactile feedback when immersed in a high-density crowd.

These three experimental studies [7], [8], [9], investigated how participants' movement behavior was affected while surrounded by virtual crowds, under different pre-scripted scenarios in a virtual metropolitan city. The results obtained from these three individual experiments revealed that: a) participants' movements were associated with the simulated characters' movements, b) the virtual crowds can indeed affect their movement behavior, especially in more "extreme" conditions (e.g. higher speed, higher density, etc.); and c) the tactile feedback conditions can also influence the user's movement behavior.

These studies and their results are particularly valuable for future researchers and experiments that take place within virtual crowds. Developers and researchers examining human-crowd interactions should consider these movement manipulation effects during programming parts of virtual reality experiences.

More specifically, these three experimental studies demonstrate that human-crowd interaction scenarios can be used to study and explore the actions and decision-making processes of humans. The movement of the participant can be captured efficiently, which is crucial for these kinds of studies. Additionally, studying human movement behavior and coordination when they are immersed in virtual crowds is an interesting direction for studying perceptual-motor tasks that require decision-making and action-planning.

The findings of the above studies could be valuable resources when developing virtual reality applications and games where the users are placed within moving virtual crowds. Additionally, we aim to set the foundations on human-movement analysis for human-virtual-crowd interactions, to create more realistic virtual experiences. Developers will then be able to develop more believable interaction scenarios, such as training applications in which humans learn how to react (e.g., evacuation or extreme weather conditions).

To conclude, virtual reality is a powerful tool that has proven effective to understand human behavior in a number of different simulated scenarios. Such technology could be quite beneficial for future studies because there is no need for humans to face real-world challenges, which can effectively eliminate serious safety risks.

1.4 Overview of the Thesis

Chapter 1 is an introductory chapter. The motivation of this research is presented. More specifically, a number of several daily activities and interactions with other people are described. With the use of modern technology, these activities and interactions can be recreated and replicated in the virtual world, in order to create improved virtual experiences and enhance the users' sense of presence in virtual environments. In addition, the scope of this research is presented, composition and characteristics of realistic virtual crowds, followed by the contributions of the three experimental studies that were designed to explore the impact of virtual crowds on users' behavior. Finally, there is an overview that shows the structure of this thesis.

Chapter 2 provides a review of the state-of-the-art in virtual reality and virtual environments, augmented reality, presence and immersion, crowds and virtual crowds simulation, and human movement in virtual environments. More specifically, virtual reality and virtual environments are presented. Presence and immersion, types of immersive systems, virtual humans in immersive virtual environments and measuring presence in virtual reality experiments are described. Furthermore, the development of crowd simulation as a subject of study that can be applied in several fields, is provided. The crowd behavior generation and the methods that are popular for simulating realistic crowd navigation are also provided. Finally, there is a review in human movement in virtual environments, avoidance behavior, coordination and movement analysis.

Chapter 3 follows a presentation of a framework for human virtual crowd interaction, which concentrates in the virtual environment modeling techniques, virtual crowd synthesis and crowd simulation techniques. More specifically, a publicly available framework is provided for the research community that can be used in Unity game engine. In this framework the researcher can simply configure patterns and variations of the virtual crowd. In addition, human performance metrics and a general model of a virtual city are provided in this framework (the researcher can also import his/her own model). There are 28 models of humans (14 female /14 male) and the virtual crowd is pre-scripted with several specifications that can be adjusted by the researcher. Finally, there are several measurements included, and the statistics are gathered every 0.10 seconds by default.

Chapter 4 provides a review on the first experimental study on the effects of virtual crowds on participants within an immersive virtual environment. More specifically, the first study explores the effects of density, speed, and direction of a virtual crowd on human movement behavior in a virtual environment. A virtual metropolitan city was designed for this study, where the participants were instructed to walk toward the opposite sidewalk. Afterwards, the speed, deviation and trajectory length measurements obtained from the virtual crowd and the participants were investigated. Moreover, the results of this study are presented in detail and followed by some conclusion for improving the results and experience in future studies. To this context, some ideas for future studies are highlighted.

Chapter 5 describes the second experimental study that was conducted to investigate the movement coordination of participants, during immersive crowd interactions. Such activity is considered a usual type of interaction among humans that they encounter on a daily basis when walking in real environments. A virtual metropolitan city scenario was created for this study.

The participants were asked to perform a road-crossing task, to reach the opposite sidewalk. Various measurements were gathered during the experiment to evaluate the movement behavior of the participants and the impact of the virtual crowd on their movements. Furthermore, the results obtained from this study are presented. Finally, some conclusions, limitations and ideas for future research are described.

Chapter 6 provides a review for the third study which investigated whether different tactile feedback conditions could affect the behavior of participants when immersed in a virtual reality environment and instructed to walk while surrounded by a virtual crowd of people. In this study, the participants performed a road-crossing task while wearing a tactile vest in a virtual metropolitan city. Six different tactile feedback conditions were developed for this study. Moreover, the measurements of the participants were captured and analyzed to understand the effects of tactile feedback on the movement behavior of the participants. Finally, some limitations and conclusions occured that may lead us to upgraded future studies.

Chapter 7 discusses the focus, the results and the contributions of the thesis. More specifically, it highlights how users behave under different conditions while immersed in a virtual environment and surrounded by a virtual crowd. In addition, we conclude in several scientific questions, such as: a) Identification of the most important characteristics that characterize a realistic virtual crowd, b) specifications of the conducted experiments, on the basis of possible improvements of the experience of virtual reality users and c) contributions in the creation of realistic virtual environments. The chapter ends with some thoughts and future directions for research in the field of virtual reality.

The final chapter (**chapter 8)** consists of the references and related bibliography information related to the topic of this thesis.

Chapter 2

Literature Review

In this chapter a theoretical basis is established as a solid foundation through our research. At the beginning of this chapter virtual reality and virtual environments are presented. Furthermore, the literature related to crowds and virtual crowds simulation is investigated and a presentation of the essential approximations on crowd navigation and behavior takes place. Immersive virtual reality systems, the percept of presence and immersion and the foundations of virtual people in immersive virtual environments are also investigated. Finally, the chapter explores the way to measure presence in virtual reality systems by performing experiments.

2.1 Virtual Reality and Virtual Environments

2.1.1 Virtual Reality

Virtual reality (VR) is an advanced human-computer interface that simulates a realistic environment. The users of virtual reality can move around, view the virtual world from different angles and even grab things inside the world (virtual objects).

Virtual reality can be applied and used in a variety of fields that involve computer graphics, electronic and mechanical engineering, cybernetics, database design, real-time and distributed systems, simulations, human engineering, stereoscope, human anatomy and artificial life. Finally, according to Zheng et al. [275], a virtual reality system should have three main characteristics: use real-time 3D graphics, provide a sense of immersion for the user, and response to user actions.

The term "virtual reality" is credited to Jaron Lanier founder of VPL research (pioneer company in the field of virtual reality products). According to Bryson (member of Lanier's core team) "Virtual reality is the use of computer technology to create the effect of an interactive three-dimensional world where the objects have a sense of spatial presence" [276]. Furthermore, to define the characteristics of virtual reality the three "I's" are used, which are:

immersion, interaction, and imagination (Figure 2) [277]. More specifically, immersion is the feature that makes the user feel immersed and overall makes the whole experience in the virtual environment more realistic and separated from the real world. Interaction is the ability provided to the user by the virtual reality system to interact with the environment (e.g. objects, characters). Finally, imagination is required to "transfer" successfully the user from the real to the virtual world.

Virtual Reality was presented as an idea that can be applied in a laboratory environment more than fifty years ago by Sutherland [48]. This idea matured in the later decades and became available in a number of different fields like education, health, entertainment training and other, to immerse humans in virtual environments which were representation of real or imaginary.

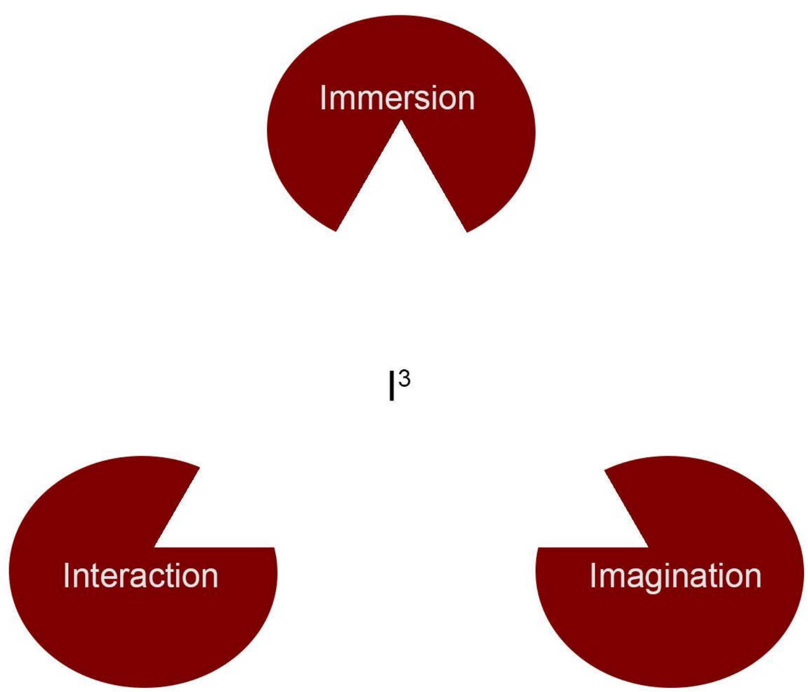


Figure 2. The 3 "I"s that define the characteristics of virtual reality, forming a triangle.

Technically, virtual reality is an artificial three-dimensional environment created by a computer and presented in an interactive way to the user and refers to an environment produced by a computer, where a user can walk around and interact with simulated computer-generated characters and objects. Usually, virtual environments are three-dimensional and try to replicate the real world visually. The user's physical presence is simulated in an artificially generated world which permits interaction with the environment [278].

In our days, virtual reality is usually created by generating visual images and effects via head-mounted displays (HMD). Head-mounted displays can be used as part of a helmet or just placed on the head of the user and they have built-in displays and lenses. Thus, the user can experience the virtual environment with a wide viewing angle. Additionally, user's head and hand movements can be tracked and controllers can be used for interactions with virtual characters or objects.

Furthermore, according to Zhang Hui [279] virtual reality is an ideal tool for training since it is possible to recreate real-world experiences in a harmless virtual environment and it is widely used in a variety of fields such as: military, aerospace, aircraft, and surgery. With the technological developments over the last years, there are still many aspects of virtual reality that need to be studied. More specifically, Zhan Hui in his study analyses and discusses the components of a virtual reality system in mining industry, a typical high risk procedure that requires satisfactory training to ensure safety.

Figure 3. A user wearing a HMD (Image credit: [280])

Reski and Alissandrakis [280] compared three different input technologies (gamepad, vision-based motion controls and room scale) used in an interactive VR environment, to provide recommendations and insights for developers of future virtual reality experiences (Figure 3 shows a user wearing a head-mounted display). More specifically, data was collected from twenty four participants that completed an exploratory task with no time limitations. According to their results, the choice of input was not decisive on the user experience and behavior.

The release of the first version of Oculus Rift which was the first consumer model (of Oculus family) in 2016 greatly affected the promotion of virtual reality and since then the interest in virtual reality and VR equipment is increasing. Additionally, massive companies such as Microsoft, Google, Sony, HTC, and Facebook are investing in this type of technology, producing new hardware and developing new applications [281]. Finally, another popular type of technology used for generating virtual reality content is the CAVE (cave automatic virtual environment, Figure 4).

Figure 4. A user within the CAVE- cave automatic virtual environment (Image credit: https://www.evl.uic.edu/pape/CAVE/DLP/)

2.1.2 Virtual Environments

Virtual environments allow the creation of incredible worlds and can come to “life” through specialized software, restricted only by the imagination of their designers. Figure 5 illustrates a virtual 3D environment. Transforming static virtual environments to live environments replicas of real world or even imaginary is a difficult and time consuming process. Nevertheless, the capability of creating such living environments is widely desired and recognized today. Several training programs, applications and experiments depend on their success, popularity and effectiveness on the creation of realistic, captivating, and functional virtual environments [289].

More specifically, three-dimensional computer graphics are used to produce visual features to isolate the visual senses of the user. Therefore, the rendering result (of the 3d graphics used in a VR environment) and the quality that the display devices can produce greatly affects the immersion feature. Moreover, as the technology advances and especially the technology responsible for simulating the senses of humans (i.e. seeing, hearing, feeling, smelling and tasting), it will be possible for the user to smell and taste objects. Interaction is the feature that provides the user with the ability to interact with objects, thus is considered as a dynamic aspect. In this condition the user involves himself deeply in the virtual world, since he can change the state of virtual objects and the overall environment. Finally, a virtual world is usually designed to provide a specific environment for a specific application, thus this virtual world is usually relevant for similar demands [290]. Consequently, the imagination of the designers is required on how the objects and the people (virtual or not) behave and work inside the virtual world. Nevertheless, and despite the different designs of virtual worlds, realistic simulation, interaction, and real-time communication are a must in virtual worlds, in order to create a suitable and functional experience.

A simple type of virtual environments to design and manage are the static virtual environments. In these environments nothing changes itself (e.g. pre-scripted elements) or from any exterior factor (e.g. from a developer). In contrast to static virtual environments, environments that somehow combine elements within the virtual world that change over time or provide the ability for interactions are usually more complicated to design and program.

More specifically, adding elements that change over time (e.g. several types of dynamics) in a virtual environment can convert it and make it more interesting compared to a static environment. Designing and programming such elements can be demanding and in addition to the computer calculations needed to create these elements it should be taken into consideration that these will be used in virtual reality systems. Virtual reality systems increase the difficulty (when creating such elements), since these systems are real-time and require variable update rates for elements that change overtime.

Figure 5. A 3D virtual environment (Image credit: The Effects of the Density, Speed, and Direction of a Virtual Crowd on Human Movement Behavior [7]).

The capability of interacting with the virtual environment is an essential part of virtual reality and especially for VR video games and applications which is one of the major differences between interactive virtual reality systems (including video games) and films. The most popular and at the same time simple interaction with the virtual environment is by allowing the user to move within the virtual world usually in a first-person way [291].

Interactive dynamics include a large number of interactions that are intrinsic to virtual reality. These are interactions that happen over time naturally, thus causing a dynamic within the virtual environment/system. Such dynamics include some basic components of virtual reality, such as direct manipulation and head tracking. Furthermore, users can interact with a dynamic component of the virtual world. The regular interactive dynamics are executed by selection of a dynamic object and an event that configures some aspect of the dynamic (e.g. stopping or pausing it). Interaction with dynamics is an acknowledged concept within the virtual reality and other related communities [282].

According to Sheridan [49], a virtual environment is a “mental model” that is produced by a presence method (i.e. a sense stimulus) to produce a physical environment which might or might not exist. To sum up, a virtual environment is a perceptual model developed by a presence medium. The virtual environment produced by the virtual reality system, is not the same with the physical environment that it represents, but it is an illusion.

The user in an immersive virtual environment can control his viewpoint by moving his head or body overall, becoming a part of it. Moreover, he can experience haptic feedback with the use of end-effectors [50], or exoskeletons fitted to the user, to transmit forces on him [51], or with tactile vest [9]. Furthermore, in an immersive virtual environment the use of persuasive audio is beneficial since it can increase the realism and improve the overall experience of the user [52].

One of the major objectives of an immersive virtual environment is to achieve a sense of presence (i.e. the sense that the user is actually there) to the users. If presence is achieved the users tend to respond to virtually generated sensory data realistically [1]. This behavior is achieved by authorizing the users in an immersive virtual environment to feel and receive realistic sensory data and not by the high fidelity to realism [53].

2.2 Presence and Immersion

Two senses that are commonly mistaken and confused are presence and immersion. In general presence can be associated with immersion but is a different term which has been investigated in detail in the last years. According to psychologists who have studied thoroughly the sense of presence, it can be divided into three major categories: physical, self and social presence.

Physical presence sense in a virtual world can be achieved if the user experiences a functional representation of the real world. The sense of users' being transferred from a real - physical environment to a virtual environment. Self-presence is the user's psychological identity inside the virtual environment. In other words, the amount of identification between the user and his virtual self in the virtual world is an indication of the level of self-presence.

Social presence according to Biocca et al. [57], is the "sense of being with another". An essential factor (of social presence) is that the virtual system has to offer to the user the feeling that there are actually other humans in the virtual environment. Considering that social presence defines the amount of social interaction that the users will expose in the virtual world [60].

According to Sheridan [49], there are three major factors to achieve presence:

1. The amount of sensory information introduced to the user.
2. The user's amount of authority over the sensor devices.
3. The capability of the user to modify the environment.

The presence experience may differ remarkably over the participants since it Is affected by the variance in perceptual-motor abilities, personalities, preferences, gender, age, psychological conditions, state of mind, etc. The basic principles of presence are that the participants in a virtual environment are exposed in an attractive experience and that the environment presented to them through displays is not just images but actually places visited [61].

Lombard and Ditton [59] described presence as the perceptual “illusion of non-mediation” that happens when a person does not acknowledge the existence of the stimulus that surrounds him and interacts and responds to the environment realistically, as he would without its existence. In Figure 6 a visual representation and explanation of presence in virtual environments is presented. There is no notable difference between the virtual or real environment in the stimuli ascension.

Break in presence (BIP) is a situation that occurs when users’ sense of presence in the virtual environment is disrupted and they become aware of the real world [287]. Such a condition usually has a negative impact on the users since their presence, immersion and overall experience in the virtual world is not continuous.

For the user to act and feel in an immersive virtual environment like he would in the real world the system must generate the feeling of presence (to the user). Consequently, presence is an outcome from the whole system that generates the virtual environment. There are two methods to increase the feeling of presence in an immersive virtual environment:

a) The first method is to produce an environment with great accuracy to reality.
b) The second method is by creating an immersive virtual reality system, while considering what is more important for the perceptual system of the user. A more independent approach according to the individual conditions.

The last method needs to set up the data presented to the user and to what extent he is able to interact and behave with the virtual environment [1]. According to several studies [60], [62], [63] immersion depends on technology. It characterizes the amount of accuracy of sensory modalities, where the immersive virtual technology is presented and delivered. In order for a system to be characterized as “immersive” it must be able technically to generate and provide sensory modalities similar to the real’s world.

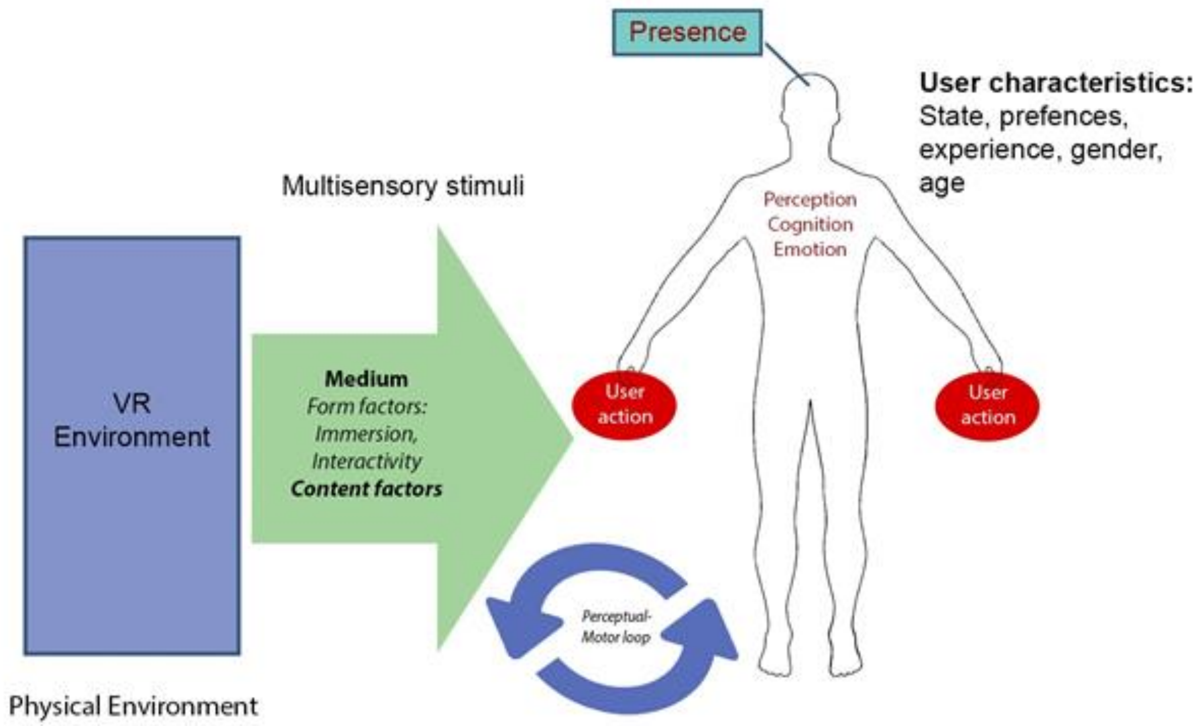


Figure 6. Visual representation and explanation of presence in virtual environments.

According to Brown and Cairns [259], immersion defines a "sense of being there" or a "Zen-like state where your hands just seem to know what to do, and your mind just seems to carry out with the story". The immersion as an experience is not something new and does not refer to an experience that can be applied strictly inside virtual environments but is possible to feel immersed even when reading books [260], watching films [261] or doing something else. As long as doing something involves us fully in order, immersion is a state of mind that can be achieved.

Taking into consideration the recent growth and use of virtual worlds in different fields, the immersion sense started to define an experience that requires not only observation of something but also active interaction with the environment. Thus, a cybernetic circuit between the user and the virtual world is established. This is an experience which is described as "presence" and "immersion". These two definitions are extensively used and explored and are essential while investigating and attempting to understand the relationship between user and virtual worlds since they represent one end of a continuum of intensity of involvement with virtual worlds and address the meaning of being in the context of such simulated environments.

According to Calleja [262], the main confusion between the two definitions is “based on a number of challenges they pose to a clear understanding of the experience (of presence and immersion) they have been employed to describe”, since neither of these definitions completely and sufficiently defines the relation between the user and the virtual environment. Supposing that the user interacts with the virtual environment in a unidirectional way, that there is a defined division between the user in his real world (here) and the virtual corresponding part he interacts with (there). Both definitions of presence and immersion are used regularly and interchangeably but there is a certain level of difference between them. On one hand, Slater and Wibur [61], determine immersion as a technological feature. An option that belongs to the part of “technicalities”, and not at the state of mind. “A technology’s description that refers to the extent to which the computer displays are effective enough to deliver an inclusive, extensive, surrounding and vivid illusion of reality to the sense of a human participant”. On the other hand, Witmer and Singer [60] define immersion as “a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences”.

Furthermore, Calleja [262] presents a more efficient and detailed definition, where “the virtual world absorbed into the user’s consciousness as a space that affords the exertion of agency and expression of sociality in a manner coextensive with our everyday reality” which is described as “incorporation”.

Immersive technologies are able to create an impression that the user is participating in a realistic experience with the use of sensory stimuli narrative and symbolism [263]. Milgram et al. [264], defined this type of experience as being on a continuum between the actual and the virtual world. This continuum model is known as Milgram’s Reality-Virtuality Continuum (Figure 7), which is a visual representation of immersive technologies. More specifically, this model describes the transitional experience moving from the real world into the world of augmented reality, where the images are digitally layered on top of reality, and finally the experience is transferred to a fully virtual environment. Figure 8 shows a refreshed version of the continuum model as illustrated by Valoriani Matteo [265].

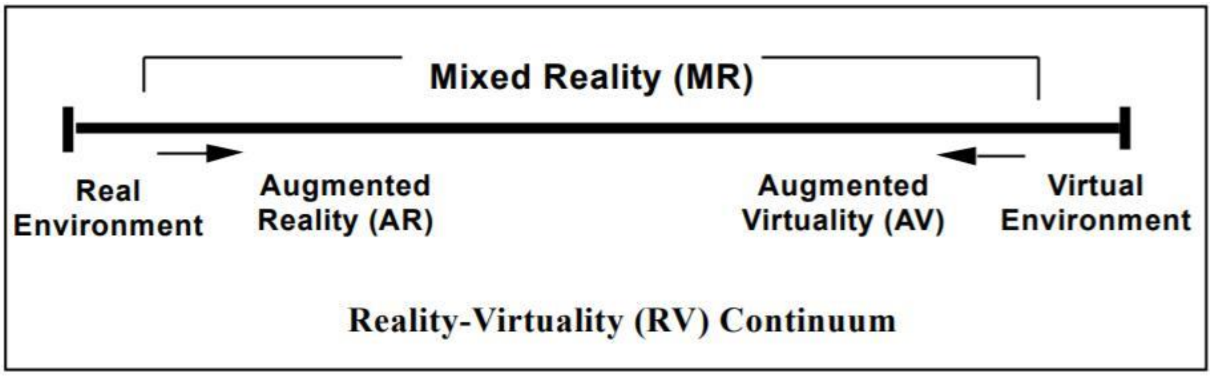


Figure 7. Milgrim's Reality-Virtuality Continuum [264].

Figure 8. Refreshed version of continuum model (Image credit: Matteo Valoriani, Etna dev 2016 – Introduction to Mixed Reality with HoloLens) [265].

Additionally, immersive technologies contain several types of equipment, hardware and software with several levels of interactivity. It is significant to understand the difference between the terms "immersive" and "interactive".

According to Dick and Burrill [266], interactive technology allows for a two-way flow of information through an interface between the user and the technology. The user usually communicates a request for data or action to the technology with the technology returning the requested data or result of the action back to the user.

While immersive technologies are generally interactive, though not all interactive technologies are immersive (or transfer the user within a realistic experience). For example, the interactivity of a tool used in real-time audience polls, where the audience input on open ended questions and features allowing for the two way flow of data. In this example sometimes an instructor is required for input or feedback and other times the software's technology is responsible for returning data back to the user. In all these cases this software cannot be considered as "immersive" since the users are never having the impression that they are having a realistic experience. The application does not bring any data or images into the real-world though immersive characteristics can be added to improve the experience but as a separate functionality.

Immersive applications transfer augmented reality images and generally content within the real-world. The user can interact with the content based on the user design of the augmented reality content. Additionally, in augmented reality experiences, the user is able to import text, photos or website links or he/she needs to be in a specific GPS (global positioning system) location to be able to use more interaction and information according to the content.

In recent years, immersive technology has gained great attention through the massive popularity of social networking applications (e.g. Facebook, Instagram, Snapchat, etc.) where the socio-cultural power of immersive technologies with digital natives is demonstrated. More specifically, social network applications use augmented reality to superimpose images on photos as a method to "chat" with friends using images. Moreover, the mobile's GPS and internal gyroscope can be used in location-based augmented reality experiences [267]. Thus, many large investments and companies' acquisitions have been done in the industry of AR/VR. For example, Facebook acquired Oculus in 2014. Furthermore, as the demand for immersive technologies increases and they become more affordable, the virtual and augmented reality applications are expected to be a 95 billion dollars industry by 2025 [268].

Immersive technologies can motivate users to become creators and generally can be applied widely in the fields of education and entertainment. Science and military training programs also use these types of technologies since virtual and augmented reality provide much safer environments for training, working under dangerous conditions, fighting, etc. Moreover, in training medical students virtual or augmented reality could be used to improve their specializations. Immersive technologies could offer unlimited supplies of virtual or augmented materials for engineering, artistic or architectural reasons, that can be reused unlimited times. Finally, these types of technologies could offer virtual trips over the world for educational reasons.

2.2.1 Types of Immersive Systems

According to Gutiérrez [64] there are three types of virtual environments with different levels of immersion, namely fully immersive, semi-immersive and non-immersive virtual environments.

Generally, fully immersive virtual environments are more complex compared to the other types of environments (semi-immersive and non-immersive), since one of its main objectives is to increase the user's awareness of the virtual world and reduce as much as possible the awareness of the real world. There are several approaches to achieve this kind of immersion. HMDs (head mounted displays) with small screens assigned in front of the eyes that can produce bi-ocular and monocular pictures is a popular method. Another approach is the Cave automatic virtual environment, which is a room-sized cube where high resolution projectors produce images directed to the walls. These systems can also provide users with the ability to interact within the virtual environment, such as interacting with objects or other characters and navigate by using several input devices (e.g. haptic deviceand joystick).

Like semi-immersive environments, fully-immersive systems attempt to reduce user's awareness of the real world, but they don't use such expensive and advanced equipment. These kinds of systems usually are achieved with the use of projectors or large screens to display the environments and wireless equipment for motion capture and navigation. Some of the advantages of such an approach (semi-immersive systems) is that they are cheaper and easier to install in contrast to fully immersive systems. The last few years there has been an increase in the use of these environments for entertainment and/or training purposes.

Finally, non-immersive virtual environments are simpler environments, desktop-based commonly found in videogames and they are categorized as the least interactive environments. Interaction in such systems can be accomplished via common input devices, such as keyboards and mice. There is an almost absolute lack of presence and immersion in non-immersive virtual environments.

2.2.2 Measuring Presence in Virtual Reality Experiments

Developers, designers and engineers most likely could have a better opportunity to create more convenient, effective and successful virtual experiences if ways to increase the presence of participants in virtual environments can be found. To do that the measurements of presence must be stable and consistent and be able to diagnose the elements that are required to increase the feeling of presence to the participant. There are several suggestions from researchers to create such measures for presence. According to Schaik et al. [85], flow is a "holistic sensation that people feel when they act with total involvement". In their work they attempt to evaluate psychometrically a measurement model of flow and also to test a structural model of flow. They found that flow experience can be generally measured (both flow proper and its precursors) in immersive virtual environments.

Ijsselsteijn et al. [86], used a large projection screen with a 50^{o} horizontal field of view, where a car which was traversing a curved track at speed was showing. In this experiment the dependent variables were subjective measures of presence, vection (an illusory perception of self-motion), involvement, sickness and lateral postural responses, and the independent variables were image motion and stereoscopic presentation. The results obtained from their study, indicated that the significant effect of both stereoscopic presentation and image motion on presence agrees with results found in other experiments, where the independent effects of stereo and motion on subjective presence ratings.

Measuring presence by using subjective approaches is a common method, since the sense of presence is subjective where post-test questionnaires are principally used. In these questionnaires the participant can present his feelings and thoughts about the experiment. Furthermore, such approaches do not require the interruption of the participant's virtual experience and are easy to handle.

Overall, there are questionnaires particularly for experiments, conditions, environments and several general presence questionnaires, [60], [73], [87] and co-presence questionnaires [88]. Eventually post-test questionnaires have some important disadvantages; specifically, they do not measure presence in different time periods but only after the completion of the experiment and can also be affected by several events that may happen while the experiment is coming to an end.

Another method less subjective (than questionnaires) is the use of behavioral measurements. In this case the participant's behavior in a virtual environment will be very similar to his behavior in a real environment if the sense of presence is high enough. A common way to evaluate the behaviors in such environments is by capturing videos of the experiments and then analyzing them. This method also has the advantage (like questionnaires) to not require any interruption during the experiment. A major disadvantage in this approach is that the experimenter is using predefined settings so specific behaviors might never be exposed during the experiment.

Finally, a third method is the use of psycho-physiological metrics related to the multisensory stimuli, such as skin temperature, galvanic skin response and heart rate [89]. The results obtained from stressful virtual environments are noticeably more objective compared to the other methods mentioned above [90]. In addition, this method requires all experimental conditions to be similar for all the participants, considering that these measurements are sensitive to the experiment's characteristics.

To sum up, the best way to measure the feeling of presence in virtual reality experiments is by synthesizing all these approaches (subjective and objective) in order to overcome limits and general disadvantages of each method [58], [91].

2.3 Virtual humans in Immersive Virtual Environments

In many cases virtual reality applications contain virtual people as part of the virtual environment or as a major subject for the user to interact with. For instance, in the experiment of Pertaub et al. [16], the user was immersed in a virtual environment and made a speech in a group of virtual humans where they interacted. According to the results of Pertaub's study the participants felt like it was a real experience and activated their social anxiety in identical levels as it would in a similar real situation. In addition, several studies in the field of virtual reality showed that participants would behave realistically concerning virtual humans. Users "attribute mental states to virtual reality characters" according to Freeman et al. [66].

Several works with virtual humans in virtual environments focused on participants keeping their interpersonal distance with the virtual humans and their overall behavior. More specifically, according to Bailenson et al. [67] participants tended to preserve a considerable distance when the virtual characters are more realistic. In the study of Wilcox et al. [68], participants displayed negative behavior when their personal space is violated from virtual agents. In addition, Llobera et al. [69] and Bailenson et al. [70] reported some interesting results in relation to the distances that the participants' tended to keep when there were virtual humans in the environment and how these distances were defined. More specifically, there was a clear increase to the behavioral reaction of the participants when they were closely engaged by virtual agents. Participants kept a significant distance when the virtual humans approached them from the front in contrast to approaching them from the back. Additionally, when virtual agents approached participants' in mutual gaze, they allowed additional personal space and lastly participants tended to keep greater distance and move away from virtual humans that came into their personal space. Obaid et al. [71] investigated participant's awareness of virtual humans when immersed in virtual environments. The outcomes of their work indicated that users in virtual environments managed to unconsciously repeat their behavior patterns discovered and memorized in natural interactions of the real world(e.g. lowering or raising their voice) when interacting with virtual humans.

Slater et al. [72] investigated a spectator who interfered to cease an angry assault by a person to another in an immersive virtual environment. The results obtained from this experiment showed that the user-spectator interfered noticeably more physically and verbally during the virtual "attack" when she/he belonged to the same group with the victim. Finally, there was a clear increase in interference when the victim was looking to him/her for assistance and also belonged to their group.

2.3.1 Virtual Humans and Presence in Immersive Virtual Environments

Friedmann et al. [73] found that when people behaved and interacted in a virtual environment like they would in the real world and manipulated objects and/or affected the virtual characters in the environment then the presence was noticeable. In addition, according to Slater et al. [74] participants' heart rate increased when virtual agents were talking to them. Therefore, interaction with virtual humans is an important element that influences the users while immersed in virtual environments.

Garau et al. [75] investigated presence's preservation over time. More specifically, they concluded that the sense of presence is eliminated in the first seconds of a simulation (when the user is trying to realize where he is and what is happening) if there is no interaction with the virtual agents. According to Fox et al. [76] user's behavior in the real world was influenced by a forceful feeling of presence in virtual reality. Other studies [77] in immersive virtual environments found that presence of observers increased the risk taking (increases the courage) by male participants. In addition, if these observers were female participants then the risk taken by males was enhanced even more.

There are several conditions we need to investigate when there are virtual crowds in the virtual environments. More particularly if a user is immersed in a virtual environment while surrounded by a virtual crowd, it is common to focus on the overall situation happening and not beware of each virtual character individually and their actions [33]. The user for example can notice the overall change of the crowd direction, a turbulence or a general situation. More advanced immersive virtual environments with increased feeling of presence (for the user) can be created if we investigate and realize how the participants behave under different virtual circumstances and events.

Several works in the field of virtual environments have used virtual crowds, to investigate how crowds' features affected the overall realism of the experiment. Peters et al. [78], created a crowd simulator called Metropolis, a guiding methodology for "corpus-based" perceptual approach to crowd modeling to ensure that a system is developed with the proper goals in mind. McDonnell et al. [79], explored human sensitivity to the coordination and timing of conversational body language for virtual characters. They captured the body motions (except hands and faces) of three actors who were having conversation in polite or argument style. Afterwards, they created the stimuli by using the captured conversations (from the actors) to virtual characters. According to their results, both conversation styles (polite and argument style) were both detectable from participants who observed them and specifically the polite conversations where the desynchronization was more noticeable. Ennis et al. [80], also used motion capture data from several polite conversations and arguments. The participants in their experiment were more sensitive to visual desynchronization of body motions compared to mismatches between the gestures and the voices of the virtual characters. Finally, they found that regardless of body motion desynchronization and/or mismatched audio, more complex conversations seem more realistic if there is a proper balance between the talker and the listener roles. The results obtained from the above works indicated a clear improvement to the realism of the virtual environment with the use of virtual crowds.

Other studies investigated the positions and orientations of virtual humans and their impact on the realism of the crowd. More specifically, according to Huerre et al. [81], simulating convincing virtual crowds is a serious challenge of computer graphics. Their work focused on the problem of simulating realistic crowd and group behavior for a variety of applications, effectively. The characteristics of the crowds were simulated based on real world data, evaluation and perceptual issues. Design of spaces and games can greatly benefit from their method.

Ennis et al. [82], evaluated the effects of position, orientation and camera viewpoint on the realism of pedestrian formations. Specifically, they explored how users perceive the characteristics of virtual crowds in static scenes reconstructed from annotated still images where the orientations and positions of the individuals were configured. According to their results, when applying rules based on the contextual information of the scene, the perceived realism of the crowd formations was greatly improved in contrast to random formations. In conclusion, in these studies it was found that virtual crowds arranged with rule-based characteristics are considered more realistic than crowds with random formations.

Pelechano et al. [83] used the feeling of presence in immersive virtual environments as a potential validation process for crowd simulation methods. The results obtained from their experiment indicated that participants interacted with the virtual crowd similarly they would in real world's conditions. Finally, Ahn et al. [84] proposed a visual validation method for crowd simulations, where they positioned the users within a virtual crowd in an immersive virtual environment.

2.4 Crowds and Virtual Crowds

Crowds are a very common feature of our daily lives (Figure 9) and people can collectively walk, observe, celebrate, and participate in several conditions and events. Science has been interested in these collective gatherings called crowds since the end of the 19th century [256]. With the use of modern technology, in addition to observing human crowds in the real world it is possible to simulate several phenomena and conditions from the field of collective behavior in virtual environments. In general, collective behaviors have been investigated and modeled with different purposes and most approaches are application specific, concentrating on different aspects of the crowd behavior. Thus, these approaches utilize different modeling techniques that could be separated into two categories:

1) Modeling techniques that do not distinguish individuals (e.g. flow and network models).

2) Modeling techniques that represent each individual and can be controlled based on physical and/or behavioral models.

Additionally, the applications used for collective behavior modeling, include animation production systems used in the industry of entertainment (e.g. cinema, video games), crowd behavior models used in several domains of training, crowd motion simulations to study and support architectural design and emergency evacuations methods, simulations of physical aspects of crowd dynamics, and sociological and behavioral simulations. The simulations focus on producing realistic scenarios of such situations that can develop in real-time, while containing a large amount of virtual humans.

Virtual crowds though are quite rare in virtual words even today. While the virtual environments have achieved a nearly photorealistic appearance, in most cases these environments look like “ghost towns” deserted or inhabited with a pretty low number of virtual people that are related directly to the developed scenarios. Even in interactive virtual environments (e.g. computer games or virtual reality educational and training systems), the simulated virtual crowds are not so common [292].

At the beginning of the development of crowd simulations the only way to increase the number of simulated characters was to downgrade both visual and behavioral details of the characters. Researchers these days aim to achieve high-fidelity believable groups and crowds combined with complicated virtual worlds and providing to the user the ability to interact with the virtual characters. Several subjects have to be investigated to achieve such results, including behavior computation, rendering, procedural generated locomotion, animation, interaction with objects, and scene management. In addition to the aforementioned subjects there are some new approaches specifically for crowd simulations, like variety and scalability that are required to be taken into consideration. Moreover, it is crucial to explore heterogeneous simulations where in the same virtual environment a smaller amount of complex virtual characters would coexist and interact with a less complex and larger virtual crowd. Finally, techniques related to level of detail (e.g. visual or behavioral details of a virtual crowd) have to be investigated to improve the computation required for real-time applications, while taking into consideration human perception.

According to Thalmann and Musse [18], to design and create a successful virtual crowd in a virtual environment, firstly we must address some issues:

1. Modeling virtual humans. Modeling virtual humans is a difficult and time-consuming process. Furthermore, if we want to create groups of virtual humans, then the process becomes even more difficult, considering we need to create different body shapes, facial appearances and clothing to accomplish a more realistic result.

2. Crowd animation. Crowd animation must be generated effectively and allow variety in animations while considering animations and locomotion of humans.

3. Crowd behavior generation. Crowd behavior generation can be separated in two different behavior levels:

On one hand, low-level behavior focuses on the navigation path of the virtual humans (e.g. going from a specific point to another) and overall the steering of the virtual agent, while avoiding collisions with other virtual agents or objects.

On the other hand, high-level behavior cares about the path planning, decision taking and the overall task completion by virtual individuals, without focusing on collisions or any other low-level behaviors.

4. Rendering of virtual crowds. Virtual crowd rendering depends mostly on the quantity (size) of the crowd than for example the rendering algorithms or the lighting. Rendering can be succeeded by using simple rendering engines that render dots, or more advanced engines that can pre-configure virtual humans, replacing geometry and represent different detail levels, adjusted to the current situation and the virtual environment overall.

5. Virtual crowds' integration in immersive virtual environments. Integration in a virtual environment, implies placing virtual characters in a virtual environment and scripting them to interact between them realistically. Avoiding collisions, walking in specific (walkable) areas, and overall behave physically while concerning the elements that affect the experience of the user.

2.5 Crowd Simulation

The representation of crowds' movements and behaviors through 2D and/or 3D computer graphics commonly refers to crowd simulation (Figure 10). In general, a crowd simulation system usually contains a crowd model which defines the behaviors and movements of a crowd, a graphics engine that is used to represent the crowd and finally, a virtual environmental model. There are many studies that have focused on the designs of crowd models (e.g. physical interactions, behavior rules, artificial intelligence, etc.) and studies that have focused on the graphic representation and simulation system hierarchy (e.g. how to increase computer program efficiency). The aim of an application determines the requirements of the application.

According to Rios et al. [258] crowd simulation models can greatly affect the overall believability of a populated environment. Additionally, it is important to investigate how humans behave in real scenarios to simulate different types of crowd and behaviors realistically. The results of their study indicated that people are not talking their own decisions and simply follow (what the most of the people in a crowd are doing), as the number of followers increases. Finally, people usually highly concentrate to complete a given task and do not much spend time exploring and inspecting the surroundings.

Figure 9. A crowd of pedestrians in China that are passing a crosswalk. Taken from Zhang et al. [257] study.

Figure 10. A simulated virtual crowd walking in a virtual environment. Taken from Alejandro Rios et al. [258] study.

In evacuation simulations and sociological crowd experiments, the behavioral aspects of the crowd are essential to be presented realistically to create a successful experiment in contrast to visual appearance which is not important in such cases. In the fields of film industry, videogames, visualizations though, the appearance, the animations and the overall actions of the crowd should feel realistic and believable. A main purpose of using crowd simulations compared to real-life observations and experiments, to explore crowd behaviors, is because it is less time consuming and does not require the same amount of resources.

In addition to the mentioned fields, crowd modeling and simulations are extensively used in the following areas:

a) **Simulations of emergency events**

According to several studies, emergency events can cause crowd panic situations which can lead to fatal accidents [224]-[227]. Nevertheless, data collection and post-analysis of such unexpected events are usually limited and difficult. The emergency evacuation training drills (e.g. fire drills, earthquake drills) could provide the research community with valuable information but they need huge amounts of resources, thus it is impossible to create a large amount of such experiments. Consequently, crowd models and simulations were developed to provide much more affordable and efficient approaches, in order to better understand crowd behavior in these situations [228]-[230].

b) Studies of collective behaviors

A collective behavior in crowd modeling and simulation, refers in a way that the crowd acting that has not been defined clearly in the crowd model. There are many studies exploring the bi-directional counter-flow of walking pedestrians [231]-[235], and studies investigating the leadership or grouping behavior [236]-[239]. In addition, there are studies exploring the pedestrian behavior in the streets [240]-[244]. In these studies the designed behaviors, crowd phenomena and conditions were studied by social psychologists and attempted to explain the reason that those behaviors occurred.

c) Building layout or user behavior evaluations

In order to evaluate the effect of the layout design of buildings on crowd behaviors (e.g. if the stairs or corridors and the exits are efficient and sufficient), crowd simulations can be used [230], [245]-[247]. Finally, crowd simulations can also be used to explore crowd behaviors and their effects in specific given buildings [236], [248]–[250].

At this point, it should be noted that crowd simulations represent crowd behavior through computer programs, and have many advantages compared to the traditional real-life experiments. Some main advantages are the following:

d) Requires less resources

Computer simulations do not require specific experimental locations or participants. Through the computer screen can be observed the virtual environment and everything happening in it. Real-life studies are more expensive to conduct compared to computer hardware and equipment required for studies that involve crowd simulations, and even modern daily computers can be used to run crowd simulations. Additionally, many crowd modeling simulation tools and software do not require any advanced knowledge in programming but even a person with some basic programming knowledge can use them.

e) Consumes less time

Real-life traditional studies are time consuming and require more time to complete. A computer simulation can dramatically decrease the time of experiments (e.g. evacuation drill). In addition, computer simulations can be repeated a lot of times compared to real-life studies that are usually difficult to repeat many times.

f) Easy to collect data

Since the simulations are designed and generated through computer programs, all the data can easily be captured for post-analysis via the software and by using the proper equipment. Moreover, it's much easier to observe specific areas in a computer generated simulation since it can be paused at any time.

g) Flexibility on configuration

Simulations can configure compositions of a crowd with several combinations, since the individuals and their abilities are completely controlled by a computer program, in contrast to real-life studies that are restricted to the available participants.

Multi-virtual human simulations have different requirements and limitations regarding the design of the system for both conceptual and technical features compared to the simulations of single virtual humans. More specifically these types of simulations (methods that simulate a large number of virtual agents) require a variety of visualizations and behaviors for the individual characters. Variety of individual trajectories for the group of characters walking along the same path, variety of animations for characters that have the same behavior or different reactions of individuals that are facing the same conditions. These varieties in different aspects of the virtual characters are essential to create a crowd that is considered overall realistic and convincing. A major technical challenge in such situations is the increased demand of computational resources which is significantly relevant with the interactions between the virtual characters and their number.

Consequently, designing a multi-character simulation is a complex and demanding task that requires the combination of simulations of several individual characters. Furthermore, new approaches are required that will allow variety between individual virtual characters and also less demanding regarding the computational power that is needed in real-time simulations.

To conclude, creating high-fidelity virtual crowds is a demanding task that requires all the associated elements (e.g. behaviors, rendering, animations) to provide a high level of detail. Considering the performance limits, usually a smaller subgroup of the virtual crowd is possible to have this higher detail. Additionally, computational resources must be distributed properly among the simulation required for different components of the population and the simulation of the virtual environment. Moreover, there are some additional issues that need to be addressed regarding the sections and objects of the scene that are not visible to the user, to achieve high-fidelity virtual crowds while taking into account the performance limitations. A common approach in these cases is to ignore such invisible sections and objects, which can lead to unpredictable situations in some occasions when the user's attention returns to these specific sections and objects of the virtual environment. Since there was no simulation generated for these specific areas, the system has to generate a new simulation which sometimes does not agree to what the user remembers from his previous visit (e.g. an object was moved). However, it is not possible and useful to run a simulation for the whole environment every time. Thus, there is some minimum simulation that has to be done in order to be able to preserve a level of consistency for the virtual environment. Some essential levels of details for the simulation are the following:

- **Full simulation** for the scene and the objects that the user can observe and interact with.

- **Simplified simulation** for the areas and objects that are further away and not clearly visible (e.g. animations are simplified, locomotion and collision detection are less accurate).
- **Minimal simulation** for the areas and objects of the virtual environment that are not visible and there are no interactions with. In this type of simulation, the internal state of the entities should be kept and the movements should be computed but there is no requirement to animate them properly.

Finally, it should be noted that crowd simulation has one major limitation. Specifically, it is a virtual simulation of the real world based on a theoretical crowd model. There is no guarantee that the findings from a crowd simulation can be actually found in real-life scenarios. While there are many studies that designed careful crowd models to calibrate real life data, in order to provide accurate results, it still remains questionable when applying them (the findings from crowd simulations) in different scenarios where the crowd, environments and conditions have been changed.

2.6 Crowd Behavior Generation – Crowd Navigation

Crowd navigation is an important research direction of crowd behavior generation. In crowd navigation the most important issue is to design virtual humans that avoid other characters and/or other obstacles realistically and in a smooth way, while displaying elements of human behavior (e.g. wave and/or talk to someone). These methods are popular for simulating realistic crowd navigation and can be separated in two different types: **macroscopic** and **microscopic**.

2.6.1 Macroscopic Methods

Macroscopic crowd navigation approaches do not require any individual character behavior and attempt to simulate the crowd navigation and/or steering as an entire pack. Using the velocity or force fields to guide the agents, researchers derive ideas from fluid mechanics and gas-kinetic modeling examples that use force fields’ velocity to navigate the virtual characters.

More specifically, according to Hughes [19], there is much room for innovative research in the domain of the flow of human crowds. Recent theory evaluated the particle paths and is based on continuum modeling and its relation with discrete modeling. Moreover, there are strong similarities between the crowd and the classical fluid dynamics, and large crowds tend to present fluid attributes when moving. Nevertheless, a crowd has the power to think (compared to classical fluid), an ability that provides complex and intriguing properties.

Adrien Treuille et al. [20] further developed Hughes model. Specifically, they presented a real-time crowd model based on continuum dynamics, where a dynamic potential field simultaneously integrates global navigation with moving obstacles (e.g. other people), and efficiently solves for the motion of large crowds without the need for explicit collision avoidance. Their approach though is not suitable for every crowd behavior, since it does not take into consideration conditions where the people are tightly packed, therefore, the contact forces between them influence the physics.

Furthermore, Hoogendoorn and Bovy [21], proposed a gas-kinetic pedestrian flow model. This model describes the dynamics of the so-called pedestrian phase-space density, which could be assumed as a mesoscopic generalization of the traditional density and can be easily generalized to multiclass pedestrian flows where class specific characteristics like occupied space, acceleration time and preferred velocities of several pedestrian types can be determined. The mutual dependence of the classes was characterized by the resulting gas-kinetic model. Finally, macroscopic methods cannot capture the behavior of each individual, but of the overall crowd. If these methods focus on one individual, the behavior result might not be realistic.

2.6.2 Microscopic Methods

Microscopic methods, in contrast to macroscopic, concentrate on the decision-making and overall behavior of individual characters and their interactions among them. More specifically, they describe every walker individually and its interactions with other walkers and the environment. Thus, there is no averaging process that could result in loss of detail and the heterogeneity of the population can be included in the microscopic model. Those methods are popular in crowd simulations and can be separated even further in two subcategories: **social forces models** and **rule-based methods**.

2.6.2.1 Social Forces Models

In terms of social forces-related methods, most of them assume that the virtual agent is a particle with mass, where a set of forces is applied. The social force models are simulations of basic pedestrian behavior that consider forces like socio-physiological and physical. In addition, these models consider repulsive interaction, dissipations, fluctuations and friction forces. Helbing's model [22] was regarded as the most notable social force model. More specifically, he showed that the pedestrian motion can be described by a simple social force model for individual pedestrian behavior. In that model to simulate the interaction between pedestrians and obstacles, tangential and repulsion forces were applied. In such methods individuals behave mostly like particles, instead of human characters, vibrating in high density crowds. Finally, according to Helbing, the variables of pedestrian motion are easily measurable, thus, the exploration of pedestrian behavior is an ideal starting point for the development of behavioral models, since the corresponding models are comparable with empirical data.

2.6.2.2 Rule-based Methods

Rule-based methods specify a set of rules that navigate the virtual human characters. In these approaches a human character follows a certain rule or a set of rules according to his current state. Reynolds [23] suggested one of the first rule-based simulations, concentrating on the flocking behaviors of animal crowds, which is characterized by three main factors: separation (a bird that belongs in a flock, tries to avoid collisions with neighbors), cohesion (staying near the center of the mass) and alignment (of their moving direction).

Subsequently, Reynolds added more factors to his rule-based model [24], [25]. Therefore, creating a more realistic simulation model with complex characters and pedestrians. These factors could individually define a specific reaction on the simulated environment and additionally, they are basic behaviors for individuals and/or pairs (e.g. obstacle avoidance, path following etc.) and synthesized behaviors for groups (e.g. leader following, flocking) as well. Many researchers and several studies approved and adapted this method, for human and animal crowds.

More specifically, Ulicny and Thalmann [26] presented the concept of levels of variety. Their work on crowd behavior simulation aimed at interactive real-time applications (e.g. computer games and virtual environments). A modular behavioral architecture of a multi-agent system allowing autonomous and scripted behavior of agents supporting variety was defined. They evaluated their approach by conducting a study where the crowd system was used to manage crowd behavior in a virtual reality training system and another study where the crowd system was applied in a virtual heritage site reconstruction.

Loscos et al. [27], presented a technique to improve local behavior of virtual pedestrians moving in a city and at the same time managing the complexity and keeping a real-time frame rate. They simulated two types of behavior, one in normal traffic conditions and another under congested conditions. Their approach used a 2D discretization of the space to execute local decisions and they introduced some automatic techniques to detect areas accessible by pedestrians. The pedestrians in their experiment were able to control their trajectory by storing the aimed direction and performing collision detection with the environment.

Furthermore, Lamarche and Donikian [28], considered that navigation activity is essential within virtual environments. That complex virtual environments and large virtual human crowds and the real-time constraint require to optimize each aspect of the animation process. Thus, they introduced a topological structuring of the geometric environment to permit fast path finding and an efficient reactive navigation algorithm for virtual humans evolving within a crowd. Their method enabled the real-time animation of hundreds of pedestrians that populated complicated and huge environments such as cities.

Finally, Shao and Terzopoulos [29], attempted to address the complicated issue that occurs when emulating real pedestrians in urban environments. They developed an advanced human animation system, “a comprehensive model” of pedestrians that consists of perceptual, behavioral and cognitive control components. Their system includes a hierarchical environmental modeling framework, efficiently composed of multiple self-animated pedestrians performing a large variety of activities in an extensive virtual environment.

All these studies mentioned concentrate on the navigational aspect of individuals and the general flow of the virtual crowd. In contrast to these studies there are several studies that "look" further away from this navigational aspect. In their study Terzopoulos et al. [30], generated suitable behaviors such as hunger and fear that were specified for simulated fish. Funge et al. [31], simulated agents that were not only aware of the environment, but also learn from it and use their knowledge to choose from a pre-configured set, the most appropriate behavior.

Musse et al. [32], specify a behavioral model, in which the virtual crowd is constructed in three level hierarchy: the crowd individually, groups, and individuals. Sung et al. [33] represent as a graph the set of behaviors with probabilities associated to the edges. According to Sung these probabilities can be updated in real-time using a set of behaviors. Finally in the studies of Farenc et al. [34] and Thomas et al. [35], information is reserved in the virtual environment and can be used to activate the characters to perform several tasks.

To sum up all these methods and approaches mentioned above can be used and applied to simulated virtual crowds. Nevertheless this could be a difficult procedure that requires time, considering that researchers usually must configure manually the rules and manually reconfigure them if a situation changes. In addition there are situations that the results from such methods are not realistic and specifically for high density crowds or panic situations [36].

2.6.3 Data Driven Methods

While real crowd behavior can be too complicated to simulate by computational models and differ according to the environment, data driven methods analyze real-world data to acquire information that can be used to improve computational models or to compose behaviors. These approaches can use examples from the real world for crowds to improve a behavior model. Metoyer and Hodgins [37] authorized the user to determine specific behaviors, while Musse et al. [38] used vision techniques to derive path information from a captured video.

Furthermore, Paris et al. [39] gathered precise behaviors from a crowd of people by using motion capture equipment. Finally, Brogan and Johnson [40] observed pedestrians' movement behaviors and used data from these observations to improve the navigation models while Lai et al. [41] used a motion graph method to synthesize group behavior. The systems mentioned above use data to improve the behavior rules or parameters of these rules.

There are several data driven approaches that obtain rules automatically by using characteristics from real world crowds. Lee et al. [42], presented a data-driven approach of simulating a crowd of virtual humans that emulate behaviors of real human crowds. Specifically, they captured the motion of a human crowd using a camcorder and then extracted 2D moving trajectories of each pedestrian of the crowd individually. Afterwards, they created an agent model from the observed trajectories which decides each agent's actions based on the environment's characteristics and the motion of nearby agents (parts of the same crowd). Thus, they created an agent model that can simulate a virtual crowd with similar behavior to a real crowd.

Pettré et al. [43], presented an approach to simulate interactions between virtual pedestrians. More specifically, a model elaborated from experimental interactions data was created. This model was able to solve and handle multiple interactions between virtual humans and simulate and reproduce experimental trajectories. Interactions were solved by a combination of velocity and orientation adaptations, which was role-dependent.

Lerner et al. [44], introduced an example-based simulation technique where after learning from real-world examples the autonomous agents showed complex natural behaviors that were often missing in crowd simulations. Specifically, they used trajectories alongside representations of the stimuli that affected them, from real world crowds extracted from videos that captured their movements. A set of stimuli that influenced a participant's movement trajectory was extracted and stored to a database (Figure 11). Their system was flexible and could simulate different types of crowds, though the virtual agents were not attempting to reach a specific location or achieve a goal.

Kim et al. [46], introduced an algorithm to create a dense virtual crowd of characters that were interacting with each other (e.g. hand shaking, hugging and carrying objects collaboratively. They tilled (with the use of the algorithm) spatially and temporally motion patches which described episodes of multiple increasing characters. The result of the tiling generated a seamless simulation of virtual characters that were interacting in a "non-trivial manner". Thus, it made it possible to produce complex animations of multiple characters that were interacting with each other, automatically.

Finally, Yersin et al. [47], similarly to Kim [46] to provide a method of decreasing the computation needed for simulating virtual crowds, created a population from a set of blocks (with the help of a library of patch templates) that contained pre-computed local crowd simulations. These blocks were called crowd patches. Therefore, their method allowed the handling of large-scale virtual populations and environments by decreasing the computational resources needed and also ensured the simulation content, since the trajectories were fully solved as soon as the motion patches were computed.

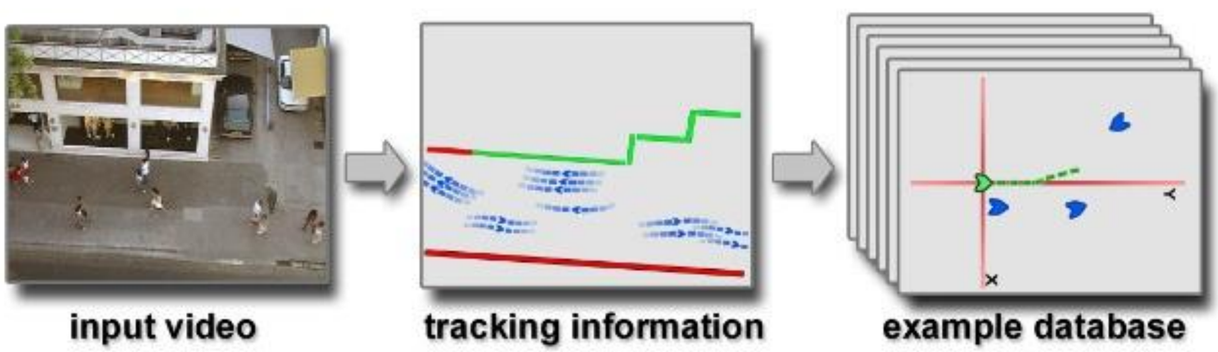


Figure 11. The captured (input) video is tracked manually to extract several trajectories. Afterwards these trajectories are stored in a database as encoded examples [44].

To summarize data driven methods in contrast to other methods (e.g. rule-based methods) can capture a remarkable amount of behaviors that in other approaches would be a serious time consuming process. Moreover, these methods do not require a researcher to manually configure sets of rules subjectively.

2.7 Human Movement in Virtual Environments

2.7.1 Avoidance Behavior

In our daily lives while walking we attempt to sustain a safe distance from other people. This movement behavior is achieved by adapting motion. In his work in laterality, Coren discovered that could model dynamic systems from interactions between the walker and the environment [92]. From a global perspective, according to several studies [93], [94] participant's heading direction changes based on the distance, the target positions, the angle between the walker and the obstacles that are placed in the environment. From a local perspective according to the results obtained from other studies [95], [96], a participant will avoid a virtual human or an obstacle using anticipatory locomotor adjustment behavior, a behavior that implies that the walker adapts the width of steps before the avoidance behavior. The anticipatory locomotor adjustment refers to speed and step's length in addition to adaptation of step width.

Basili et al. [97], examined locomotor trajectories of participants that were avoiding collisions with other humans who were crossing their path orthogonally. The participants in their experiment were changing their walking speed and at the same time they were keeping the path between start and destination at a straight line. Additionally, the results revealed that the chosen trajectory (in order to avoid collisions) was not completely smooth and that there will always be a smoother trajectory but deviated from the straight line.

Cinelli and Patla [98], conducted a study where six participants walked 9.5 meters towards a human doll that approached them on some of the trials. A doorframe was placed along the path as a spatial constraint to examine if they would pass that constraint in advance to avoid collision or not. According to their results, the placement of the spatial constraint (doorframe) had a remarkable impact on their avoidance behavior. Specifically, they firstly changed heading and then adjusted their walking velocity.

Huber et al. [99], explored pedestrians' adjustment on path and speed when crossing a human interferer with different speeds and angles. If the pedestrian was not adjusting his/her speed, the collision with the interferer was always happening. Their results showed local planning of the collision avoidance strategy (avoidance strategy that was temporally controlled) since there was a strong dependence of speed and path adjustments on crossing angle and walking speed.

Knorr et al. [100], explored how personal and/or situational characteristics in human locomotion, and at which range affect role attribution and contribution to avoid collision successfully. Specifically, they explored whether crossing order, path and speed adjustments correlate with subject-specific parameters (e.g. gender, height and personality characteristics) and additionally, to predict the crossing order, the initial walking speed and heading were used. According to their results, in human locomotion the collision avoidance strategies are based on situational and not on personal characteristics.

Finally, Olivier et al. [101], in their study investigated collision avoidance between two walkers. They focused on the conditions that lead to avoidance "maneuvers" in locomotor trajectories. Several locomotion tasks assigned to 30 participants who were divided in groups of two. Their results indicated that only when required the participants adapted their motions and specifically, when the minimum predicted distance was too low. The participants were able to evaluate their reciprocal distance accurately the time the crossing would happen, and to adapt the distance manually.

Usually in virtual reality experiments, the users are requested to wear a HMD and a motion capture system, and then perform locomotion sequences avoiding the virtual content at the same time. A number of experimental studies [102], [103], concentrated instead on virtual humans on objects (e.g. cylinders) collision avoidance. The results obtained from Llobera et al. [69], indicated that participants tended to preserve a greater distance from virtual humans when they walked toward them from their fronts instead of their backs. Olivier et al. [104] compared collision avoidance trajectories in real and virtual world conditions while according to Bonsch's et al. [105] the participants preferred collaborative collision avoidance in small-scale virtual environments. Furthermore, Cinelli [106] et al. in their work they investigated at which distance users started to deviate from their initial path while Sanz et al. [107] studied the walking behavior of participants when avoiding real and virtual static obstacles (anthropomorphic and inanimate). The results obtained from Sanz's work indicated that participants demonstrated different locomotion behaviors between real and virtual obstacles and anthropomorphic and inanimate objects. Eventually Silva t al. [108] investigated participants' interaction behavior with virtual agents in immersive virtual environments.

2.7.2 Following Behavior and Coordination

Many studies in the field of virtual reality examined how the virtual environment affects human movement or investigated human movement coordination and regulation during locomotive behavior in real and/or virtual environments. There has been considerable research on how humans coordinate and adjust their movement behavior in relation to others or according to various walking tasks [112], [113] and human's behavior in team sports and teams generally [116]. Moreover, several works on movement regulation, including following behavior, side by side walking, face to face walking [120], [121], while group formations and collision avoidance [104], have also been investigated.

Minor neurons are the reason that movement coordination and synchronization develop. As specified by the literature, the mirror neuron fires when a human acts or when a human observes another's human action.

More specifically, according to Vignemont and Singer [123], we can share the emotions of someone else's. This happens by means of shared affective neural networks. These neural networks are activated when we feel our own emotions and moreover, when we watch others feeling emotions.

Heyes [124], describes "automatic imitation" as a type of stimulus-response compatibility effect. In this effect the topographical features of task-irrelevant action stimuli facilitate similar responses while interfere with dissimilar responses. Automatic imitation is a newer behavioral phenomenon which provides evidence that humans copy the actions of others in an unwilled and unreasoned way.

Furthermore, according to Keysers [125], mirror neurons are multimodal association neurons in which activity is increased while certain actions are performed and when hearing or observing corresponding actions executed by other people. Brain areas that are thought to contain mirror neurons are responsible for contributing to our perception of the actions of others.

Rizzolatti et al. [126], [127] described mirror neurons as a type of neurons that discharge when individuals execute a given motor act and when they watch others executing the same motor act. These neurons were firstly discovered in the premotor cortex of monkeys. There is a lot of evidence that proves the existence of cortical networks with the characteristics of mirror neurons in humans. Figure 12 illustrates the location of areas with mirror properties in humans' brains.

Consequently a neuron "mirrors" the behavior of the other human as though the observer was acting [128]. While we watch someone performing an action we tend to perform the same actions ourselves. In general humans tend to coordinate their actions (when performing a task) in agreement to others' actions even if these actions are not associated with their task. An issue in such behavior is that this coordination might affect the performance in the task they are performing according to several studies [126], [129], [130].

In addition, several works had concluded that when humans are able to predict the upcoming movements of others, this expectation activates the electrophysiological markers of motor preparation even before observing the expected movement. Specifically, the results obtained from Kanakogi and Itakura [131], study indicated that the ability to predict the actions goals and a motor action in general of others appears in infancy (six months and older). The emergence of this ability occurs simultaneously with the emergence of infants' own motor ability of the same action. Their results showed that the ability to predict the action goals of others, requires the ability to perform the corresponding motor action.

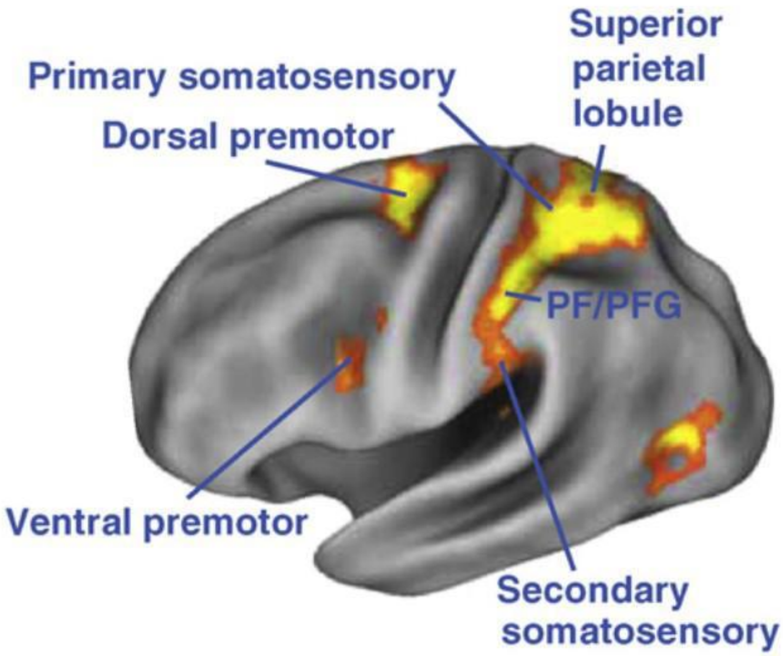


Figure 12. Voxels showing mirror properties (Image credit: Expanding the mirror: vicarious activity for actions, emotions, and sensations [283]).

Moreover, Kilner et.al. [132], reported that certain areas of our brain are activated when we observe another person performing actions, similar to what is happening when we execute the same actions. Additionally, when the nature and the onset time of the upcoming action is predictable (knowledge of upcoming action) automatically activates the motor system. Consequently, our brain has the ability to predict someone's action before their realization.

Finally, according to Southgate et al. [133], the ability to form predictions about the possible outcomes of events occurring is a precondition for several social cognitive abilities like coordinating actions with others, which is fundamental for cooperating with others. Furthermore, the results obtained from their study indicated that even infants (9 months old) can form such predictions.

Preparedness and motion anticipation are crucial for various tasks, from simple (e.g. walking) to more complex tasks (e.g. dancing with a partner, interacting with teammates). Several studies [134], [135], concluded that the leader is responsible for configuring his/her actions to ensure movement coordination with others, to indicate his/her intentions for action change to their partner. Finally, humans tend to incorporate other humans' dexterity within their planning strategy to succeed in their objective [114]. In consequence, humans are able to regulate their movement to perform coordinated and synchronized actions with others.

Several domains have studied movement coordination and regulation, including real world [136] - [138], and virtual reality [140], [141] scenarios where people coordinate while crossing an intersection with real or virtual people present. According to other studies [143], [144] when two humans, being part of a group, cross a road, they become sensitive to each other's presence and tend to simultaneously change their actions or decisions, in contrast to when they are crossing a road alone. Warren [145], in his experiment found that participants (followers), matched the leaders' velocity instead of keeping a constant distance. A dynamical model has been derived from this finding of how a pedestrian aligns his/her motion with a neighbor's speed and how these binary interactions are combined into a neighborhood of interaction. In another study conducted by Rio et al. [146] they explored the neighborhood of interaction in a virtual crowd. More precisely, they investigated which neighbors have an impact on pedestrian's behavior, how this depends on neighbor position and how the influences of multiple neighbors are synthesized. They concluded that neighbor influence is linearly combined and doesn't decrease with lateral position but only with distance.

Moreover, several works have found that when a participant's personal space is violated by a virtual character then negative reactions are triggered [68], [70], consequently participants tend to keep a greater distance when interacting with virtual characters and especially when interacting with realistic virtual characters [67]. Likewise, participants tended to keep significantly more distance from virtual characters that approached them from front instead from behind [69]. Finally, Bruneau et al. [147] found that when participants are surrounded by dense groups of virtual characters, they tend to follow longer paths.

2.7.3 Movement analysis

Kinesiology researchers in addition to virtual reality researchers have studied and analyzed human locomotion extensively and proposed several methods of analyzing locomotive behavior of participants. Several studies have used criteria associated with task completion time, number of collisions, traveled distance and path precision with respect to the ideal path.

Specifically, Cirio et al. [148], proposed three locomotion techniques, specifically for immersive spaces with four sided displays like cube or CAVE, where the walking is limited due to the physical space. An improved version of the wand technique where the wand is constrained to use in unsafe zones, a way to increase the amount of real walking (Magic Barrier Tape technique [284]) and a virtual companion to help the users during their navigation. The aim in this study was to present techniques in order to keep the users safe, encourage them to walk and provide a new ecological interaction technique.

Iwata and Yoshida [149], created a virtual “infinite surface” driven by actuators for enabling a sense of walking. That infinite surface is generated by treadmills’ motion. More specifically, they developed a device (called Torus Treadmill) that uses twelve sets of treadmills, (Figure 13) that were connected side by side and driven in perpendicular directions. According to their results, the walking accuracy of the participants was improved on the Torus Treadmill and the walking was smooth for the participants.

Souman et al. [150], similarly to Iwata and Yoshida [149], created an omnidirectional treadmill system called CyberWalk (Figure 14). Specifically, a surface was created where the users could walk endlessly in any direction, change their speeds and stop walking at any time. Their results indicated that especially after about 15 minutes (which was the time that the users needed to adapt the treadmill's behavior), the users’ walking performance was steady and allowed them to walk normally within virtual reality scenarios.

Moreover, Lapointe et al. [151], they investigated the overall performance for simple walking tasks with the use of four different input devices: a mouse, a keyboard, a joystick and a gamepad. They concluded that a single-handed controlled device (i.e. a mouse) compared to other devices has better performance results. The users completed the given task faster and with less collisions.

Finally, Zanbaka et al. [152], investigated the differences in cognition and understanding within a virtual environment, between the use of a joystick and real walking. Their results suggested that the participants who physically walked felt significantly more comfortable, avoided more collisions with objects in the virtual environment and overall performed considerably better compared to the participants that used the joystick. There are also some alternative approaches that include the empirical observations of trajectory visualizations [153].

Distance metrics between trajectories have been used in several studies. Arechavaleta et al. [154], investigated goal-oriented locomotion and attempted to describe the shape of trajectories via optimal control. Their results depict that the forward human locomotion which is represented by the torso position and direction, obeys the motion of a nonholonomic system with linear and angular velocity inputs.

Brogan and Johnson [155], presented a behavioral model of path planning that generates walking paths. This model used pedestrian performance statistics (kinematic and dynamic constraints) from five experiments, where they observed and obtained salient features of pedestrian behavior. According to their results, this model added considerable realism to the generated paths.

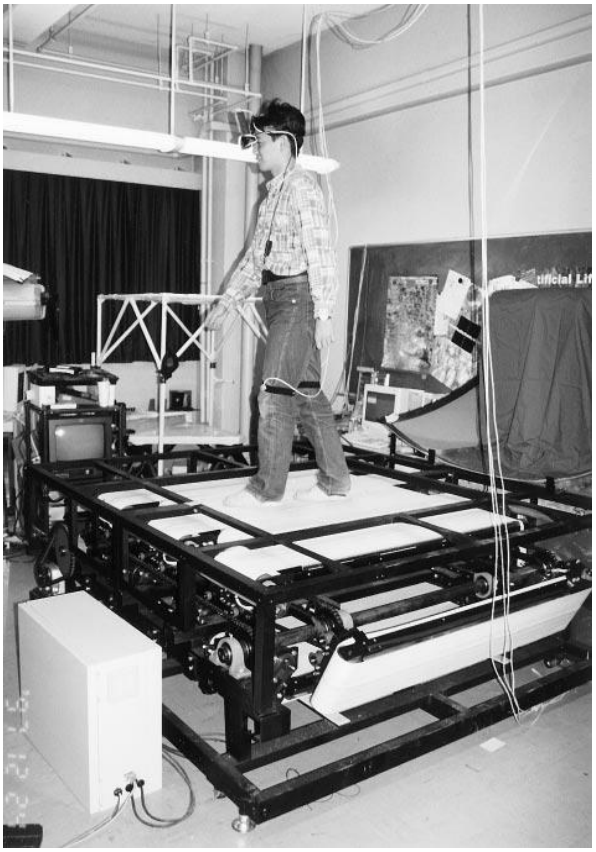


Figure 13. The Torus Treadmill device (Image credit: Path reproduction tests using a torus treadmill [149]).

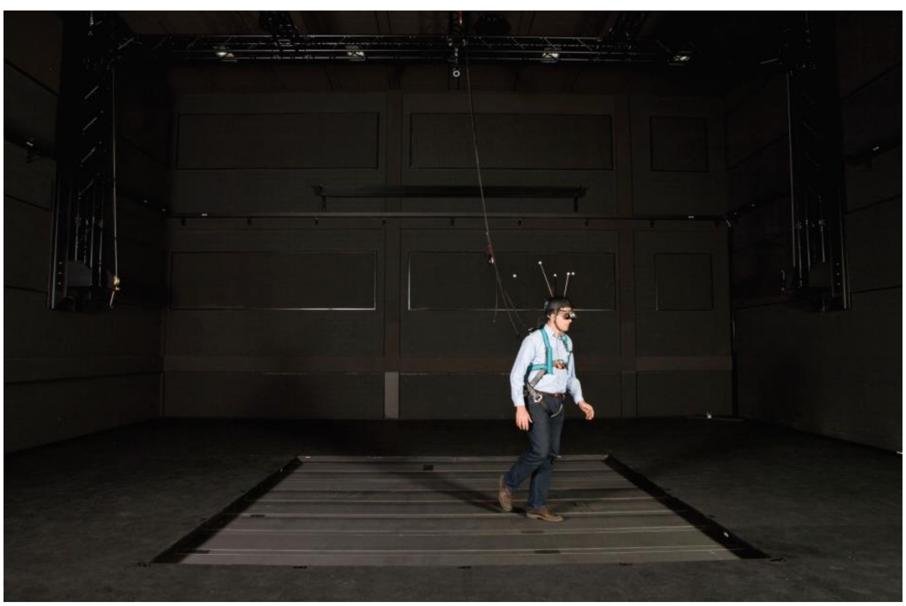


Figure 14. The CyberWalk system (Image credit: CyberWalk: Enabling Unconstrained Omnidirectional Walking through Virtual Environments [150]).

Furthermore, Pham et al. [156], presented a model for the formation of human locomotion trajectories. Additionally, they tested four optimization models (minimum velocity, minimum acceleration, minimum jerk and minimum snap models) by applying them to a wide range of locomotor tasks that involved trajectories of several lengths and curvatures. They concluded that the minimum jerk and the minimum snap models provided predictions significantly close to actual trajectories, at kinematic and geometric levels.

Fink et al. [102] proposed a set of metrics, namely the means 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. Analysis of the main components of a set of trajectories have also been used [158]. Furthermore, in order to compare and evaluate trajectories generated in real and virtual environments based on the gait cycle of walkers, have used data from the stride length, step width, variability in stride velocity and variability in step width [151], [159]. Eventually Cirio et al. [160] in their work proposed nine metrics that could be used to compare real and virtual trajectories, associated to the shape, performance and kinematic features.

2.8 Design of Virtual Reality Environment

The design of a virtual reality environment (refers specifically to the papers produced throughout this thesis, Chapters: 4, 5, and 6) can be described by the following five steps that the definition of:

1. A virtual reality content.

2. A virtual environment, and the degree of immersion (for immersive virtual reality environment).

3. The virtual crowd, (for interactive virtual reality environment).

4. The method of interaction between the user and the virtual crowd.

5. Respective data collection.

Based on the above 5 steps, the proposed virtual reality environment and the system requirements are summarized in Figure: 15.

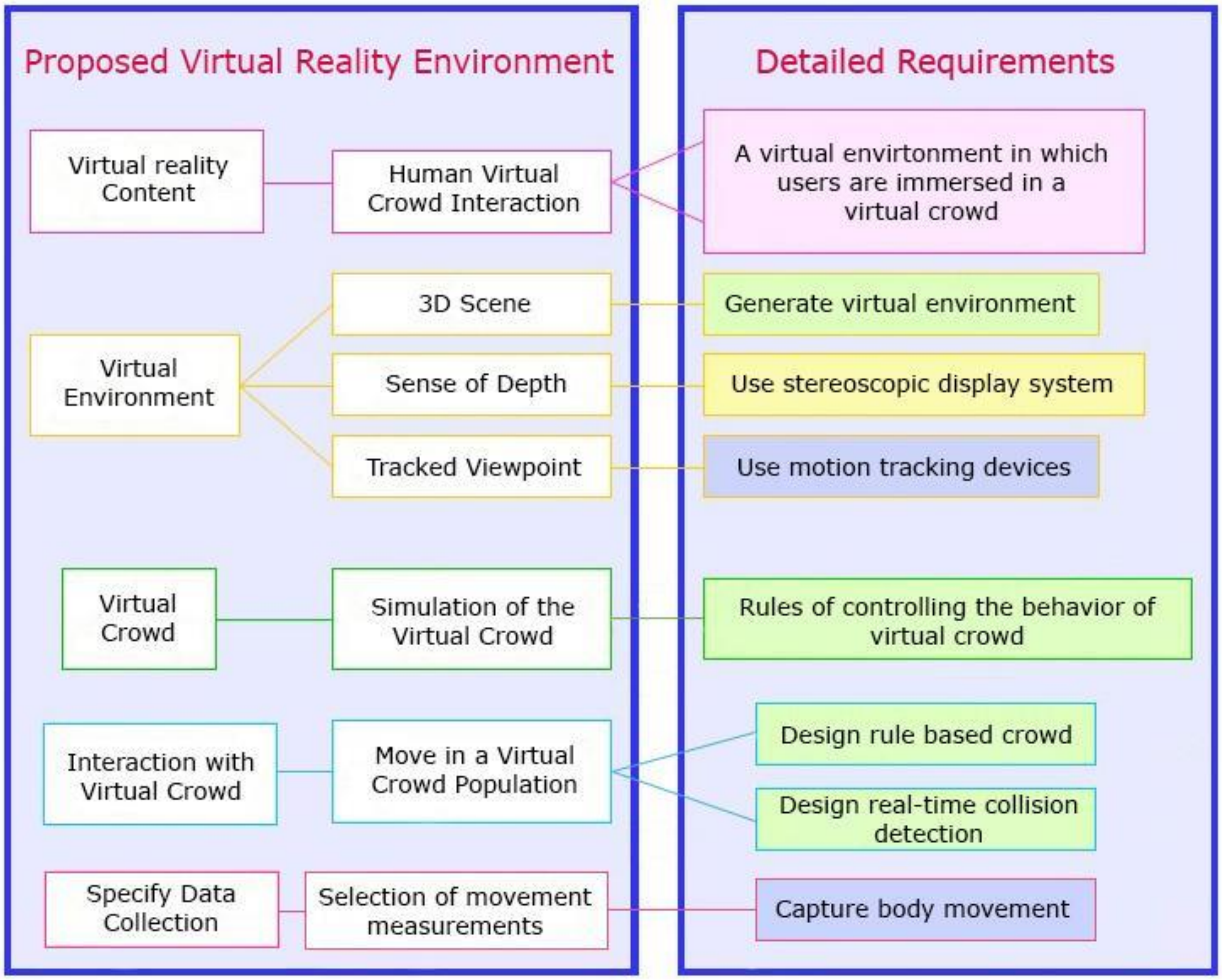


Figure 15. Requirements of proposed virtual reality environment.

The proposed virtual reality content which led to the creation of a 3D scene is a virtual metropolitan city where the users are immersed within a virtual crowd of people. The sense of depth and good tracking quality were essential for the successful conduct of our studies. Moreover, the virtual crowd was designed and simulated with specific techniques that gives emphasis to realistic appearance, walking, and overall behavior. Finally, we selected specific movement measurements in accordance with the aim of each one of the three studies to get accurate results.

Chapter 3

A Framework for Human-Virtual Crowd Interaction

3.1 Introduction

In daily activities humans need to navigate through crowds of people. An essential factor that needs investigation in order to understand humans' behaviors in virtual environments would be the absence of uniformity [67] in interactions between real and virtual environments. Understanding this factor could be very beneficial for researchers that are looking for techniques on how to manipulate physical patterns (e.g. speed, avoidance), psychological and physiological states and for virtual reality systems overall.

Virtual reality locomotion would benefit from studying the effects of crowd patterns on human movement since virtual crowds have a dynamic structure and can affect and change the movement behavior of participants in the same (with the crowd) virtual environment. The development of a generic framework in how several crowd models and setups can affect participants' movement, could be really beneficial for researchers to conduct new experiments quickly and gather data fast. Furthermore, it can be expanded according to the needs of each experiment.

The Unity game engine was used to execute the developed framework which can be applied in any virtual environment. This framework provides human performance metrics (e.g. time to cross, speed of crossing, under and over taking behaviors, crowd avoidance behavior, trajectory length and other).

This framework is a ruled-based system and composed of several elements as shown in (Figure 16). Specifically, the elements are: a) a Game Controller that controls the game state, b) the Pedestrians in the virtual crowd and c) the Participant. Moreover, it is customized with a Crowd Controller that specifies the several trials that the system will test and an Area Controller that specifies the area where the participant and the crowd will navigate. The tracked data of the participant is sent through the Game Controller to the Data Manager where it is stored for analysis.

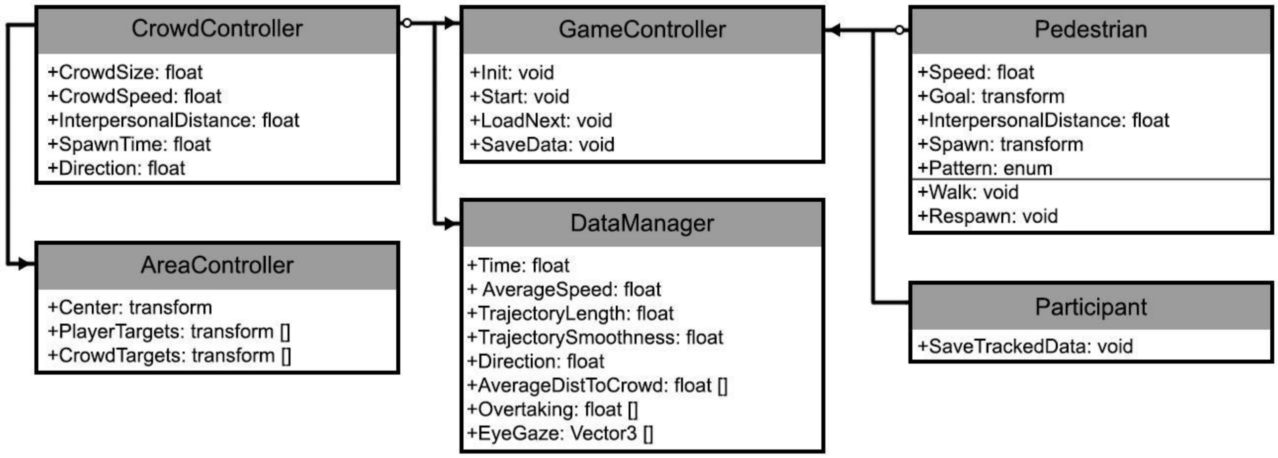


Figure 16. The structure of the proposed framework

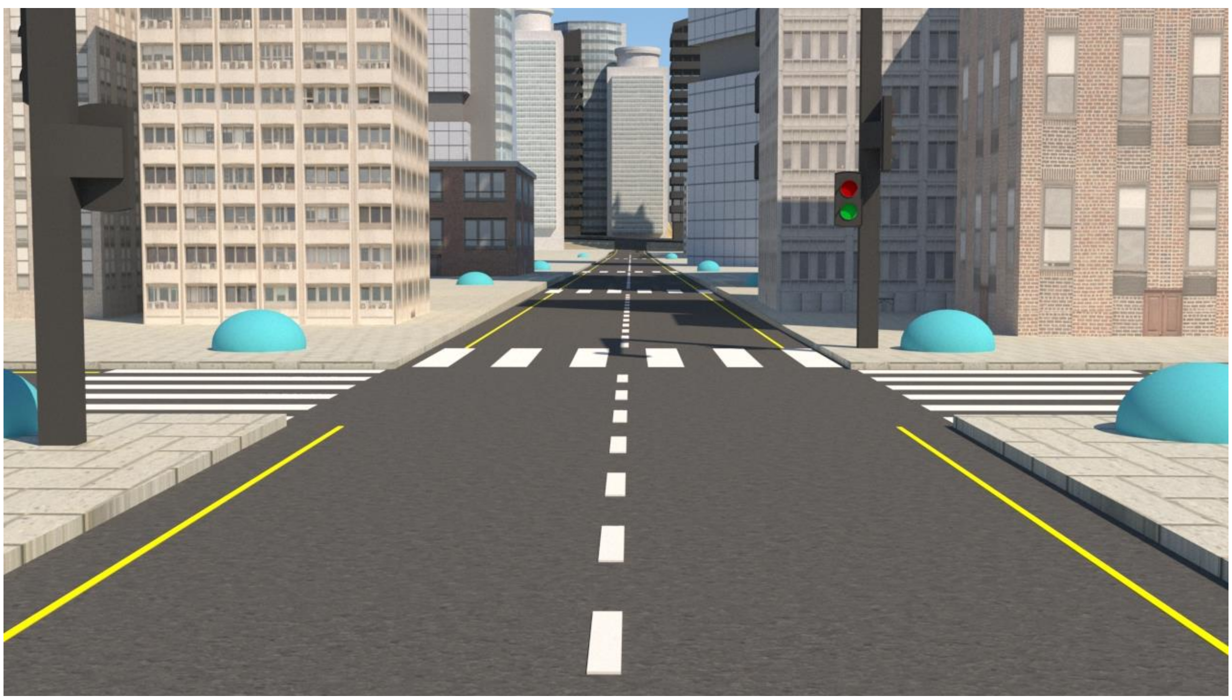


Figure 17. The spawn locations of the virtual characters as they are shown in the developer view (These indicators are not visible to the participant).

Figure 18. The 28 (14 female /14 male) characters created for this framework.

3.2 Virtual Environment – Modeling

The researcher can import his/her own model of a virtual environment but there is already a general model of a city contained. It is important to select the destination points for the crowd at the beginning since the Nav Mesh (Navigation Mesh, a type of data structure used in pathfinding) functionality of Unity game engine is used for the crowd (Figure 17). The virtual characters from the crowd are able to walk to any direction (e.g. can move to any corner or middle of an edge) in a four way intersection scenario. There is no need to use all the waypoints. The used waypoints though should be selected when configuring a test. Additionally, the user configures the start points where the participant will begin walking and the end points where he will stop. Furthermore, he/she should also determine the start and end points for the crowd and some intermediate points to reduce any congestion that may happen during the experiment. Finally, once all the points are defined and participants are positioned, an audio and/or visual signal is given to start walking and another signal once they have reached their destination, to stop walking.

3.3 Virtual Crowd

There are 28 models of humans (14 female /14 male) contained in the framework (Figure 18), depending on the needs of the experiment though any number of models is acceptable. The aim here is to supply researchers with a number of fairly realistic characters with low poly-count (polygons number) in order to run in a variety of different equipment (e.g. older HMDs) and applications. In their study, McDonnell et al. [161] concluded that the realistic appearance of virtual agents can improve participants' immersion and feeling of presence. Finally, all human models come with variances in clothing and ethnicity to improve the realism in the virtual environment.

3.4 Crowd Simulation

In order for the framework to be functional and useful for the completion of experimental studies by the researcher, some hypotheses are established. One of them involves the physical requirements for the creation of a walking experiment, namely a sufficient area where the participant will be able to move around and navigate. In addition, several kinds of equipment are needed, such as cordless HMDs or HMDs with integrated wireless adapters that support Oculus VR or Steam VR (e.g. Oculus Rift/Quest, HTC Vive) and backpack computers to secure unrestricted movement of the participants. Finally, the virtual crowd is pre-scripted with several specifications set by the researcher such as:

- **Crowd Size:** Declares the highest number of virtual agents that will consist of the virtual crowd.
- **Crowd Speed:** Initiates the top seed that each virtual agent of the crowd can walk.
- **Interpersonal Distance:** Refers to the lowest distance that individual agents can walk nearby others and the user.
- **Spawn Gap Time:** Defines how quickly a new virtual agent will spawn. This rate is calculated in seconds.

- **Spawn Radius:** Specifies the cyclical space where the virtual characters will spawn around their spawning spots.

- **Direction:** Sets an offset to configure the marked position where the virtual crowd can walk. Several walking patterns where the virtual agents (of the virtual crowd) can walk in, can also be specified. In addition, the researcher must specify a square space in the virtual environment by a location and a walkable area. Eight spawn points placed at the corners and center edges and twelve final target spots where the virtual agents can walk between are in the walkable area. The virtual characters are defined to spawn at particular places by several pre-scripted booleans.

3.5 Data Acquisition

There are some measurements included in this framework. Statistics are gathered every 0.10 seconds by default. Figure 19 shows the Xsens motion capture system used for collecting motion data. All statistics are exposed automatically as soon as each trial finishes. Extra measurements can be simply added to the framework while the techniques included are the following:

- **Time and speed to cross:** This measurement starts when the participant is told to start walking until he reaches the marked destination.

- **Trajectory length:** Defines the total walking length between start and end point of the participant.

- **Trajectory smoothness:** Defines the deviation from a straight line.

- **Direction:** Specifies the total deviation from the target's node until he arrives at the other side.

- **Average distance to crowd:** This measurement calculates the five closest neighbors to define the distance to the virtual crowd for avoidance behavior usage.

- **Over/undertaking behavior:** Calculates if the participant is passing or being overtaken by the virtual agents of the crowd.

Figure 19. Xsens motion capture system.

Figure 20. The HTC Vive Eye Pro HMD, which has eye-tracking technology.

Figure 21. iMotions Electrodermal activity sensor (for capturing electro-dermal activity).

There is also the possibility for further collection of measurements (other than movement) through several libraries. Such as eye-tracking data and electro-dermal activity.

- **Gaze data:** The system supports eye-tracking functionalities with the use of an HTC Vive Eye Pro HMD, which has integrated eye-tracking capabilities (Figure 20). With the use of such equipment it is possible to record eye gaze data (e.g. fixation, gaze points, heat maps, locations of interest) that afterwards can be used to investigate how and where participants focus during interactions with virtual crowds.
- **Electro-dermal activity:** The system supports physiological data capture (electro-dermal activity) that can be used to understand participants' emotional reaction when interacting with virtual crowds (Figure 21). Electro-dermal can be measured as a result of eccrine sweat gland activity which is associated with emotion, cognition and attention [288].

Chapter 4

Effects of the Density, Speed, and Direction of a Virtual Crowd on Human Movement Behavior

A variety of real-world interactions between humans and crowds can be relocated and conducted to virtual worlds [162]. Let's assume that someone wants to travel to a virtual metropolitan city and walk around the area or virtual reality users that want to be taught in buildings' evacuation methods or even in a movie production where the actor is needed to walk around people. In all these examples it is possible that the users of these virtual reality experiences could be surrounded by virtual crowds of people that have different density and move with different speeds and directions.

There is an increased volume of published papers in the literature related to the modeling, simulation and overall analysis of virtual crowds and crowds' dynamics [163] – [170]. Several articles investigate interactions between individual users and groups of virtual people while there is limited research that investigated how users behave and walk while surrounded by virtual crowds [2], [171]. As a result of this absence of convincing results, studying and understanding if a virtual crowd has or hasn't an impact on the movement behavior of users might be very useful in the creation of virtual experiences that comprise interactions with virtual crowds.

The first study (Study 1) of this thesis investigates three parameters (Figure 22) density, speed and direction to understand if a user's movement behavior is affected by a moving virtual crowd [161]. The participants (of this study) were instructed to cross a virtual crosswalk in a virtual metropolitan city, while surrounded by a virtual crowd that was pre-scripted to walk towards the opposite sidewalk. In each condition that was examined, the participants were instructed to perform a simple walking task while their movements were captured. In addition, three measurements (speed, deviation and trajectory length) were extracted to investigate the effects of crowd movement on the movement behavior of the participants'.

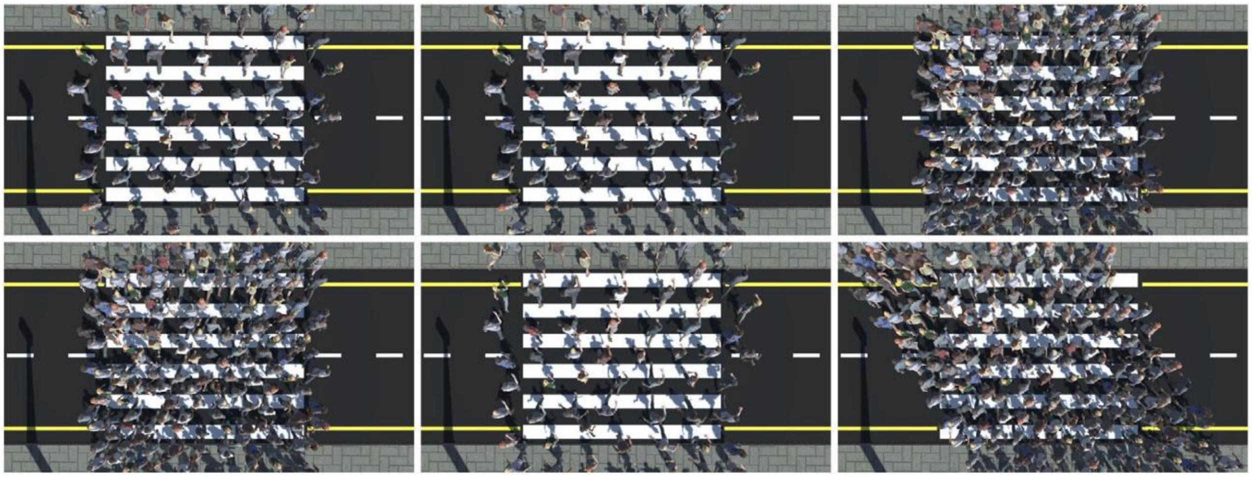


Figure 22. The parameters that were examined in our paper [7]. Left: low density (top) versus high density (bottom) situations. Middle: low speed (top) versus high speed (bottom) situations. Right: straight direction (top) versus diagonal direction (bottom) situations.

4.1 Methodology

4.1.1 Participants

Eighty (80) individuals (*age: M* = 22.51, *SD* = 3.02, gender: Male = 58, Female = 22) were recruited from a university setting. The recruitment was performed through class announcements, emails, and posters placed on announcement boards in Purdue University. The participants were volunteers and there was no compensation offered. Motion sickness or any other types of cyber sickness was not reported. Each participant performed a single walking task for each condition while all participants were exposed to all examined conditions.

4.1.2 Conditions of the experiment

Based on *density*, *speed* and *direction* that characterize a virtual crowd, eight experimental conditions were developed and tested. A 2x2x2 withing-group (i.e. low versus high density, low versus high speed, and straight versus diagonal direction) study design was chosen to directly compare the different parameters of a virtual crowd across the examined conditions of the study. The eight conditions that were examined were formed in three pairs: low density versus high density (*density*), low speed versus high speed (*speed*), and straight direction versus diagonal direction (*direction*). Figure 25 shows each parameter.

In terms of *density*, a virtual crowd with one pedestrian for every square meter was simulated for the low density condition while a virtual crowd with 2.5 virtual characters for every square meter was simulated for the high density condition. For this study, the density model proposed by Still [164] was considered and applied to handle the density parameter of the virtual crowd and to define the amount of pedestrians for every square meter.

For the *speed* parameter, a normal walking speed was assigned to each virtual character in the crowd for the low speed condition, according to the US Manual of Uniform Traffic Control Devices [172], which reports that the estimated normal walking speed of humans is 1.2m/s. For the high-speed condition, a running motion of 3.8m/s was assigned to each virtual character, according to Miller's et al. [173] estimations.

For the *direction* parameter each virtual character was scripted to cross the road with a 0^o angle for straight direction condition. For the diagonal direction condition, the angle value was set to 30^o. Consequently, in the diagonal direction condition, each virtual character reached the opposite sidewalk with an offset distance. Several other directions could have been assigned to the virtual crowd, including the opposite (i.e. crowd moving against the participant) and also perpendicular ones. In this study it was investigated if a crowd that is moving to the opposite sidewalk (the virtual crowd is moving along with the participants) could have an impact on movement behavior of the participants. In addition, Nelson et al. [174] found no significant effects if crowd direction on movement behavior of participants when 2^o, 4^o, 6^o, 8^o and 10^o angles were applied to the characters and examined. Therefore, we decided to explore a 30^o angle condition to examine if such direction could affect the participants' movement behavior.

4.1.3 Measurements

To define the impact of each experimental condition on participants, the movements of participants were captured using a motion capture system. Later on, the trajectory of the root was exported from the full-body motion sequence and the data were down-sampled in 100 equidistant points [175], as was done in other studies [174], [176]. The three following parameters were measured for this study:

• ***Speed:*** The average speed of participants’ while walking towards the opposite sidewalk (measured in meters/second).

• ***Deviation:*** The *x*-axis deviation (absolute value) of the participants upon their arrival at the opposite sidewalk. Deviation was calculated using the difference between participants' initial *x*-axis positions (initial positions at the sidewalk) and final *x*-axis positions (final positions at the opposite sidewalk, measured in meters).

• ***Trajectory length:*** The participants' total trajectory length (total distance covered to reach the opposite sidewalk, measured in meters).

4.1.4 Experimental setup, equipment, and virtual reality application

The motion capture studio in Purdue University was used to conduct this study which is 8m long and 8m wide and has a ceiling height of 4m. The studio was free of obstacles (just a couple of chairs and a desk with a computer on one side of the room) to provide free space to execute the experiment. The participants were instructed to walk 7m for the purposes of our study, leaving some space to avoid collisions with walls.
For this study the following equipment was used: i) HTC Vive Pro head-mounted display to project and immerse the participants in the virtual environment, ii) Xsens inertial motion capture system to record participants’ motions, iii) a backpack computer (MSI VR One) to run the virtual reality application and iv) a Dell Allienware Aurora R7 desktop computer to remotely control the backpack computer and to change the conditions of the experiment. Figure 23 shows a participant while walking in the motion capture studio and the content displays on the head-mounted display.

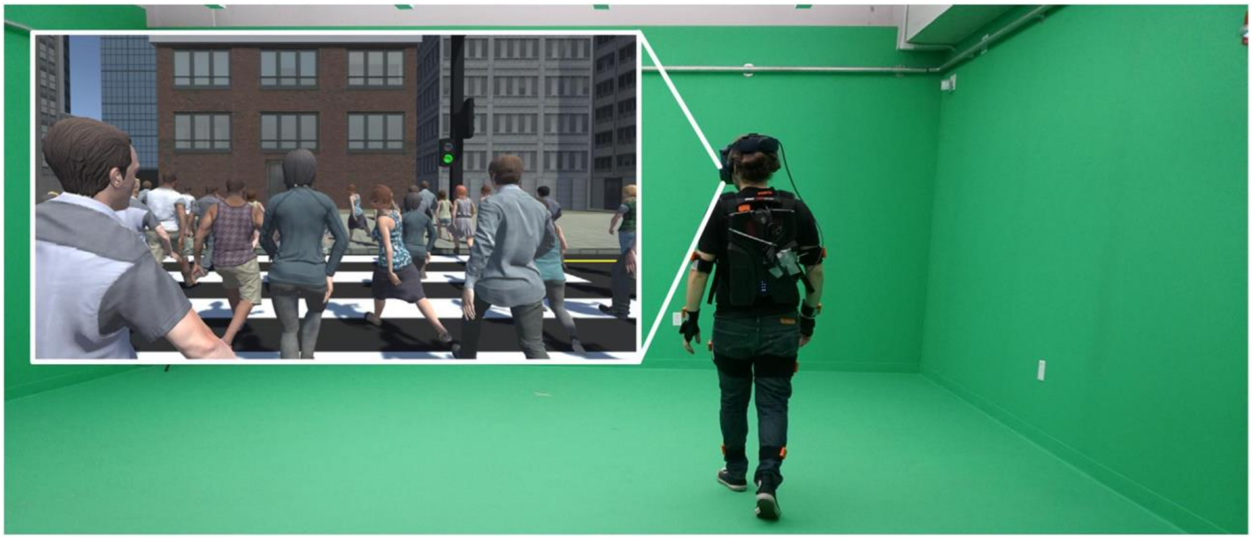


Figure 23. participant walking in the studio and moving toward the opposite sidewalk in the virtual metropolitan city. A third-person view of the virtual environment observed by the participant is also shown. The participant is wearing all the devices used in this study (an MSI VR One backpack computer, an HTC Vive head-mounted display, and an Xsens motion capture system).

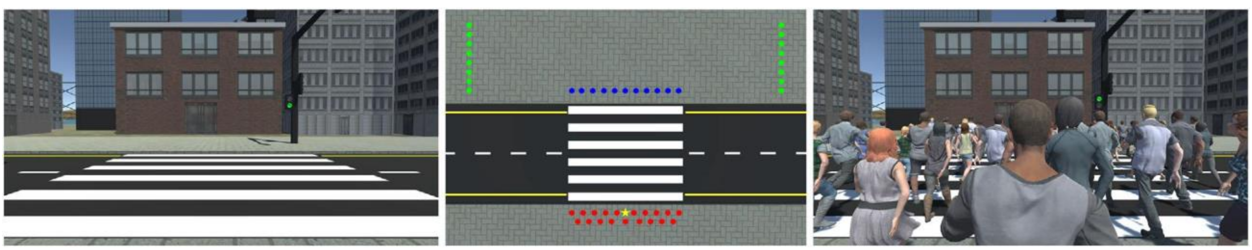


Figure 24. Left: The part of the metropolitan city (virtual crosswalk) that was used in our study. Middle: Each pedestrian in the crowd was initialized at the red circles and was asked to first reach the blue circle (target position) on the opposite sidewalk and then one of the green circles on the sides of the opposite sidewalk to alleviate congestion. The participant was initialized at the yellow star position, which means that the participant was surrounded by virtual pedestrians. For the diagonal situation, the target positions were shifted toward the left side. Right: A first-person view of the low speed, high density, and straight conditions of the virtual crowd to which the participants were exposed.

The virtual metropolitan city was designed using Autodesk 3ds Max. Afterwards, the model was imported to Unity3D game engine version 2019.1.4 which was used to develop and run the virtual reality application. Figure 24 shows the part of the metropolitan city where the participants were placed and asked to cross the virtual crosswalk. In order to have virtual pedestrians on the right and left sides (of the participants), participants were placed in the middle of the sidewalk. The virtual characters of the crowd were individually scripted to walk toward the opposite sidewalk. The crowd simulation was arranged to surround the participants during the walking task process (Figure 24). Virtual pedestrians were scripted individually to avoid participant's presence in the virtual environment, using the collision avoidance mechanism provided by the NavMesh Agent functionality of Unity. While the simulated crowd was scripted to follow a specific behavior (cross the virtual crosswalk and reach the opposite sidewalk), participants might have experienced slight variations of the crowd simulation, since each participant's behavior was unique and had a unique trajectory. Taking into consideration that the variations of the virtual crowd would appear in all conditions for all the participants and that the participants were surrounded by a virtual crowd with pre-scripted parameters, it was defined that such variations would not affect our results. Specifically, since the scope of the study was to investigate if the whole virtual crowd (not the individual virtual characters) are affected by the movement behaviors of the participants. Moreover, thirty (30) virtual characters were generated using Adobe Fuse software. The heights of the virtual characters varied to realistic values to create a realistic crowd. More specifically, the rounded approximations of the global average height (for females and males)[162] was used to design the virtual characters which is 1.70m for male and 1.60m for female characters. This was a decision that helped standardize the study. All the character designs were repeated multiple times during the road-crossing scenario. The virtual characters were created and rigged with the use of the developed framework (Chapter 3).

The Mecanim animation engine [285] of Unity3D was used to animate the virtual characters. Furthermore, Unity3D's motion blending functionality was used along with the proper blend weight assigned to the motion sequences to configure our characters to walk at a specific speed. Consequently, we were able to produce walking and running motions with the aforementioned speed specifications. Lastly, all the eight conditions were pre-scripted and used the buttons on Unity3D's inspector window to control the conditions to which the participants would be exposed.

To create an impression that the entire interaction was performed during the daytime, sunlight was used to illuminate the virtual metropolitan city. Audio and sound effects relevant to similar backgrounds and crowd-simulation scenario were used to increase the immersion and presence of the participants. Several studies found that sound related to the visual content increases the immersion and presence of a virtual reality experience [177], [178]. Eventually, it was decided not to use avatars to represent the participants since in a previous study, it was found that the use of virtual avatars that represent the participants during a walking task might have an impact on their movement behavior in the virtual environment [112]. This was a significant factor to consider (not to use a virtual avatar) in order to extract movement behaviors that were not affected by any other parameters than those examined (e.g. virtual body that doesn't match participant's body in terms of size and/or appearance).

4.1.5 Procedure

Each participant scheduled the day and time to participate in the study. Upon arriving at the studio, each participant was properly informed and asked to sign consent forms that indicated their agreement to participate in the study. The study was authorized by the institutional review board of Purdue University. The experimenter handed a demographics questionnaire to each participant as soon as the consent forms were signed. Afterwards, the research team assisted the participants to wear all the equipment needed for their participation in the virtual experiment. Then a member of the research team asked each participant to walk around the studio while they were exposed in a virtual environment identical to the motion capture studio (where the study took place). This protocol was strictly followed,, to ensure that the participants were able to perform regular walking without experiencing any sort of sickness (simulation or motion).

Immediately after each participant stated that he/she was comfortable with all the equipment attached to his/her body when immersed in the virtual environment, he/she was asked to remove the head-mounted display and go to a specified location within the studio and face the opposite wall. The research team was supervising whether the participant faced the forward direction while ensuring that the participant was exposed to the proper condition immediately after facing the forward direction. The participants were told that they would be located on the sidewalk of a virtual metropolitan city and to perform a simple walking task to reach the opposite sidewalk. In addition, they were informed that they will be surrounded by virtual people who will also walk in the same direction with them (reach the opposite sidewalk). Figure 23 shows a participant wearing all the required equipment and walking toward the opposite sidewalk. The research team didn't provide any further instructions to participants regarding the movement of the virtual crowd. Participants were informed that they should start walking as soon as the traffic light at the opposite sidewalk turned green and that a "beep" sound signal would inform them to stop walking once they have reached the opposite sidewalk. Furthermore, they were told that a black screen would appear once they have reached their destination (opposite sidewalk) and stopped. Once that happened, they were instructed to remove the head-mounted display and walk to the specified location in the motion capture studio to prepare for the next condition of our study. Finally, the participants were informed that the research team would inform them as soon as the experiment was complete and that they could take breaks between conditions and that they were allowed at any time to withdraw from the experiment if needed.

The research team helped the participants to remove all the equipment attached to their bodies, after completing all eight variations of the study. Then they were asked to provide feedback on the experimental study by writing their personal views on a blank sheet of paper that was handed to them. The research team was willing to answer any questions that they might have after the end of the study. The Latin squares ordering method [179] was used to secure a balance of first-order carryover effects between conditions. Lastly, should be noted that none of the participants spent more than 30 minutes in the motion capture studio.

4.2 Results

The acquired data were analyzed using a three-way repeated measure analysis of variance (ANOVA) with the **density**, **speed** and **direction** factors. The data were screened for normality using Q-Q plots of the residuals [180] which indicated that the assumption of normality was sufficient. *A* $p < 0.05$ was used to identify statistical differences, and post hoc corrected estimates using Bonferroni was adopted for cases in which the ANOVA produced significant results. Figure 25 shows the plots of the trajectories of participants for each of the eight conditions exposed.

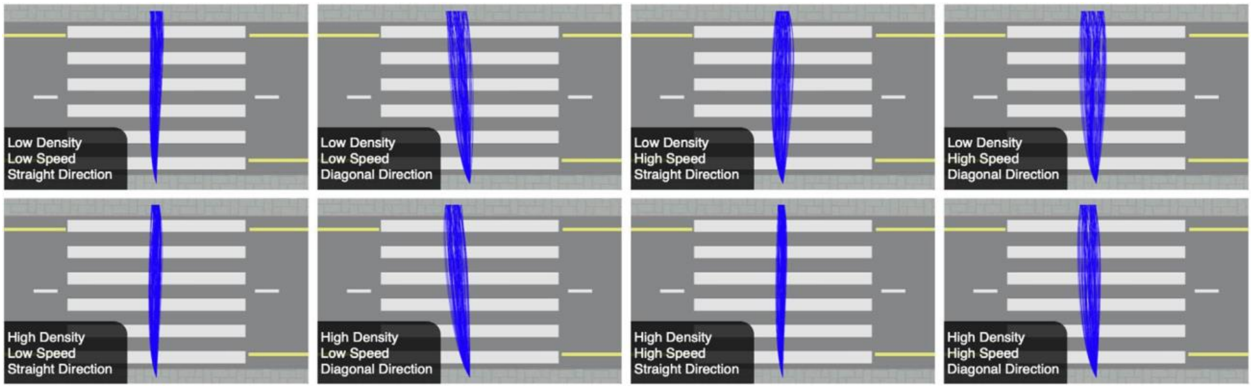


Figure 25. The participants' trajectories for each condition (combination of the different density, speed, and direction parameters) to which they were exposed.

4.2.1 Speed

We found significant main effect regarding the speed measurement for the **density**, $\Lambda=.076, F(1,79)=953.875, p < 0.001, \eta_p^2 = 0.924$, and **speed**, $\Lambda = 0.869, F(1,79) = 11.890, p < 0.01, \eta_p^2 = 0.131$ parameters; however, no significant results were found for the **direction** parameter, $\Lambda = 0.998, F(1,79) = 0.195, p = 0.66, \eta_p^2 = 0.002$. In addition, a pairwise comparison with the Bonferroni correction revealed that the participants' **speed** were significantly higher for the low-density crowd situation $(M = 1.38, SD = 0.02)$ than for the high-density crowd situation $(M = 1.09, SD = 0.01)$. This pairwise comparison also showed that the participants' speeds were remarkably higher for the high-speed crowd situation $(M = 1.24, SD = 0.01)$ than for the low-speed crowd situation $(M = 1.22, SD = 0.01)$. A two-way significant interactions effect was found between **density** and **direction**, $\Lambda = 0.948, F(1,79) = 4.305, p < 0.05, \eta_p^2 = 0.052$. The estimated marginal means showed that the participants' walking speeds were significantly higher when exposed to low-density and straight direction crowd conditions. Also, a three-way significant interaction effect between *density*, *speed* and *direction* was found, $\Lambda = 0.813, F(1,79) = 18.212, p < 0.001, \eta_p^2 = 0.187$. Finally, the estimated marginal means indicated that the speeds of the participants were particularly higher when exposed to low-density, high speed and straight direction crowd situations. Figure 26 shows the estimated marginal means of the plots.

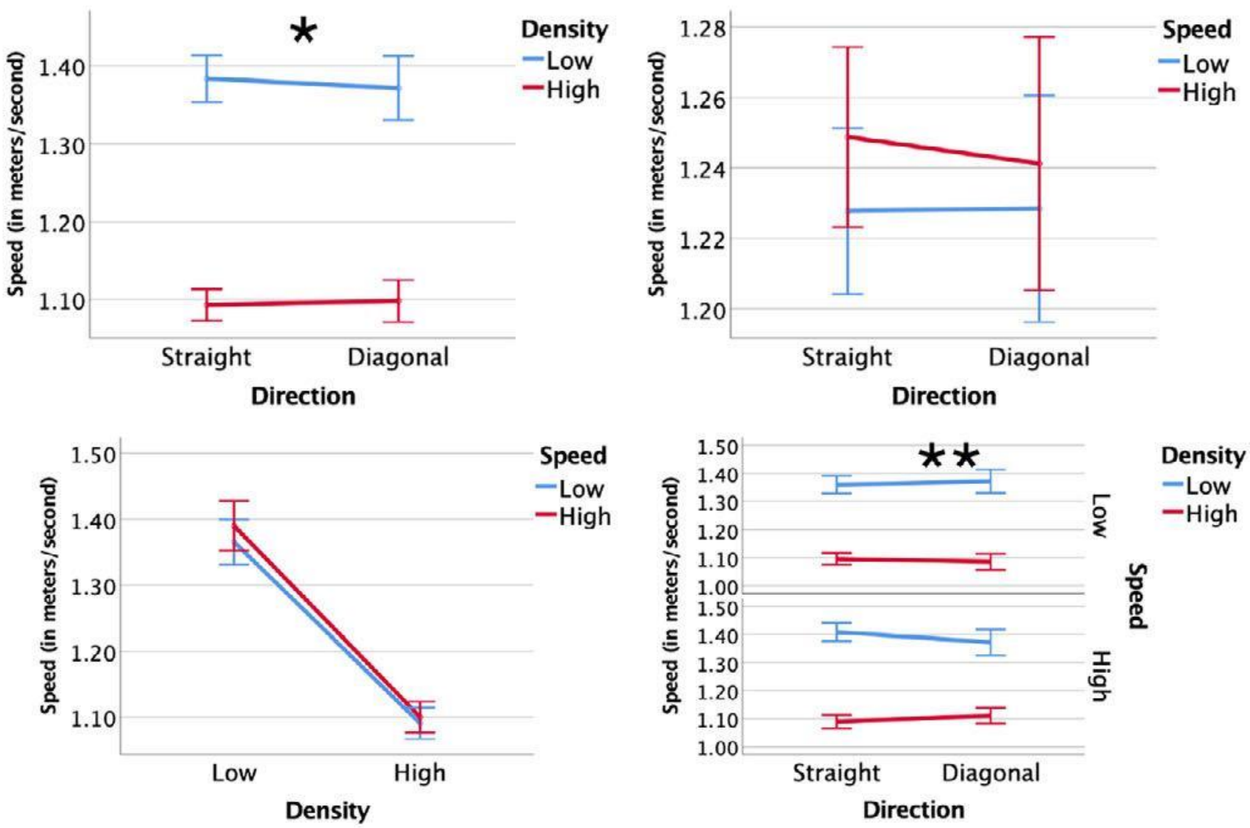


Figure 26. The plots of the estimated marginal means of the speed (in meters/second). State of direction × density, state of direction × speed, state of density × speed, and state of direction × density × speed. Significant results are indicated with *$p < 0.05$ and**$p < 0.001$.

4.2.2 Deviation

Significant main effect was found when examining the **deviation** measurement, for the **density**, $\Lambda = 0.857$, $F\,(1,79) = 13.169$, $p < 0.01$, $\eta_p^2 = 0.143$, and *direction*, $\Lambda = 0.722$, $F\,(1,79) = 11.890$, $p < 0.001$, $\eta_p^2 = 0.278$, parameters; however, no significant results were found for the **speed** parameter, $\Lambda = 0.994$, $F\,(1,79) = 0.491$, $p = 0.66$, $\eta_p^2 = 0.006$. A pairwise comparison with the Bonferroni correction revealed that the deviation of participants was significantly higher for the high-density crowd situation *(M = 0.24, SD = 0.02)* than for the low-density crowd situation *(M = 0.20, SD = 0.01)*. This pairwise comparison showed as well that the participants' deviation was remarkably higher for the diagonal crowd situation *(M = 0.27, SD = 0.02)* than for the straight crowd situation *(M = 0.16, SD = 0.01)*. Significant interaction effect were also found, between **density** and **direction**, $\Lambda = 0.811$, *F*

(1,79) = 18.470, p < 0.001, η_p^2 *= 0.189,* and between **speed** and **direction**, *Λ= 0.868, F (1,79) = 12.053, p <0.01,* η_p^2 *= 0.132.* The estimated marginal means indicated that the participants deviated more when exposed to a) high-density and diagonal crowd situations and b) low-speed and diagonal crowd situations. Three-way interaction effects were not found. Figure 27 shows the plots of the estimated marginal means.

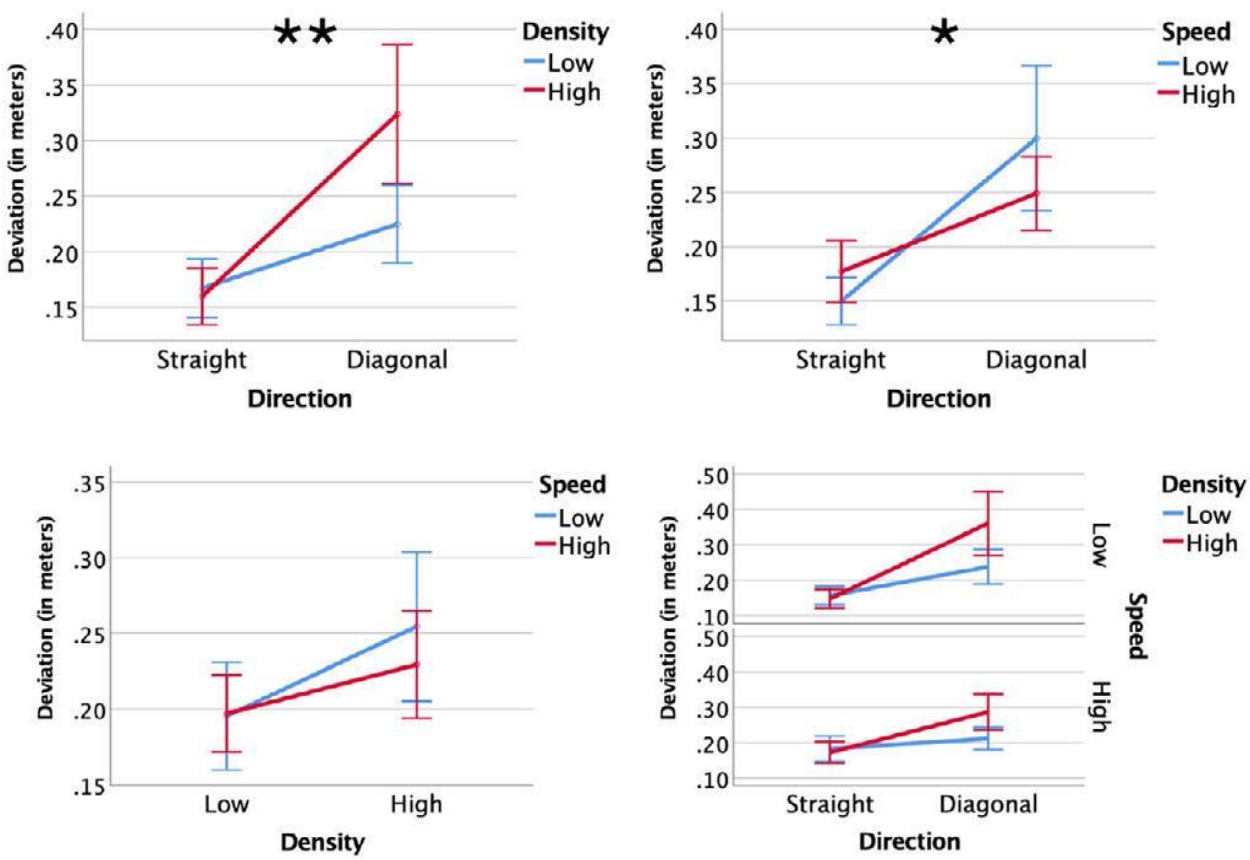
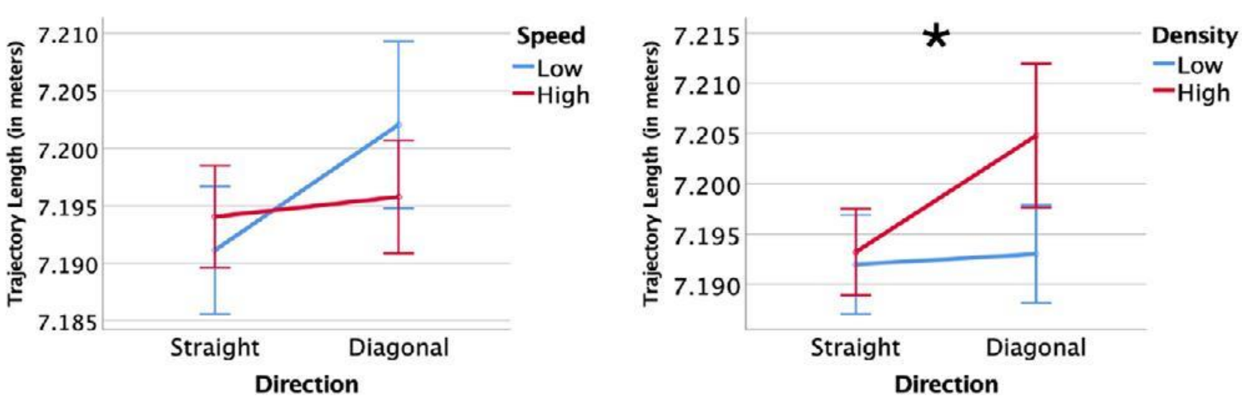


Figure 27. The plots of the estimated marginal means of the deviation (in meters). State of direction × density, state of direction × speed, state of density × speed, and state of direction × density × speed. Significant results are indicated with **p < 0.01 and **p < 0.001*.

4.2.3. Trajectory length

Regarding the trajectory **length** measurement, we found a significant main effect for the **density**, *Λ = 0.811, F (1,79) = 7.685, p < 0.01,* η_p^2 *= 0.089,* and **direction**, *Λ = 0.737, F (1,79) = 5.347, p < 0.05* ,η_p^2 *= 0.063,* parameters; however, we didn't find significant results for the **speed** parameter, *Λ = 0.886, F (1,79) = 0.347, p = 0.559,* η_p^2 *= 0.004.* A pairwise comparison with the Bonferroni correction revealed that the participants' trajectory length was significantly higher for the high-density crowd situation *(M = 7.20, SD = 0.04)* than for the low-density crowd situation *(M = 7.12, SD = 0.06).* This pairwise comparison also revealed that the participants' trajectory length was significantly higher for the diagonal crowd situation *(M = 7.21, SD = 0.11)* than for the straight crowd situation *(M = 7.05, SD = 0.07).* Significant interaction effect was also found between **density** and **direction**, *Λ = 0.852, F (1,79) = 3.153, p < 0.05,* η_p^2 *= 0.048.* The estimated marginal means indicated that participants' trajectory length was higher when they were exposed to high-density and diagonal crowd conditions. There were not found three-way interaction effects. Figure 28 shows the plots of the estimated marginal means.



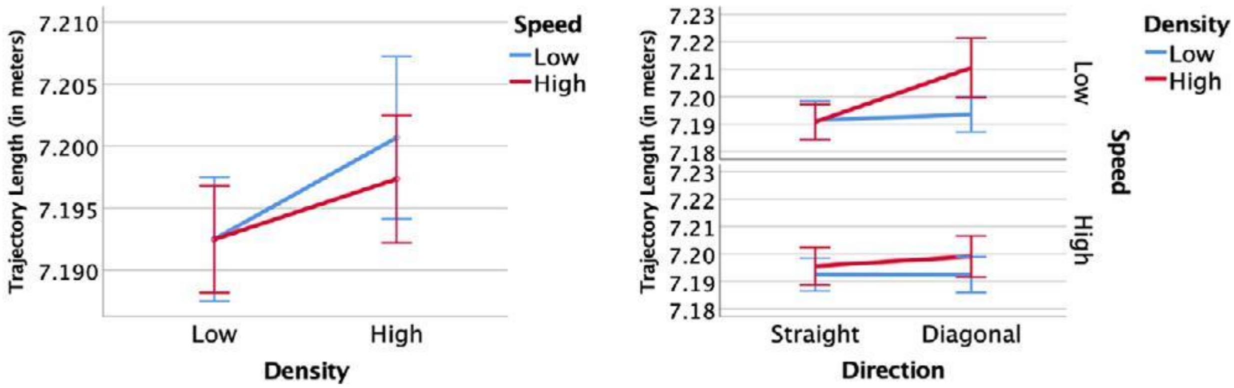


Figure 28. The plots of the estimated marginal means of the trajectory length (in meters). State of direction × density, state of direction × speed, state of density × speed, and state of direction × density × speed. Significant results are indicated with *$p < 0.05$.

4.3 Discussion

In our virtual reality study, participants were instructed to cross a virtual crosswalk and reach the opposite sidewalk while surrounded by a virtual crowd that was walking in the same direction. Three parameters (*density, speed,* and *direction*) were investigated that describe a moving virtual crowd. We developed eight virtual reality conditions related to the crowd parameters. Participants' motions were recorded using motion capture equipment and used to extract the speed, deviation and trajectory length measurements to understand the effects of the different conditions assigned to the virtual crowd on human movement behavior. The results obtained from this study indicated that the assigned three parameters (density, speed, and *direction*) to the virtual crowd definitely affected participants' movement behavior in the virtual environment.

After consideration of the results of our study, it can be said that the *density* and *speed* parameters of the virtual crowd can be used to manipulate the walking speed of participants, something that is in line with previous works conducted by Nelson et al. [174] and Dickinson et al. [181]. Nevertheless, this does not apply to the *direction* parameter of the virtual crowd. Moreover, the results obtained in this experiment indicated specifically that an increase in the speed of the virtual crowd corresponds to an increase in the speeds of participants. The participant's speed was also increased when he was exposed to a low-density virtual crowd. A two-way and three-way interaction effect was also found. Finally, our results showed that the participants had significantly higher speeds when they were exposed to low density and straight conditions in addition to low density, high speed and straight conditions.

Considering our findings, we could say that humans attempt to secure distance when avoiding virtual people [67], [112], consequently, the participants decided to decrease their movement speeds to avoid collisions with the virtual people, as soon as they became aware of the nearby virtual people that were surrounding them [68], [70]. Few participants reported that they were not fully aware of their exact distance from the opposite sidewalk due to limited visual information in high density crowd situations. In this situation (high density crowd) the participants were located and exposed in an environment full of virtual characters while the virtual crowd in front of them blocked the opposite sidewalk. That blocking affected all participants regardless of their height. Therefore, they decided to proceed carefully by reducing their speed as they walked to the opposite sidewalk according to their comments.

The results obtained from the deviation measurements indicated that the *density* and *direction* of the virtual crowd were the parameters that made participants deviate significantly from the exact forward position on the opposite sidewalk. No significant results were found regarding the *speed* of the virtual crowd. The results in our experimental study suggested that the participants exposed to the high-density virtual crowd deviated remarkably more from the exact forward position than compared to when exposed to a low-density virtual crowd. Moreover, the results indicated that the deviation of the participants was significantly higher when they were exposed to the diagonal direction of the virtual crowd compared to the straight direction (of the virtual crowd). We also found a two-way interaction effect in addition to the one-way effects. More specifically the results showed that the participants' deviation was greater when they were exposed to either a high-density virtual crowd or to a low-speed virtual crowd that moved diagonally. This is illustrated in Figure 27.

The results obtained from the deviation measurements suggest that the *density* and *direction* of a virtual crowd can affect participants' movement behaviors. More specifically, the way the participants deviate from the exact straight position on the opposite sidewalk. The interaction effects regarding *density* and *direction*, as well as *density* and *speed*, gave even more information into how the participants decided to adjust their movements in the virtual environment. An interpretation could suggest that the participants might have felt trapped once they were surrounded by the high-density crowd. Therefore, the participants might have decided to walk with the flow of the crowd instead of attempting to free themselves from it [121], [141]. Previous studies have shown that humans tend to coordinate with virtual characters when in their presence [142] – [144]. In addition, the *direction* and *speed* interaction effect shows that the participants might have been more comfortable to follow the virtual crowd that was moving on low speed instead than when it was moving on high speed. In order to interpret this result, all conversations with the participants were recalled after the completion of the walking tasks. Notably, a number of participants did not deviate significantly from the forward position on the opposite sidewalk because they felt less safe when they were following fast moving virtual characters. Additionally, the high-speed motion assigned to the virtual characters annoyed several participants (according to their comments) and had trouble concentrating on their target destination.

No significant results were found when examining the trajectory length measurement, regarding the *speed* parameters assigned to the virtual crowd. However, the *density* and *direction* parameters assigned to the virtual crowd, made the participants follow longer paths when they were crossing the virtual crosswalk. More specifically, the results showed that the participants followed longer paths when they were exposed to the high-density virtual crowd in contrast to the low-density virtual crowd. Furthermore, our results revealed that when the participants were exposed to the diagonal direction of the virtual crowd the length of their trajectories were higher compared to when they were exposed to the straight direction. Lastly, we found a two-way interaction effect between the *density* and *direction* parameters in addition to the one-way effects that were found. The results showed that the participants followed longer trajectories when they were exposed to the high-density crowd that was moving in a diagonal direction compared to their trajectories when they were exposed to the low-density crowd that was moving in a forward direction.

Previous work that has addressed virtual crowd density and humans' collective behavior and movement coordination is the main base for the interpretation of our findings. More specifically, previous work on crowd density [181] concluded that different density conditions affect the trajectories of participants. In addition, considering the interaction effect between *density* and *direction*, clarifies that this finding could be relevant to prior studies that investigated simultaneous and collective human actions [115], [157], [182], [183], such studies found that humans tend to coordinate with nearby humans or virtual characters when performing tasks simultaneously. This study explains why participants' movements were affected by the virtual crowd population that surrounded them. In addition, some participants stated that they felt suffocated by the virtual crowd that was surrounding them and that made them move with the flow, specifically during the high-density situation. This implies that the paths that participants followed were affected by the high-density virtual crowd. As a result of that the chosen paths of the participants were based on the ability of the virtual crowd to manipulate their movements in the virtual crowd and not on their intentions.

Some additional participants' comments are possible to help us interpret and understand the reason that they decided to adjust their movement behaviors when they are exposed to certain conditions. More specifically, some of the participants mentioned that they were scared to move too fast, because they might need more time and space to slow down and stop once reaching the opposite sidewalk to not collide with the front wall. Furthermore, some participants reported that they were afraid to move too fast in order to avoid any possible collisions with the virtual characters, something that they thought that might affect the characters (generate a domino effect) and destroy the entire simulation process. Something that would be impossible to happen since there was no physics applied to the virtual characters. These comments might explain why the participants decided not to run very fast when they were exposed to the high-speed crowd situations. Lastly, some participants stated that they forced themselves to walk on a straight path and avoid deviating from that path since they were afraid that they might collide with the side walls of the studio. We found that when participants were exposed to the diagonal crowd direction then the deviation was increased (see Figure 28), that explains why they did not deviate so much compared to the crowd's deviation. The characters of the virtual crowd deviated approximately 4m, on average, while the participants deviated approximately 0.27m during the diagonal direction situation.

There are some speculations made by the research team related to their observations during the study that are worth noting. The participants were highly immersed with the virtual environment and they were concentrated on accomplishing their given task. According to the results, the virtual crowd was entirely responsible for manipulating the movement behaviors of the participants. We only gave the participants a single instruction to cross the virtual crosswalk and reach the opposite sidewalk. Consequently, the participants chose their own speeds and directions while immersed in the virtual environment. The high-level immersion that the participants experienced, we believe that was the result of a combination of factors. More precisely, they were exposed to a compelling virtual reality experience, where the visual, aural, haptic, proprioceptive, and vestibular systems were occupied throughout the experiment. This speculation, in conjunction with the data analysis results, indicates that the virtual crowd manipulated the movement behavior of the participants, since an assessment of their intentions showed that they adjusted their movement behavior according to the virtual characters' movements that were surrounding them. Something that was even more observable in low-speed and high-density crowd situations.

There are three limitations that were uncovered through discussions with the participants. The first limitation is related to the absence of haptic feedback. Few participants mentioned that they were expecting to feel the virtual characters touching their bodies, especially when they were exposed to the high-density crowd. The lack of haptic feedback made them believe that the virtual reality scenario was not sufficiently realistic, according to their comments. Another limitation is related to the motion capture studio where the study took place. Specifically, the participants said that they didn't want to increase their speed because they were afraid they might collide with a wall, since they knew that the space in front of them was limited. Finally, the third limitation is related to the equipment that was used in this experimental study. The participants stated that even though they felt comfortable while wearing the equipment, they thought that running while wearing all the gear might cause trouble, and might detach the backpack computer from its harness or that the sensors of the motion capture system might detach from the Velcro straps. Something that was not possible to happen when dealing with the aforementioned equipment, according to our experience. Nevertheless, this was a limitation that caused participants to not increase their speeds within the virtual environment. In conclusion, these are some limitations that should be considered by researchers when conducting studies that require participants to walk within virtual environments while surrounded by a virtual crowd.

Chapter 5

Evaluating Human Movement Coordination in a Virtual Crowd

In our daily activities we are surrounded by other people, walk side-by side and coordinate our movements based on the people who surround us (e.g. playing team sports, dancing, walking side by side on sidewalks, through parades, etc.). According to previous studies [3], [4], when two or more people perform an action with other people (e.g. walking toward a target position), one person's actions mutually influence the actions of the other people, resulting in that particular group acting as a unit. In addition, people tend to synchronize their movements and their steps by following a tempo when walking together [5], [6], [139].

Study 2 investigates the movement coordination of participants, during immersive crowd interactions, a usual type of interaction that people encounter on a daily basis when walking in real environments. For example, someone might want to travel virtually to a metropolitan city and take a walk on a sidewalk to explore the surroundings. During such an experience the users are possible (to increase the level of immersion) to be surrounded by a virtual population. Consequently, in order to develop virtual reality experiences that better replicate the aforementioned interactions with virtual pedestrians, it becomes essential to investigate and understand how the virtual population affects a user who is walking in a virtual environment. In this paper, the participants were placed at a crosswalk in a virtual metropolitan city and were instructed to cross the road and reach the opposite sidewalk. There was also a virtual crowd that was scripted to walk in the same direction. Several measurements were captured during the road crossing experiment to evaluate participants' movement behavior. Moreover, the initial direction and the time step of the simulation in which the participant started walking toward the opposite sidewalk parameters were captured and used afterwards to simulate the virtual characters that were scripted to be part of the crowd. All the examined measurements for the simulated characters were calculated and used as a baseline to a) explore whether the movement behaviors of participants differed from the movement behaviors of the simulated characters, and b) investigate the possible relationships between the participants' movements and the movements of the simulated characters. We considered the movement behaviors of the simulated characters to be ideal, since they were scripted to become part of the moving crowd using Reynolds' rules [23] on flocking behavior (separation, alignment, and cohesion).

In this study we investigate how participants coordinate their movement behavior when immersed in a virtual crowd interaction scenario. According to Reynolds' rules [23], the simulated characters coordinated with the virtual crowd and became part of it. We explored whether the participants coordinated with the virtual crowd and consequently, whether the human participants became part of it, by exploring potential differences and associations between the participants' and the simulated characters' movements. Significantly different movement behaviors for some of the participants' measurements compared to those of the simulated characters were found. In addition, substantial relationships between the participants' movement behaviors and those of the simulated characters were found. Finally, the results in this study demonstrate how the participants coordinated their movements in agreement with the movements of the virtual crowd that surrounded them when performing a locomotive task, and if the participants became members of the virtual crowd (acted as boids [23]) by following similarly the movement behaviors that the simulated characters were scripted to perform.

5.1 Methodology

5.1.1 Participants

The eighty (80) participants who comprised the group that participated in the study were recruited through class announcements and emails. Twenty-two (22) of them were female and fifty-eight (58) were male. Their age ranged from 19 to 37 years old, with a mean of M = 22.51 (SD = 3.02). All the participants were volunteers and forty-three (43) of them had prior experience with virtual reality. There was no report for any type of cybersickness or motion sickness. In most of the previous studies that explored movement behavior in virtual reality environments, small sample sizes were used [4], [17], [104] and each participant performed an increased number of trials to smooth out the movement behavior that was captured. Recommendations on sample size for linear regression made by Dupont et al. [184] were taken into consideration. Consequently, to ensure the reliability of the results, a larger sample was recruited and participants performed multiple trials (like Jiang et al [4] and [185]) to smooth out the behavior of their recorded movement.

5.1.2 Setup and Virtual Reality Application

Study 2 was conducted in the motion capture studio of Purdue University. To project the virtual reality content the HTC Vive Pro head-mounted display device was used. To capture the movement of the participants an Xsens inertial motion capture system was used and a MSI VR One backpack computer (Intel Core i7, NVIDIA GeForce GTX1070, 16GB RAM), to run the virtual reality application. It should be noted that it was decided to use a common head-mounted display in the study, since users are most likely to use a similar device to experience immersive walking in their own setup.

Unity game engine version 2019.1.4 was used to develop the application used for this study. 3ds Max was used to design the virtual metropolitan city that was imported afterwards to the Unity game engine to be used for the study. Figure 29 illustrates the virtual environment (crosswalk) that was used for this experiment, where also each participant was placed. Thirty pedestrians (15 female and 15 male) were designed in Adobe Fuse and rigged in Adobe Mixamo, for the virtual crowd simulation. To animate the virtual pedestrians, the Unity's Mecanim animation engine was used along with the motion data downloaded from the Unity Assets Store. The virtual pedestrians were placed behind the participant's position in the virtual environment (Figure 30) where they generated on a constant basis one in every second from ten spawn points. Each character's crossing was repeated multiple times.

The virtual characters were scripted to cross the road and reach the opposite sidewalk (same direction with the participants). Each participant was scripted to move to another location in the virtual environment to alleviate congestion, as soon as he reached the opposite sidewalk. Several studies found that the violation of personal space of the participants might trigger unnecessary alterations in their behavior [68], [174], thus was decided to simulate a crowd with a medium density (1.5 pedestrians per square meter, see Figure 31) [164].

To enhance users' immersion within the virtual environment, audio effects that mimicked the sounds of a metropolitan city full of pedestrians were used and sunlight to light naturally the scene as well. No self-avatar was used to represent the participants' body in the virtual environment, since a previous study found that a self-avatar may alter the movement behavior of the participants [112]. The participants were requested to walk 7 meters which was also the distance of the opposite sidewalk from the participant's position within the virtual environment.

Figure 29. The virtual crosswalk used in this study and the virtual crowd that was scripted to move toward the opposite sidewalk.

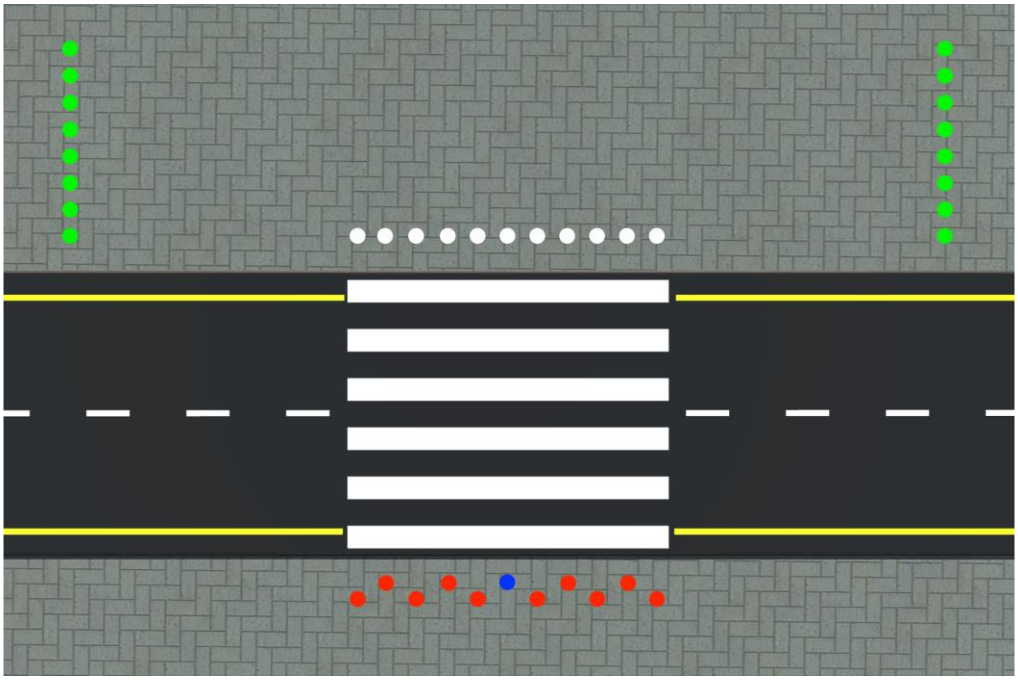


Figure 30. The positions the virtual pedestrians were initialized on the sidewalk are indicated by red circles, and they were scripted to reach one of the target positions indicated by white circles. Then the virtual pedestrians were asked to reach one of the green circles to alleviate congestion on the sidewalk. The participants were placed on the blue circle. All circles were not visible during the study. The blue circle corresponded to a marked location in the motion capture studio.

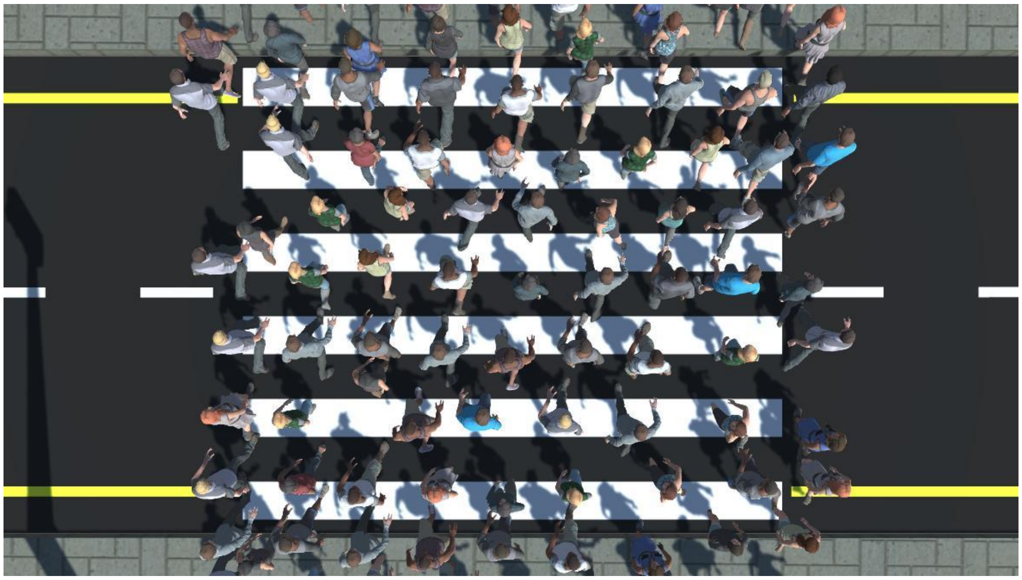


Figure 31. The medium size density model (1.5 pedestrians per square meter) that was used in the conducted experimental study.

5.1.3 Measurements

Behavioral, motion and electrophysiological recording techniques are typically used [13], [112], [131], [132], [151], [158], [159], to analyze and evaluate human behavior. In this study, in order to determine how participants coordinated their movement compared to simulated characters, measurements related to the task and the objectives of the experiment were computed. Thus, the captured motion of the participants was downsampled in one hundred equidistant points [110]. Afterwards, we extracted the data of each measurement. The following six measurements were extracted for this experimental study:

- ***Speed:*** The average speed of the participants' walking motion when walking towards the opposite virtual sidewalk (measured in meters/second).
- ***Time:*** The time needed by the participant to cross the virtual crosswalk (and reach the opposite sidewalk, measured in seconds).
- ***Length:*** The total trajectory length (covered distance) of the participants (measured in meters).
- ***Direction:*** The average absolute y-axis rotation on the (x, z) plane of the participant when walking towards the opposite sidewalk (measured in degrees). Zero degrees indicated that the participant was moving parallel to the segment that corrected his/her initial position and the forward position on the opposite sidewalk.
- ***Smoothness:*** It was computed as the average flicker of the trajectory [156] (it was measured in meters). Low flicker values denoted a smoother trajectory.
- ***Distance from nearby pedestrians:*** The average distance from the closest four virtual pedestrians in front of the participant, when moving toward the opposite sidewalk, was computed. The selected (four) virtual pedestrians were the same for the participants and the simulated characters and did not change during the walking task. It should be noted that for each trial, different nearby virtual pedestrians were chosen. The distance from nearby virtual pedestrians was measured in meters.

5.1.4 Procedure

We provided information about the experiment to the participants once they arrived at the motion capture studio. The participants were also asked to sign the provided consent form that was approved by the Institutional Review Board of Purdue University [286] and they also completed a demographic questionnaire. Then we assisted the participants to wear the Xsens motion capture system, the backpack computer and the head-mounted display. Afterwards, to ensure that the participants were comfortable wearing all the equipment, they were asked to take a short walk within the motion capture studio. Figure 32 shows a participant wearing all these devices. Then the experimenter asked the participants (since they were familiarized with the equipment) to move toward a marked location in the motion capture studio and face the opposite direction.

As soon as the participants went to the specified location, they were informed that they will be placed in a virtual metropolitan city, once the application started and they should cross the virtual crosswalk by walking toward the opposite sidewalk. They were also informed that they will be surrounded by a virtual population and that it was up to them to decide whether they should start walking. In addition, it was added that when they reach the opposite sidewalk, a "beep" sound would signal them to stop moving and that they will perform this task ten times. At the end of each trial, the participants were requested to take off the head-mounted display and go back to the marked location on the other side of the studio. Also, participants were instructed that they would be informed once the experiment had ended. The research team assisted the participants to remove all the devices after the tenth trial of the study. Afterwards, they were asked to write on a blank sheet, which was provided to them, describe their overall experience, and provide feedback on their movement behavior within the virtual environment. None of the participants spent more than 40 minutes in the motion capture studio.

Figure 32. The participant wearing all devices (MSI VR One backpack computer, HTC Vive head-mounted display, and Xsens motion capture system) used for this study.

5.1.5 Simulated Characters

In this study we evaluated whether the participants coordinated their movement behaviors according to the simulated characters, and therefore, whether they became members of the virtual crowd (acted as boids). Data related to the timestep in which the participants started walking toward the opposite sidewalk and the direction of the participants at that time were collected in addition to the measurements that were collected to analyze the movement behavior of the participants. These data were crucial to initializing the parameters of the simulated characters and were used to evaluate the participants' movement behavior.

The simulated characters were designed according to Reynolds' rules [23] on flocking behavior:

- **Separation:** The simulated characters should steer to avoid crowding nearby virtual pedestrians.
- **Alignment:** The simulated characters should steer toward the average heading of the nearby virtual pedestrians.
- **Cohesion:** The simulated characters should steer toward the average position of nearby virtual pedestrians.

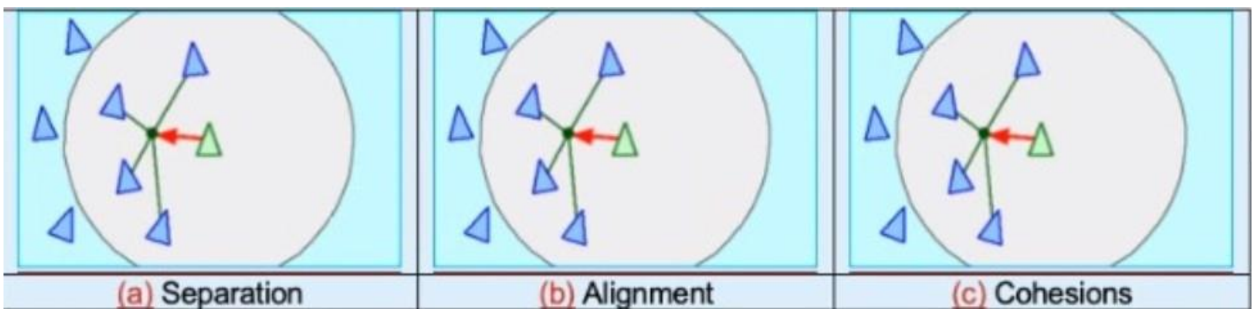


Figure 33. Rules applied in simple Boids based on Reynolds' rules [23], on flocking behavior.

While the movement of the virtual pedestrians was not affected by the movement of participants and the simulated characters that were used afterwards to evaluate the movement coordination of participants, the movement behavior of simulated characters is greatly affected by the behavior of nearby virtual pedestrians (the characters that compose the virtual crowd). Our system estimated the updated position of the simulated virtual character at a frame-by-frame rate until the character would reach the opposite sidewalk, based on the nearby pedestrians. Furthermore, two additional parameters were applied, such as: a) the closest distance between two virtual pedestrians, which was chosen to be the boundaries of the close phase of the personal space (76cm) according to the proxemics model [186], [187] and b) the crowd's speed set not to exceed 1.2m/s, which corresponds to the normal walking speed of humans, based on the U.S. Manual of Uniform Traffic Control Devices [172].

5.2 Results

The analysis of the results was performed using IBM SPSS version 24.0 [188] software. To determine differences between the measurements obtained from the participants and the simulated characters, paired-samples t-tests were used. Afterwards, to explore how the participants' movement behavior is associated with the movement behavior of the simulated characters, simple linear regressions took place. The normality assumption of the collected data was evaluated graphically using Q-Q plots of the residuals [180]. The obtained data fulfilled the normality criteria according to the Q-Q plots. Finally, a $p < 0.05$ value was deemed statistically significant.

5.2.1 Movement Behavior Differences

The pairwise relationships between the measurements obtained from the participants and those obtained from the simulated characters were compared using paired-samples t-tests. Figure 34 shows boxplots of all measurements. A significant difference between the **speed** (meters/second) of the participants, was identified *(M = 1.05, SD = 0.10)* and the simulated characters *(M = 1.12, SD = 0.05); t (79) = -7.111, p < 0.001*. The difference in **time** (seconds) among the participants *(M = 6.93, SD = 0.62)* and the simulated characters *(M = 6.45, SD = 0.32)* was also significant; *t (79) = 8.269, p < 0.001, p < 0.001*. Furthermore, the **trajectory length** (meters) was significantly different among the participants *(M = 7.52, SD = 0.076)* and the simulated characters *M = 7.09, SD = 0.06); t (79) = 22.716, p = 0.001*. The **direction** (degrees) was not significantly different among the participants *(M = 3.12, SD = 2.49)* and the simulated characters *(M = 2.70, SD = 1.13); t (79) = 1.879, p = 0.064*. In addition, the **smoothness** (meters) was significantly different among the participants *(M = 0.04, SD = 0.01)* and the simulated characters *(M = 0.02, SD = 0.01); t (79) = 8.738, p < 0.001*. Lastly, the **distance from nearby pedestrians** (meters) was significantly different among the participants *(M = 0.96, SD = 0.08)* and the simulated characters *(M = 0.90, SD = 0.06); t (79) = 9.543, p < 0.001.*

Figure 34. Boxplots of the results of all measurements for the participants (P) and simulated characters (C). Boxes enclose the middle 50% of the data. The median is denoted by a thick horizontal line.

5.2.2 Movement Behavior Relationship

Simple linear regressions were used to evaluate the relationship between the measurements obtained from the participants and those obtained by running the simulations. By using the measurements extracted from our participants, and the measurements extracted from the simulated characters as dependent variables, we conducted linear regression. The detailed results are shown in the regression table (Table 1). Linear regression was used for three reasons: a) previous studies [7], [174], found that the participants' movement behavior can be affected by the virtual crowd's movement behavior, b) since in this experiment the virtual crowd was scripted to move independently of participants, the movement behavior of participants could not affect the movement behavior of the virtual crowd and c) linear regression was used to measure the range of the linear relationship among the examined values.

	B	*SE B*	*β*	*t*	*p*
Speed	1.146	0.205	0.535	5.593	0.001
Time	1.106	0.180	0.570	6.134	0.001
Length	-0.148	0.234	-0.071	-0.630	0.531
Direction	0.743	0.102	0.636	7.275	0.001
Smoothness	0.176	0.099	0.196	1.769	0.081
Distance from nearby pedestrians	0.674	0.098	0.599	6.606	0.001

Table 1. Regression table for all examined measurements. The unstandardized coefficient (B), the standard error for the unstandardized coefficient (SE B), the standardized coefficient (β), the t-test statistic (t), and the probability value (p).

The results demonstrated that the participants' **speed** (meters/second) was associated significantly with the simulated characters' speed $(F\ (1, 78) = 31.284, p < 0.001, R^2 = 0.286)$. The results also indicated that the participants' **time** was significantly associated with the simulated characters' time $(F\ (1, 78) = 37.626, p < 0.001, R^2 = 0.325)$. The participants' trajectory **length** (meters) was not associated with the trajectory of the simulated characters $(F\ (1, 78) = 0.396, p = 0.531, R^2 = 0.005)$. Furthermore, the participants' **direction** (degrees) was associated significantly with the direction of the simulated characters $(F\ (1, 78) = 52.922, p < 0.001, R^2 = 0.404)$. There was no significant association of trajectory **smoothness** (meters) between the participants and the simulated characters $(F\ (1, 78) = 3.130, p = 0.081, R^2 = 0.039)$. Lastly, the results indicated that the participants' **distance from nearby pedestrians** (meters) was associated significantly with the distance from nearby pedestrians of the simulated characters $(F\ (1, 78) = 43.635, p < 0.001, R^2 = 0.359)$.

5.3 Discussion

Study 2 aimed to determine how participants coordinate their movement behavior when they cross a road to the opposite sidewalk while surrounded by a virtual crowd that is moving in the same direction. The participants were surrounded by the virtual population from the beginning of each trial. No additional instructions were given to the participants in terms of movement behavior of the nearby virtual pedestrians. The captured data were afterwards analyzed to determine if the participant was successfully embodied in the virtual crowd, thereby becoming boids (matching the movement behavior of the simulated characters).

According to the results obtained from this study, participants reveal a clear disinclination to walk their path similar to the way the simulated characters did. More specifically, the participants tend to move slower, spending more time to accomplish the task. It is shown that they follow longer paths, they perform less-smooth motions, allowing more distance between themselves and the nearby virtual pedestrians. Moreover, participants perform their movements differently from the simulated characters. Nevertheless, after examining the relationships between the participants' movement behaviors and those of the simulated characters, the speed, time, direction, and distance measurements from the nearby pedestrians were remarkably associated.

The analysis of the results shows that the virtual crowd did affect the movement behaviors of the participants, because it seems that the participants associated their movement with the virtual crowd's movement. Though, the impact of the crowd on the movement of the participants was not enough to make the participants follow the crowd's movement with the exact same pattern in contrast to the simulated characters. It is possible that this outcome might be related to various other studies that have investigated concurrent and joint human actions [115], [157], [182], [183]. To clarify this outcome, we turn our attention to perception-action-related studies that concern human movement behavior. Specifically, Gibson [189], found that when humans walk with each other, they need time to process their course of action and they initiate their walking only after they feel safe enough to merge between themselves and the nearby humans. In addition, Brass et al. [129] proposed that the observation of a movement influences the execution of a similar movement, while Watanabe [190] derived that humans tend to modify their movement, since the speed of other humans may affect the timing of the movement execution. This could explain why the participants decided to follow the movement of the virtual crowd to a moderate degree and not to highly coordinate their movements.

Our results indicate that the participants were highly immersed in the virtual environment, and engaged with it. They were highly focused on accomplishing the task that was given to them. Several factors can explain this high level of immersion and engagement. First, no external parameters existed to interfere with the participants' sensations since they were wearing a full-blind head-mounted display. This is significant, because this action triggers the sensory motor system (haptic, proprioceptive, and vestibular systems) of humans that supports locomotion. Thus, a compelling experience was created from the combination of these factors.

Furthermore, the participants' decision and movement behavior were made autonomously, since they were not asked to follow or imitate the movement behavior of the virtual crowd. The participants decided how they should move and how they should coordinate with the nearby pedestrians. There are some interesting questions that could be raised about the decision of the participants to adjust their movement behavior when moving within a virtual crowd. The perception of the movement of others has been researched from the field of psychology [191] and provides some interesting insights about the definition of such decisions. Specifically, it has been found that it is possible to extract useful information about the actions, moods, and intentions of others, by observing their motions, which renders this observation into a critical channel of communication [192] – [194]. Additionally, Adams [195] has addressed the nature and contribution of sensory feedback in movement coordination (timing and positioning) and stated that there is no a priori reason why feedback from any sensory system cannot inform movement. This could explain why the participants, after evaluating their intention of how and when to move toward the opposite sidewalk in the virtual environment may have responded to the movement behavior of the nearby virtual pedestrians.

While we found several significant relationships between the movement behaviors of the participants and the simulated characters, we also found significant differences. This indicates that the participants walked differently than the simulated characters. Few participants stated that they were concerned about damaging the equipment they were wearing, so they decided to move slower. Some other participants stated that they did not feel comfortable within the virtual population. Therefore, this might lead to an attempt to avoid nearby pedestrians and deviate from the ideal path and follow longer routes. Similarly, other participants reported that in order to move more freely, they were trying to follow clear or less dense areas. Moreover, some participants said that they felt confused with the absence of a self-avatar, something that made them unaware of their exact position, their boundaries, and if they collided with the virtual pedestrians. Lastly, some participants mentioned that they did not have previous experience moving within virtual environments, thus they moved slower.

According to the literature, humans' fear of colliding with obstacles (including walls) in real environments when immersed in a virtual environment often reduces their natural locomotion behavior and gait, consequently changing their movement behavior in virtual environments [196]. Additionally, aesthetic mismatching between real and visual environment can also influence the participants' movement behavior [110], [175]. Even though the real environment was free of obstacles, and the virtual environment was constructed in a similar way (free from obstacles and flat terrain), fear of collision and aesthetic mismatch might have affected the participants' movement behavior.

It should be noted that the simulated characters were scripted to move toward a specific direction. In our study, even if the simulated virtual character had self-awareness of its relative position, direction, speed, and collision with the virtual pedestrians, it would move to the opposite sidewalk without being affected by external parameters and visual stimuli, like our participants were. This could explain to an extent why the trajectories of the simulated characters were smoother than those of the participants. Another factor that explains this reduced smoothness might be that the signal from the motion capture system may be affected by the presence of unwanted noise.

The comparison and evaluation of the movement behaviors between humans and simulated characters, might be problematic. This is due to the fact that such evaluation between natural human behavior and computer-generated behaviors which are highly constrained and scripted to follow specific rules without deviations. Data-driven crowd simulation techniques [42], [197], [198], might be more suitable for synthesizing the movement of virtual pedestrians, because the extracted measurements will be closer to the real-life measurements. However, in order to arrive at more substantial conclusions, further experimentation is required. Overall, significantly useful information regarding human movement behavior could still be obtained, despite that the use of measurements obtained from the simulated characters and from the participants is considered too constrained due to the nature of simulation.

Chapter 6

Effects of Tactile Feedback during Immersive Walking in a Virtual Crowd

The development of virtual reality devices and interfaces during the last years, offers people the ability to experience and immerse themselves in virtual environments that are totally different from the place that they are actually located. Besides the visual information which is sent through the head-mounted display that is used to project the virtual content, to the virtual reality users, in order to have a compelling experience, the aural, haptic, proprioceptive, and vestibular systems should also be engaged during the experience [4], [199]. Nevertheless, several additional pieces of equipment are necessary to achieve a compelling experience.

After taking into consideration the recent progress in commercial virtual reality tactile feedback devices that have been evolved to provide to the users the ability to sense a virtual reality experience, a study was conducted on human body contact imposed through a wearable tactile vest. This study visually places the users within a virtual environment, where they were instructed to perform a walking task while surrounded by a virtual crowd of people, by combining the tactile feedback with the ability of the virtual reality headset to track the user's position. Tactile feedback can be used to guide users and help with navigation [200] – [203], and there are several studies that have investigated the impact of tactile feedback on the participants' self-reported ratings [13], [65], [204], [205]. However, there is limited research that explores the impact of tactile feedback on participant movement and self-reported ratings, especially, on whether and how tactile feedback affects participants that are surrounded by a virtual crowd.

Due to these limitations, investigating and understanding how tactile feedback may or not affect the users' movement behavior and self-reported ratings could be very useful in the development of virtual reality experiences, because it will allow the developers to design certain aspects (of virtual reality experiences), including the effective use of tactile feedback and immersive interaction with virtual crowds. Study 3 explored further how the tactile feedback affects the participants that were immersed in a virtual reality scenario and asked to walk while being surrounded by a moving virtual crowd. Therefore, a simple scenario was created that placed the participants at a crosswalk in a virtual metropolitan city, surrounded by a virtual population. Participants were asked to walk across the virtual crosswalk (Figure 35), whilst wearing a tactile vest, until they reached the opposite sidewalk, while one of the six tactile feedback conditions (i.e., No Tactile, Side Tactile, Back Tactile, Front Tactile, Accurate Tactile, and Random Tactile) was applied and investigated. The research team, decided to immerse the participants in a virtual crowd to provide a virtual reality experience that allowed for tactile feedback to be considered in combination with the visually projected content, since other studies [206], [207], have found that tactile devices can trigger sensations when the stimulus is related with the task and the virtual environment [208].

The trajectory of each participant was captured during the road-crossing task that they were asked to perform, and the measurements associated with the movement behavior of the participants were acquired. In addition, the participants were asked to complete a questionnaire regarding their experience with the tactile feedback, immediately after the end of each condition.

Figure 35. A participant surrounded by and observing a virtual crowd of people while walking at the motion capture studio, and consequently crossing the virtual crosswalk

6.1 Methodology

6.1.1 Participants

An a priori power analysis was conducted to define the appropriate sample size for this study using G*Power version 3.1.9.3 software [209]. The calculation was based on 95% power, a medium-effect size of 0.25 [210] six conditions, a nonsphericity correction $\in = 0.60$, and an $\alpha = 0.05$. The analysis concluded in a recommended sample size of 42 participants. All the participants were students from Purdue University, 9 of them were female and 33 were male with their ages ranging from 19 to 27 years old ($M = 21.55$, $SD = 2.33$). There was no report for nausea or cybersickness from students. In addition, none of them reported any motor implications or musculoskeletal disorders that might have affected their movement behavior.

6.1.2. Lab space and equipment

This study was conducted at the motion capture studio (of Purdue University), which is 8m long and 8m wide, with a ceiling height of 4m. The studio was appropriate for the experimental study as it had almost no obstacles, except a desk and a couple of chairs along a sidewall, thus, the participants were able to walk freely during the experiment. The HTC Vive Pro was used to project the virtual reality content and a bHaptics tactile vest to provide tactile feedback. Additionally, the MSI VR One backpack computer (Intel Core i7, NVIDIA GeForce GTX1070, 16GB RAM) was used to run the application. A participant wearing all the equipment used for this experimental study is shown in Figure 36.

Figure 36. A participant wearing all devices (HTC Vive head-mounted display, bHaptics tactile vest, and MSI VR One backpack computer) used for study 3

6.1.3 Virtual reality application

Unity game engine and Autodesk 3ds Max were used for the development of the application and the design of the virtual environment respectively. Adobe Fuse was implemented to design the virtual characters that belong to the virtual crowd, while the characters were rigged in Adobe Mixamo. Unity Asset Store was used to download the animations assigned to the virtual characters and the Mecanim animation engine of Unity3D to animate the characters. The path planning of virtual characters was executed using the NavMesh functionality of Unity3D.

The virtual characters were generated constantly once per second from 10 different spawn points, located behind the participant's position in the virtual environment. Each character's crossing was repeated multiple times. The virtual pedestrians (i.e. virtual crowd) were scripted to cross the virtual crosswalk and reach target positions on the opposite sidewalk. Additionally, each virtual character after reaching the opposite sidewalk, in order to alleviate congestion, was assigned to either move to the right or to the left on the virtual pavement. Figure 37 shows the virtual environment and a generated crowd simulation used for this experiment from a bird’s-eye view.

The simulated crowd was designed with a high density (2.5 characters per square meter, Figure 38), as proposed by Still [164], since we wanted the virtual characters in the crowd to violate the participants’ intimate space. More specifically, we were required to provide tactile feedback that was related with the visual information that was presented to the participants through the VR headset. The purpose was to ensure that the participants' feeling of the tactile feedback was realistic and to provide them the impression that it was associated with their collisions with the virtual characters. According to a previous study conducted by Lee et al. [208], the tactile feedback combined with visual information increases the perceived realism of interactions.

Sunlight was used to light the scene, since the virtual reality scenario was set to take place during the daytime. In order to create a convincing virtual reality experience that matched the real-life scenario, sound effects were used related to a metropolitan city full of pedestrians. Previous studies have found that sound related to the virtual content enhances the participants’ feeling of presence in a virtual environment [178]. Another important aspect of the virtual environment is associated with the participants’ self-presence in it. More specifically, it was decided to not use a self-avatar to represent the participants for two reasons. First, a previous study found that a self-avatar may affect the participants’ movement behavior [112], within a virtual environment, since the participants can become more sensitive to their virtual body. Secondly, to represent the participants effectively, a motion capture system should be used, something that could make participants feel uncomfortable. Moreover, participants have reported feeling uncomfortable wearing an inertial motion capture system device with the rest of the gear used for this study, during our pre-testing period. Consequently, such a piece of equipment was not included. Lastly, it should be noted that the distance between the two sidewalks in the virtual environment was set to seven meters.

Figure 37. From a bird's-eye view, the metropolitan city and the virtual crowd that was used to immerse participants in this experimental scenario

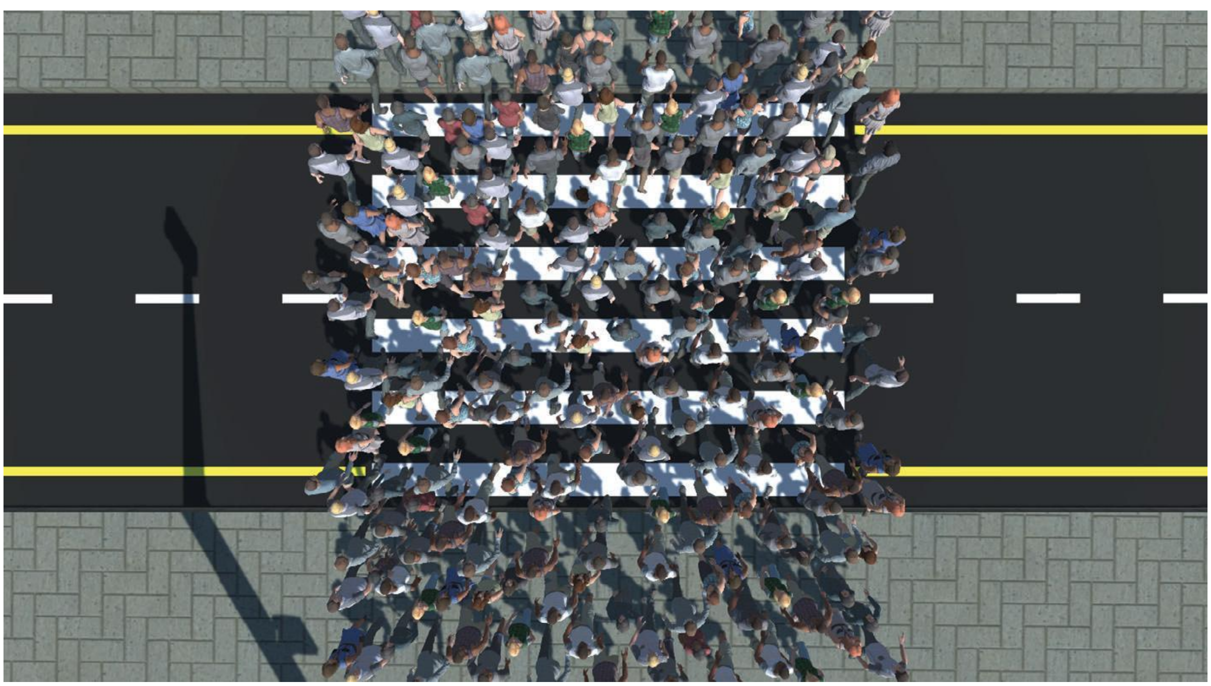


Figure 38. The high-density crowd model (2.5 characters per square meter) that was used in the experimental study

6.1.4 Experimental conditions

To understand the effects of tactile feedback on human movement behavior and changes in the self-reported ratings during immersive human-crowd interaction, we developed six experimental conditions. Each condition was performed by each participant only once, as in Mousas et al. [112]. The six experimental conditions developed for this study included the following:

- **No Tactile Feedback (NT):** In this condition, no tactile feedback was activated during the participants' walk despite the fact that the participants were wearing their tactile vest. In order to establish a baseline condition in which the participants walk without being affected by any type of tactile feedback, this condition was included in our experimental study. Such condition might be used to further understand the participants' movement behavior based only on visual information and could also help to identify and understand differences in the movement behavior of the participants between the no tactile and tactile feedback conditions/scenarios.
- **Side Tactile Feedback (ST):** In this condition the tactile feedback was generated on the left or right side of the tactile vest. This condition was included to investigate and further understand whether and how contacts that occur on one side only would affect the participants walking motion. The right or left side tactile actuators were chosen randomly before beginning the walking task and every time there was a collision with a virtual character on a side of the invisible presence of the participant, the chosen side actuators were activated. It should be noted that the actuators remained active for the duration of the collision.
- **Back Tactile Feedback (BT):** In this condition only the actuators located at the backside of the tactile vest were activated every time there was a collision with a virtual character walking behind the participant. These actuators also remained active for the duration of the collision.
- **Front Tactile Feedback (FT):** Similarly to the BT condition, for the FT condition the actuators located on the front part of the tactile vest were activated every time a participant collided with a virtual character who was walking in front of the

participants. The front actuators also remained active for the duration of the collision.

- **Accurate Tactile Feedback (AT):** In this case, all actuators were used to provide sensory stimuli for collisions with the virtual characters. More specifically, the participants received tactile feedback every time a collision (contact) occurred, between a body part of the invisible self-avatar and a virtual character. The actuator on the tactile vest that was assigned to the specific body part was activated once a collision between the body parts (colliders) was detected. The actuator remained active for the duration of the collision.
- **Random Tactile Feedback (RT):** This scenario was used to randomly generate tactile feedback that was received by the participants. To create the RT feedback condition, we assigned during the preprocessing strage a random sequence and timestep to each actuator (tactor) that would be activated. Each actuator was set to remain active for one second and provide tactile feedback to the participants. The random initialization was performed only once, and the output configurations for each actuator were stored, thus, all the participants experienced the same random tactile feedback condition.

6.1.5 Measurements

To determine how participants perceived and reacted across the six different tactile feedback conditions, both objective (i.e., movement behavior) and subjective (i.e., self-reported ratings) data were collected, which are described below in the following subsections.

6.1.5.1 Movement measurements

The position functionality of the HTC Vive head-mounted display and a wireless Xsens inertial measurement unit (IMU) sensor attached to the participant's chest were used to capture the movement behavior of participants. Specifically, the tracking functionality of the HTC Vive was used to capture the first five measurements presented below, and the IMU sensor was used to capture the sixth measurement (i.e. direction) of the participants. Afterwards, the collected data were downsampled in 100 equidistant points. The six measurements that represented the spatiotemporal properties of human movement included the following:

- **Speed*:*** The average speed of the participant's walking motion when crossing the virtual crosswalk (measured in meters/second).
- **Length:** The total trajectory length (covered distance) of the participant (measured in meters).
- **Duration:** The time needed for the participants to cross the virtual crosswalk (measured in seconds).
- **Smoothness:** The smoothness was computed as the average flicker of the trajectory [156]. Low flicker values denoted a smoother trajectory (measured in meters).
- **Deviation:** The average deviation (absolute value) of the participant upon reaching the opposite sidewalk. The deviation was calculated using the difference between the participant's x-axis position (i.e. the initial position at the sidewalk) and final x-axis position (i.e. the final position at the opposite sidewalk, measured in meters).
- **Direction:** The average absolute y-axis rotation on the (x,z) plane of the participant when walking toward the opposite sidewalk (measured in degrees). Zero degrees indicate that the participant was moving parallel to the segment that connected his/her initial position and the forward position on the opposite sidewalk.

6.1.5.2 Subjective measurements

In order to investigate the effects of tactile feedback conditions in the participants' experiences during their exposure to the six experimental conditions, a questionnaire was developed (Table 2). Twelve items were included in the developed questionnaire. Q1 and Q2 were added to explore the realism of tactile feedback based on a previous research from Wilson et al. [211]. Q3 and Q4 explored the emotional reactivity to the tactile feedback, and Q5 and Q6 investigated the emotional reactivity associated with crowd interaction. Q3-Q6 were inspired by methods from Mousas et al. [176]. Q7 and Q8 explored the participants' sensation of colliding with the virtual bodies and was developed by the research team of this study. Q9 and Q10 examined body ownership and were adopted from Slater et al. [212], and Q11 and Q12 evaluated participants' presence and were adapted from Slater et al. [87]. Worth noting that some questions were modified to fit the purpose of this specific experiment. Additionally, participants exposed to the no tactile feedback (NT) condition were not asked questions about tactile feedback (Q1-Q4). The questionnaire was given to participants in a paper-based format after they completed the movement segment of each tactile feedback condition. Finally, the participants were also allowed to include comments or concerns about the experimental study, in a designated space provided on the questionnaire.

Label	Question	Anchors of the Scale	Concept
Tactile Feedback			
1	How realistic was the tactile feedback?	1 indicates not realistic at all, 7 indicates totally realistic.	**Realism of the Tactile Feedback**
2	How accurate was the tactile feedback?	1 indicates not accurate at all, 7 indicates totally accurate.	
3	Was the tactile feedback pleasant?	1 indicates not pleasant at all, 7 indicates totally pleasant.	**Emotional Reactivity to the Tactile Feedback**
4	Was the tactile feedback comfortable?	1 indicates not comfortable at all, 7 indicates totally comfortable.	
Virtual Crowd Interaction			
5	I felt comfortable moving within a virtual crowd.	1 indicates not comfortable at all, 7 indicates totally comfortable.	**Emotional Reactivity to the Virtual Crowd**
6	I felt ease moving within a virtual crowd.	1 indicates not ease at all, 7 indicates totally ease.	
7	I felt that the virtual crowd was composed of real people.	1 indicates not at all, 7 indicates totally.	**Body Sensation of the Visual Crowd**
8	I felt that the virtual characters I contacted belonged to real persons.	1 indicates not at all, 7 indicates totally.	
Self-Perception			
9	How strong was the feeling that the body you saw was your own?	1 indicates not strong at all, 7 indicates totally strong.	**Body Ownership**
10	How much did you feel that you were looking at your own body?	1 indicates not at all, 7 indicates totally.	
11	Please rate your sense of being in the virtual environment.	1 indicates not at all, 7 indicates totally.	**Presence**
12	To what extent were there times during the experiences when the virtual environment felt realistic to you?	1 indicates feeling completely in the real world, 7 indicates feeling completely in the virtual environment.	

Table 2. The questionnaire that was developed and used for this study (Study 3)

6.1.6 Procedure

As soon as the participants arrived at the motion capture studio, the researchers provided information about the experiment. In addition, they were given a consent form to read, which was approved by the Institutional Review Board of Purdue University and they were asked to sign it to indicate that they agreed to participate in the study. A paper-based demographic questionnaire was also given to the participants. Afterwards, the research team assisted the participant to wear the tactile vest, the IMU sensor, the backpack computer, and the head-mounted display. Then to ensure that the participants were able to walk safely and were comfortable wearing all the equipment used for this experimental study, the research team asked participants to walk within a virtual replica of the motion capture studio for a few minutes.

Participants were informed that they would be placed in a virtual metropolitan city and surrounded by a virtual crowd of people, before the beginning of the experiment. They were aware that immediately after the traffic light turns green, the virtual crowd will start moving toward the opposite sidewalk. The participants were instructed that they should also cross the street in the virtual crosswalk to reach the opposite sidewalk, and that immediately after they have reached their destination (opposite sidewalk), an on-screen instruction will sign them to stop moving, and a black screen will then appear. Once they reached the opposite sidewalk and the black screen appeared, they were told to remove the head-mounted display and walk to the desk to complete the paper-based questionnaire. Afterwards, they were instructed to go back to the marked location and prepare for the next condition. This process was repeated for each of the six conditions used in this study. The balance for first-order carry-over effects between the experimental conditions was ensured using Latin squares [179]. The participants were informed that if they got close to the sidewalls or to the front wall of the studio, an on-screen message would warn them to stop walking to prevent any accidental injury. Note that none of the participants collided with any wall during the study.

The participants were also informed that they could have breaks between each condition and that they had full permission to withdraw from the experiment at any time. In addition, they were told that they would be informed when the experiment had ended. The researchers helped the participants to remove all the equipment (i.e. head-mounted display, backpack computer, tactile vest and IMU sensor) as soon as the study ended. Then the research team asked the participants if they were willing to answer questions about the experiment. Finally, they were also questioned to express their thoughts about the experiences and provide feedback regarding their movement behavior, tactile feedback, and interaction with the virtual crowd of people. It should be noted that none of the participants spent more than 45minutes in the lab.

6.2 Results

The following two subsections are presenting the results of Study 3. To define whether the tactile feedback conditions influenced participants' movement and ratings, we compared the movement behavior measurements and self-reported ratings from the participants across the experimental conditions (Table 3 and 4 illustrate the descriptive statistics of this study). A one-way repeated analysis of variance (ANOVA) was used, to analyze the collected data. The experimental conditions were determined as independent variables and the movement measurements and self-reported ratings as the dependent variables. The post hoc differences were evaluated using Bonferoni corrected estimates when the ANOVA was significant. Using Q-Q plots of the residuals [180], the normality assumption of the movement-related measurements and self-reported rating were evaluated graphically. The Q-Q plots indicated that the obtained data fulfilled the normality assumption. Furthermore, the internal validity of the individual components of the questionnaire was measured using Cronbach's alpha coefficient, yielding. $0.72 < \alpha < 0.97$. With sufficient scores, a cumulative score was used for each of the two items that belong to each questionnaire component.

Variable	Condition	M	SD	Min	Max	Results
Speed	NT	1.22	.14	.96	1.44	(FT=RT)<(NT=BT)
	ST	1.17	.14	.93	1.39	FT<AT
	BT	1.25	.14	1.01	1.43	
	FT	1.09	.13	.86	1.29	
	AT	1.19	.12	.96	1.38	
	RT	1.12	.15	.88	1.36	
Length	NT	7.15	.07	7.05	7.27	(NT=BT=FT=AT)<(ST=RT)
	ST	7.25	.08	7.10	7.38	
	BT	7.16	.05	7.07	7.26	
	FT	7.16	.07	7.06	7.29	
	AT	7.15	.07	7.04	7.29	
	RT	7.25	.12	7.11	7.47	
Duration	NT	5.95	.73	5.00	7.41	BT<(ST=FT=RT)
	ST	6.31	.79	5.26	7.87	(NT=BT=AT)<FT
	BT	5.82	.69	4.99	7.12	
	FT	6.65	.79	5.50	8.34	
	AT	6.09	.65	5.12	7.48	
	RT	6.60	.88	5.42	8.43	
Smoothness	NT	.07	.02	.04	.11	NT=ST=BT=FT=AT=RT
	ST	.09	.04	.03	.14	
	BT	.08	.02	.04	.12	
	FT	.08	.03	.03	.13	
	AT	.07	.02	.04	.11	
	RT	.08	.03	.03	.12	
Deviation	NT	.06	.03	.02	.11	(NT=BT=AT)<(ST=RT)
	ST	.11	.03	.06	.16	AT<ST
	BT	.06	.02	.03	.10	
	FT	.07	.03	.02	.11	
	AT	.06	.03	.02	.11	
	RT	.09	.04	.02	.17	
Direction	NT	2.86	2.18	.12	6.53	NT=ST=BT=FT=AT=RT
	ST	3.36	2.47	.13	7.22	
	BT	3.83	2.27	.22	7.20	
	FT	3.11	2.52	.02	7.41	
	AT	2.53	1.75	.27	6.20	
	RT	3.13	2.21	.38	7.54	

Table 3. Descriptive statistics (Mean [M], Standard Deviation [SD], Minimum [Min], and Maximum [Max] value) across the experimental conditions for each movement measurement, and the obtained results. NT: No Tactile, ST: Side Tactile, BT: Back Tactile, FT: Front Tactile, AT: Accurate Tactile, and RT: Random Tactile.

Variable	Condition	M	SD	Min	Max	Results
Realism of the Tactile Feedback	**ST**	2.99	1.20	1.00	5.00	(ST=BT=FT)<(AT=RT)
	BT	3.01	1.05	1.00	5.00	
	FT	3.48	1.14	1.00	5.50	
	AT	4.63	1.07	3.00	7.00	
	RT	4.30	1.31	2.00	7.00	
Emotional Reactivity to the Tactile Feedback	**ST**	3.40	1.12	1.00	5.50	ST=BT=FT=AT=RT
	BT	3.06	1.00	1.50	5.00	
	FT	3.44	1.10	1.50	5.50	
	AT	3.60	1.25	1.50	6.00	
	RT	3.29	1.12	1.00	5.50	
Emotional Reactivity to the Virtual Crowd	**NT**	4.51	1.20	2.50	7.00	(ST=BT)<(NT=AT)
	ST	3.62	1.19	1.50	6.00	
	BT	3.50	1.30	1.50	6.00	
	FT	3.94	1.30	1.50	6.50	
	AT	4.48	.93	3.00	6.50	
	RT	4.27	1.45	1.00	6.50	
Body Sensation of the Visual Crowd	**NT**	2.87	1.04	1.00	4.50	(NT=ST=BT=FT)<(AT=RT)
	ST	2.98	.90	1.00	5.00	
	BT	3.06	.94	1.50	5.00	
	FT	3.51	.96	1.50	5.50	
	AT	4.56	1.26	2.00	7.00	
	RT	4.35	1.09	2.00	7.00	
Body Ownership	**NT**	2.83	1.11	1.00	4.50	NT<(AT=RT) ST<AT
	ST	3.04	1.10	1.50	5.00	
	BT	2.99	1.22	1.00	5.00	
	FT	3.10	1.02	1.00	5.00	
	AT	3.94	1.36	2.00	7.00	
	RT	3.75	1.26	1.50	6.50	
Presence	**NT**	2.96	.90	1.00	5.00	(NT=BT)<(AT=RT) ST<AT
	ST	3.11	1.11	1.50	5.50	
	BT	3.20	1.23	1.00	6.50	
	FT	3.60	1.50	1.00	6.50	
	AT	4.67	1.65	1.50	7.00	
	RT	4.30	1.70	1.50	7.00	

Table 4. Descriptive statistics (Mean [M], Standard Deviation [SD], Minimum [Min], and Maximum [Max] value) under the experimental conditions for each self-reported rating and the obtained results. NT: No Tactile, ST: Side Tactile, BT: Back Tactile, FT: Front Tactile, AT: Accurate Tactile, and RT: Random Tactile.

6.2.1 Movement behavior

Each of the six movement measurements were analyzed statistically across the six different experimental conditions. Figure 39 illustrates boxplots of the obtained data. The statistical analysis did not show significant results for **smoothness**, $\Lambda = 0.756, F(5,37) = 2.395, p =$

0.056, $\eta_p^2 = 0.244$, or **direction**, $\Lambda = 0.903$, $F(5,37) = 1.820$, $p = 0.133$, $\eta_p^2 = 0.197$, measurements across the experimental conditions. The statistical analysis revealed significant results for the **speed** measurement, $\Lambda = 0.422$, $F(5,37) = 10.141$, $p < 0.001$, $\eta_p^2 = 0.578$. Post hoc results showed that the participants' mean speed under the FT condition was significantly lower than the mean speed under NT condition at the $p < 0.001$ level, the BT condition at the $p < 0.001$ level, and the AT condition at the $p < 0.05$ level. Furthermore, the mean speed of the participants under the RT condition was significantly lower than that of the NT condition at the $p < 0.05$ level and the BT condition at the $p < 0.001$ level.

Regarding the **length** measurement, the statistical analysis provided significant results, $\Lambda = 0.286$, $F(5,37) = 18.485$, $p < 0.001$, $\eta_p^2 = 0.714$. Post hoc results showed that the mean lengths of the NT, BT, FT, and AT conditions were significantly lower than those of the ST and RT conditions, all at the $p < 0.001$ level.

The **duration** measurement revealed significant results across the experimental conditions, $\Lambda = 0.403$, $F(5,37) = 10.966$, $p < 0.001$, $\eta_p^2 = 0.597$. Post hoc results indicated that the mean duration of the BT condition was significantly lower than that of the ST condition at the $p < 0.05$ level, the FT condition at the $p < 0.001$ level, and the RT condition at the $p < 0.001$ level. Furthermore, the mean duration of the FT condition was significantly higher than that of the NT condition at the $p < 0.001$ level, the BT condition at the $p < 0.001$ level, and the AT condition at the $p < 0.05$ level.

Finally, the **deviation** measurement was also found to be significant across the experimental conditions, $\Lambda = 0.319$, $F(5,37) = 15.806$, $p < 0.001$, $\eta_p^2 = 0.681$.The post hoc results revealed that the mean deviation of the ST condition was significantly higher than those of the NT, BT, FT, and AT condition, which were all at the $p < 0.001$ *level*. Furthermore, the mean deviation of the RT condition was remarkably higher than those of the NT, BT, and AT conditions, which were all at the $p < 0.05$ level.

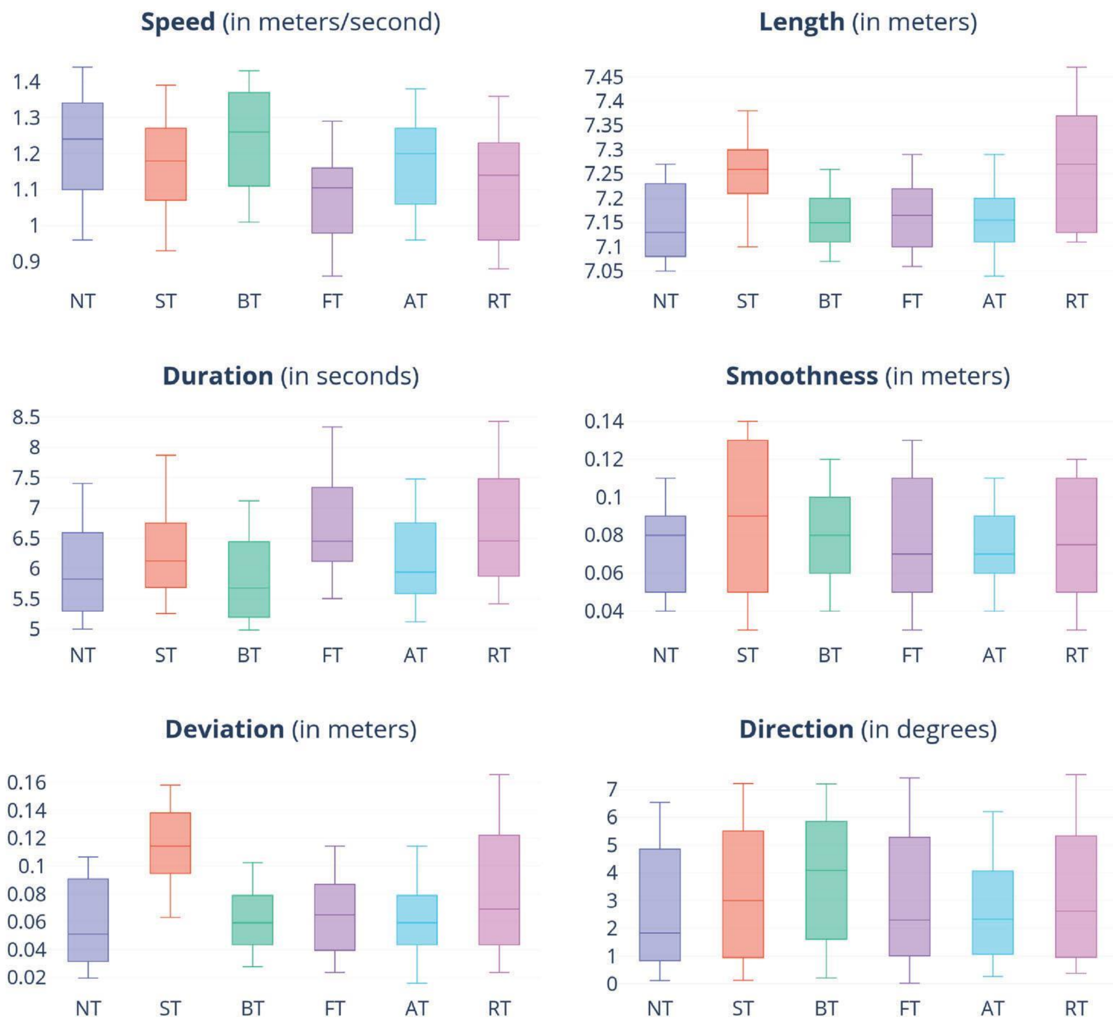


Figure 39. Boxplots of the movement measurements. Boxes enclose the middle 50% of the data. The median is denoted by the thick horizontal line. See the supplementary material document for means and standard deviations.

6.2.2 Self-reported ratings

We investigated the six self-reported concepts across the experimental conditions. Figure 40 illustrates the boxplots of the self-reported ratings. The statistical analysis did not reveal significant results for the **emotional reactivity** of the tactile feedback measurement, $\Lambda = 0.875$, $F(4,38) = 1.396$, $p = 0.253$, $\eta_p^2 = 0.125$.

The statistical analysis revealed significant results, regarding the **realism** of tactile feedback, $\Lambda = 0.336$, $F(4,38) = 18.711$, $p < 0.001$, $\eta_p^2 = 0.664$. Post hoc results revealed that the mean rating of the AT condition was remarkably higher than that of the ST, BT, and FT conditions, which were all at the $p < 0.001$ level. Furthermore, the mean rating of the RT condition was significantly higher than that of the ST and BT conditions, which were all at the $p < 0.001$ level, and the FT condition, which was at the $p < 0.05$ level.

The **emotional reactivity** to the virtual crowd measurement was significant as well, across the experimental conditions, $\Lambda = 0.496, F(5,37) = 7.515, p < 0.001, \eta_p^2 = 0.504$. Post hoc results revealed that the mean rating of the ST condition was significantly lower than those of the NT and AT conditions, which were all at the $p < 0.05$ level. Furthermore, the mean rating of the BT condition was significantly lower than those of the NT and AT conditions, which were all at the $p < 0.001$ level.

The statistical analysis revealed significant results for the **body sensation** of the visual crowd measurement, $\Lambda = 0.245, F(5,37) = 22.793, p < 0.001, \eta_p^2 = 0.755$. Post hoc results revealed that the mean ratings of the AT and RT conditions were significantly higher than those of the NT, ST, and BT conditions, which were all at the $p < 0.001$ level. Furthermore, post hoc results also revealed that the mean ratings of the AT and RT conditions were significantly higher than those of the FT condition, which were both at the $p < 0.005$ level.

The **body ownership** measurement was also significant across the experimental conditions, $\Lambda = 0.523, F(5,37)=6.746, p<0.001, \eta_p^2 = 0.477$. Post hoc results revealed that the mean rating of the NT condition was remarkably lower than that of the AT condition at the $p < 0.001$ level and the RT condition at the $p < 0.05$ level. Furthermore, the mean rating of the ST condition was significantly lower than that of the AT condition at the $p < 0.05$ level.

Lastly, significant results were found across the experimental conditions, regarding the **presence measurement**, $\Lambda = 0.435, F(5,37) = 9.870, p < 0.001, \eta_p^2 = 0.565$. Post hoc results revealed that the mean presence rating of the AT condition was significantly higher than that of the NT condition at the $p < 0.001$ level, the ST condition at the $p < 0.005$ level, and the BT condition at the $p < 0.001$ level. Furthermore, the mean presence rating of the RT condition was significantly higher than that of the NT condition at the $p < 0.001$ level and the BT condition at the $p < 0.005$ level.

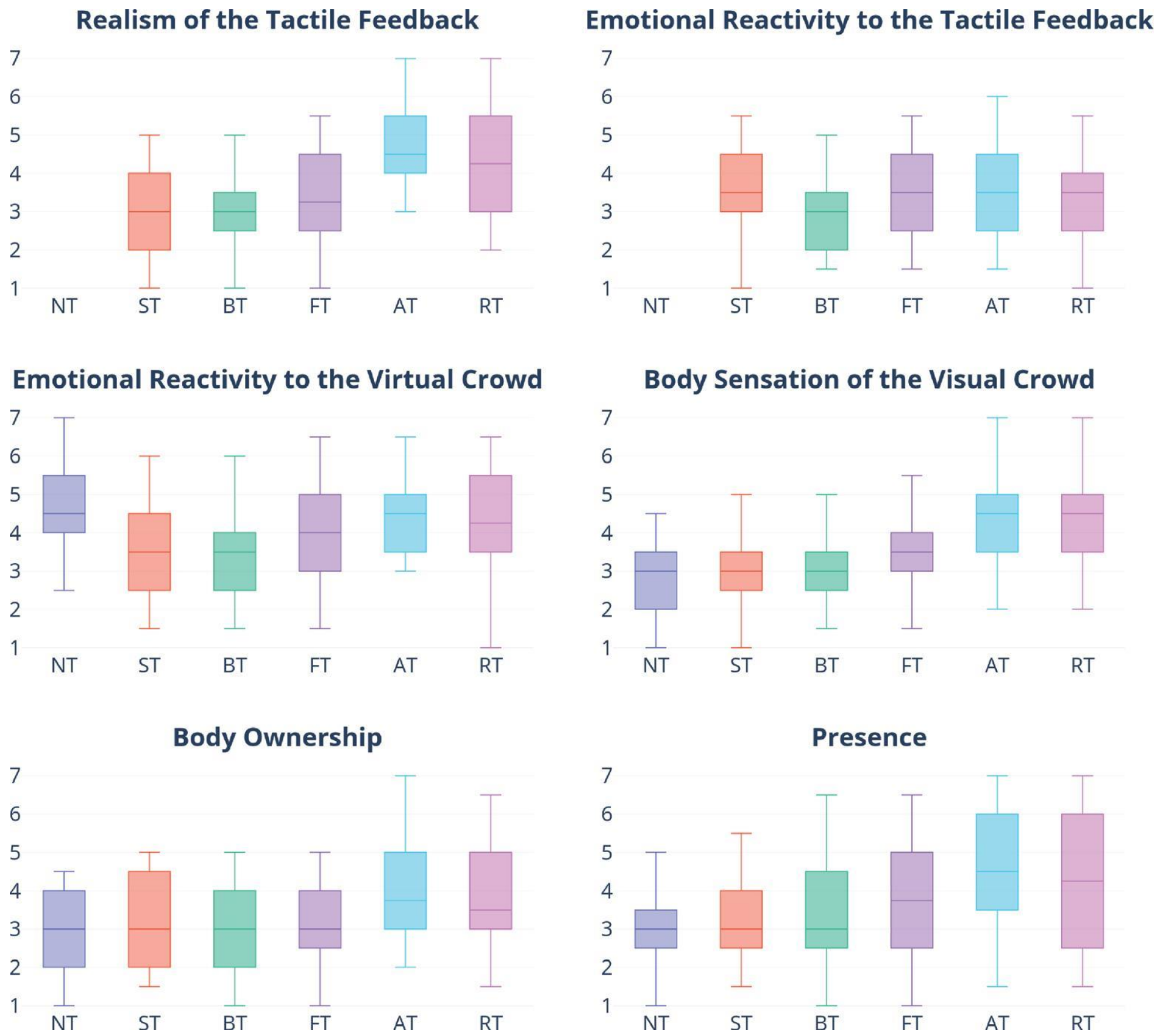


Figure 40. Boxplots of the participants' self-reported ratings. Boxes enclose the middle 50% of the data. The median is denoted by the thick horizontal line. See the supplementary material for means and standard deviations.

6.3 Discussion

This study investigated the effects of tactile feedback during immersive crowd interaction. Several movement behavior measurements and self-reported ratings revealed a number of interesting results. The influence of tactile feedback on the participants' walking behavior was examined primarily when they were surrounded by a virtual crowd of people that was walking toward the opposite sidewalk in a virtual metropolitan city. To understand whether and how six different experimental tactile feedback conditions could influence the way that our participants decided to execute the requested task (RQ3), we used the movement-related measurements of participants.

Significant results were found, related with the participants' speed as they walked across the virtual crosswalk. Specifically, the generated tactile feedback at the front of the tactile vest seems to significantly affect the participants' speed in contrast to the absence of tactile feedback and the condition where the tactile feedback was generated at the back of the side of the tactile vest. Since there was no notable difference between the no tactile feedback and the back tactile feedback conditions, we could presume that the front and the side feedback conditions were responsible for reducing the participants' speed when crossing the virtual crosswalk. We also found some interesting results between the random tactile feedback condition with the no tactile and back tactile feedback conditions. Participants were immersed in a high-density crowd, thus, it might not have been possible (for them) to decide whether the tactile feedback was random or from an actual collision with a virtual character. This unawareness worked as pseudo-sensation [216] that tricked the participants that the tactile feedback during the random condition was not actually random. Participants interpreted this tactile feedback as a result from collisions with the virtual characters.

Moreover, significant results were found regarding the length and deviation measurements. More specifically, the side (ST) and the random (RT) tactile feedback conditions influenced the length of the trajectory and therefore the path that the participants followed. Taking the results of the ANOVAs for both length and deviation together, it was possible to conclude that the higher length resulted from the participant's decision to deviate from the straight path and reach a different horizontal position on the opposite sidewalk compared to their initial horizontal position. The side tactile feedback condition apparently worked as a force that made the participants move toward the left or right side, and consequently, they deviated from their initial horizontal position as they reached their destination (i.e. opposite sidewalk). The random tactile condition appears to confuse the participants since the visual and tactile stimuli were not synchronized. This mismatch between the two stimuli (visual and tactile) may have simply served to confuse the participants [175]. It should be noted that none of the participants knew that the tactile feedback was randomly generated and which tactile feedback condition was being applied each time. Thus, it could be possible that our participants might have believed that the collisions with the virtual characters caused the tactile feedback. Consequently, they decided to deviate from their straight path, while they also tried to avoid collisions with the virtual characters, as they thought that such an action might eliminate the tactile feedback.

Significant results were also found regarding the duration measurement. More specifically, as shown by the duration results, when the tactile feedback was generated on the participants' back, they were forced to move faster, and consequently, less time to reach the opposite sidewalk was necessary. In contrast, the tactile feedback generated on the front side of the vest forced participants to move slower, therefore they needed more time to reach the opposite sidewalk. An interpretation for the back tactile feedback condition could be that the participants felt that they were pushed from the virtual characters located behind them, thus, they decided to move faster to avoid this action. However, when the front tactile feedback condition was applied, they decided to move slower to avoid such interactions. This was due to the fact they did not want to contact or collide with the virtual characters that were walking in front of them.

No significant results were found for the smoothness measurement. An explanation regarding the smoothness was that the participants under all the experimental conditions, tended to perform similar movements. Additionally, the captured motion of the participants was based on the tracking functionality of the VR headset, which provides a fairly smooth motion tracking [217], [218], due to the implemented tracking algorithms that smooth out the movement of the users. In Study 3, the simple task that the participants were instructed to perform and the device that used to capture the movement of the participants could be the factors for this absence of significant results regarding the smoothness measurement.

To conclude with the movement behavior measurements, it should be noted that no significant results were found for the direction measurement. An interpretation for this finding could be that our participants were following similar paths across the experimental conditions as they were crossing the virtual crosswalk. Even when the participants deviated while the side and random tactile conditions were applied, these deviations did not happen due to direction changes but because they decided to change their step width while moving toward a near-forward direction. In any case, it is not possible to verify this hypothesis, since we did not capture the full-body motion of the participants.

In order to better understand how they perceived the tactile feedback provided across the experimental conditions, we collected several self-reported ratings regarding the various concepts (RQ4). Specifically, our participants found their interaction with the virtual crowd to be more realistic, regarding the realism of the tactile feedback and the body sensation of the virtual crowd. They also stated that during the accurate and random tactile feedback conditions, they felt that the virtual crowd was composed of more real people in contrast to the side, back, and front tactile conditions. According to these results, the realism of an immersive interaction with a virtual crowd can be affected by tactile feedback that is considered accurate and tactile feedback that cannot be distinguished by the participants. This tactile feedback made the participants also feel that their interaction with the virtual crowd provided the sensation of interacting with real people [13].

The results associated with emotional reactivity of the tactile feedback were also interesting. The participants rated the five tactile feedback conditions fairly consistently, which suggests that tactile feedback could affect their emotional reactions in similar ways, regardless of whether the tactile feedback was considered accurate. In contrast, the results of emotional reactivity to the virtual crowd were significant. The side and back tactile conditions had less impact on the emotional reactions of the participants compared with the no tactile and accurate tactile feedback conditions. We could say that the results regarding the accurate tactile feedback were somehow expected, since accurate tactile feedback provided the illusion that participants were part of the virtual crowd. A previous study found that the participants were more sensitive to logical (accurate) tactile feedback compared to one that is illogical (inaccurate or random) [13]. The results regarding the no tactile feedback condition though, could not be considered as expected. More specifically, the results indicated that less accurate tactile feedback might have less impact on the participants' emotional reactions compared with no tactile feedback. It could also be possible that the participants during the no tactile feedback condition might have been expecting a tactile sensation. This expectation might have provoked an increased emotional reaction from the participants.

Regarding the self-reported ratings, when evaluating the participants' self-perception (body ownership and presence), the accurate and random conditions were rated both higher compared with no tactile and back tactile feedback conditions. These findings complement the findings regarding the realism of tactile feedback and the body sensation of the virtual crowd. Even when the participants were placed within the virtual crowd without a self-avatar to represent them, they were clearly sensitive to their bodies. Results from previous work that investigated the effects of tactile feedback on body ownership [214], [215], agree with this finding. In addition, the significant results regarding the participant presence, also agree with previous work that associated participants' sense of being in a virtual environment with the provided tactile feedback [60], [213]. Thus, the accuracy of tactile feedback or when the participants cannot judge the accuracy of the tactile feedback (RT condition in our case), that inability of participants to distinguish the inaccurate tactile feedback affected their self-perception in a positive way. More specifically, they rated higher their sense of body ownership and presence during the accurate and random tactile feedback conditions.

There are some comments that participants made concerning their experience with the tactile feedback and the applications developed that are worth mentioning. There are many participants that reported that they were really impressed when the tactile feedback conditions were included compared with the no tactile feedback condition, and that their overall experiences became more positive. Several participants also stated that they felt that there were periods that the virtual crowd was really surrounding them. Some other participants reported that they liked the idea of using tactile feedback to feel nearby characters, and that they also expected some kind of visual effects to simulate their body shaking when they collided with the virtual characters. In addition, many participants said that they would like to see a self-avatar that represented them, since such an avatar could have assisted them to avoid collisions with the characters. Few participants stated that the overall experience felt somehow less realistic, due to the absence of tactile feedback being applied to their lower body. Lastly, there was no complaint from our participants about the weight of the equipment they were wearing during the experiment (tactile vest 2.75kg and backpack computer 3.6kg), all of them were feeling comfortable while wearing and walking with all the gear attached to their bodies.

Additionally to the interesting findings, we found some limitations that should be considered by researchers who may conduct additional studies in the area of virtual reality research. The first limitation is associated with the participants' representation in the virtual environment. We decided to not represent participants with a self-avatar (virtual body) within the virtual environment for two reasons. First, we understood during the preliminary experimentation process that it was difficult to attach the inertial motion capture system to participants, since the participants were already wearing a tactile vest and a backpack computer. While several studies have found that the self-representation [112] and movement artifacts [219] affects the participants' movement behavior in this experimental study might be beneficial, since participants could see the collision with a virtual character in addition to sense it. Thus, it might be possible to capture the full-body motion of participants and use an avatar to represent them, with the use of an optical motion capture system. A second limitation is that we investigated conditions associated with the position of the tactile feedback without including duration and intensity variations. Exploring additional tactile feedback conditions that include both duration and intensity variations seems mandatory to better understand the effects that tactile feedback may have on movement behavior and self-reported ratings.

The participants were clearly sensitive to tactile feedback conditions after taking into consideration the results of movement behavior and self-reported ratings together, and despite the aforementioned limitations. Participants' movement behavior and self-reported ratings both differed across the experimental conditions and we found that the most differences were related with the accurate and random tactile feedback conditions. According to the results obtained from our study, the participants became sensitive to tactile feedback when they were immersed in a high-density crowd simulation. Nevertheless, the participants were not able to distinguish between accurate and random tactile feedback. The virtual environment was crowded with virtual characters and was difficult for the participants to judge whether random tactile feedback was accurate, consequently, they were not able to distinguish the mismatched stimuli. These findings contradict the results reported in several other studies regarding mismatched stimuli [220], [221], and studies that found that accurate or logical tactile feedback increased the realism of the interaction compared with illogical tactile feedback [13], [222]. Nevertheless, if we consider that most of them are related to a more discrete visual and haptic interaction, compared to this study, we could assume that our results have extended the literature a step further. More precisely, our findings indicate that the participants perceive inaccurate (random) tactile feedback as realistic feedback. They could not distinguish the individual components of the visual information they received, which included the collisions with the virtual characters in our virtual crowd.

Chapter 7

Conclusions

This thesis focuses on investigating the behavior of users while immersed in a virtual environment and surrounded by a crowd of virtual humans. Various different conditions as well as the most important characteristics (e.g. density, direction, speed) that a virtual crowd may have in order to be considered realistic were investigated. The understanding of how and to what extent a virtual crowd affects the behavior of users, could greatly contribute to the creation of more realistic virtual crowds and improve the virtual experiences and immersion of users overall.

To this end and in order to explore and analyze in-depth the users' behavior within a virtual environment, three experimental studies were conducted, as analytically described in Chapters 4, 5 and 6.

7.1 Main contributions of the Thesis

In **Chapter 4,** we explored how different parameters of a virtual crowd that was surrounding our participants, who were instructed to cross a virtual crosswalk within a virtual environment (metropolitan city) did or did not affect their movement behaviors. The results obtained from this study specifically reveal that the *density* and *speed* conditions (of the virtual crowd) affected the speeds of the participants, and the *density* and *direction* conditions affected the deviation and trajectory lengths of the participants. We have also identified some interaction effects among the conditions that indicated a relationship between the examined conditions and how the movements of the participants were affected. Additionally, this study (Study 1) is exploring further the interactions between humans and moving virtual crowds and specifically, the effects of crowd movement on human movement behavior. Finally, developers and researchers who examine human-virtual crowd interactions should consider these movement manipulation effects when developing the parts of a virtual reality experience that involve humans completing walking tasks.

In the next Chapter (**Chapter 5),** we investigated the participants' movement coordination when immersed within a virtual crowd. The results obtained from this study indicated that the movements of the participants were associated with the movements of the simulated characters. The degree of this association (between participants' and simulated characters' movements) is moderate, particularly in the direction and distance from nearby pedestrian cases. Overall, in these experiments the influence of the virtual crowd on the movements of the participants was not enough to make them coordinate with the simulated characters, follow the movement of the crowd and become a part of it. Furthermore, several interesting insights about the movement behavior and coordination of the participants, within a virtual crowd were obtained. More specifically, Study 2 demonstrates that immersive human-crowd interaction scenarios can be used to study the actions and decision-making processes of humans, since the developed experimental conditions can be controlled by the experimenter and replicated by other researchers. Additionally, participant movement can be captured efficiently, which is crucial for such experiments. Exploring human movement behavior and coordination when the participants are immersed in virtual crowds is an interesting direction for studying perceptual-motor tasks that require decision-making and action-planning. Finally, the findings of this study could be valuable resources when developing virtual reality applications and games, where the users are placed within moving virtual crowds.

Finally, in **Chapter 6,** we investigated the effects of tactile feedback on the movement behavior of the participants and self-reported ratings as they were exposed to different conditions. The collected data revealed several interesting results that indicated that different tactile feedback conditions could affect both the participants' movement behavior and the self-reported ratings. The results obtained from this study (Study 3) are definitely valuable for future research and development of virtual reality interactions with a virtual crowd of people when different tactile feedback conditions are applied. Virtual reality application developers aiming to immerse users within moving crowds of people in virtual environments, should definitely consider our research. Such studies will improve our understanding of how humans perceive and interact with virtual environments, virtual characters, and tactile feedback, while they can also be used to refine such interactions to make them feel more realistic.

It is safe to conclude that virtual crowds can enhance the users' sense of presence and immersion in virtual environments, while they (virtual crowds) can also greatly influence movement behavior and decision-making of the users, depending on their characteristics and conditions applied. Exploring in depth and understanding such interactions between virtual reality participants and virtual crowds will greatly improve the development of virtual applications.

7.2. Future Directions

The three experimental studies that are presented in the three previous chapters revealed several aspects that need to be further examined, regarding the virtual crowd and the user's behavior. Important directions for future work concerning the virtual crowd behavior and how it affects users' behavior in immersive virtual environments arise.

More specifically, a future research could explore the human walking pattern while he/she is immersed in a virtual environment and surrounded by a virtual crowd population that is moving in perpendicular and/or opposite directions. Furthermore, the topic of how humans walk within a virtual crowd moving in several directions should be further investigated. We are also interested in conducting studies to identify the effects of assigning various social behaviors (e.g. politeness) to virtual pedestrians. Human-virtual crowd interaction could be studied with a virtual crowd that is walking within a constrained environment or along curved paths, rather than in a straight line as the virtual crowd in our studies did. It is crucial to further examine the movement behaviors of humans walking along with virtual characters that have been grouped into small teams that are moving in a specified direction. We also plan to confirm whether humans' movement behaviors correlate significantly with two important theoretical concepts of virtual reality and specifically, presence and embodiment. It would also be interesting to explore the movements of humans who are immersed in a virtual crowd population composed of characters of different ages and genders, as this would enable further understanding of how they perceive and interact with virtual characters.

Additionally, in a future work, someone may investigate several effects such as: a) the interaction effects of crowd movement variations (speed, direction and density) on human movement behavior, b) the effects of virtual pedestrians' appearance and motion assigned to a crowd on participants' emotional reactivity [176], c) the effects of tactile feedback during immersive walking in virtual crowds [9], and d) the effects of self-avatars on human movement and flocking behavior. Other forms of data may be collected, such as eye tracking, electro-dermal activity, and subjective ratings [13], [223], to study the interactions between humans and virtual crowds. Experimentation with data-driven techniques for simulating the movement of virtual pedestrians could also be part of a future study.

Furthermore, we aim to conduct additional studies concerning the effects of tactile feedback on participants walking in immersed virtual reality scenarios. More specifically, we are preparing a virtual reality study for crisis management such as evacuation of buildings, interactions in extreme weather conditions or natural disasters, such as earthquakes and hurricanes. We believe that such studies will greatly improve our understanding of how humans perceive and interact with virtual environments, virtual characters, and tactile feedback and thus generate much more realistic scenarios. Finally, by understanding how participants interact with such events, it might be possible to provide instructions and design guidelines for various Human Computer Interaction problems that remain unsolved.

8. References

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