



Perception visuelle du mouvement humain dans les interactions lors de tâches locomotrices

Sean Lynch

► To cite this version:

Sean Lynch. Perception visuelle du mouvement humain dans les interactions lors de tâches locomotrices. Education. Université Rennes 2, 2018. Français. NNT : 2018REN20046 . tel-01944500v2

HAL Id: tel-01944500

<https://inria.hal.science/tel-01944500v2>

Submitted on 9 Jan 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

THESE DE DOCTORAT DE

L'UNIVERSITE RENNES 2
COMUE UNIVERSITE BRETAGNE LOIRE

ECOLE DOCTORALE N° 603
Education, Langages, Interaction, Cognition, Clinique
Spécialité : STAPS

Par

Sean LYNCH

Visual perception of human movement during walking task interactions

Perception visuelle du mouvement humain dans les interactions lors de tâches locomotrices

Thèse présentée et soutenue à Université Rennes, le 24 Octobre 2018
Unité de recherche : Laboratoire M2S - EA 7470

Rapporteurs avant soutenance :

Victoria INTERRANTE
Professeure, University of Minnesota

Nicolas BENGUIGUI
Professeur, Université de Caen-Normandie

Composition du Jury :

Victoria INTERRANTE
Professeure, University of Minnesota

Nicolas BENGUIGUI
Professeur, Université de Caen-Normandie

Gilles MONTAGNE
Professeur, Aix-Marseille Université

Isabelle SIEGLER
Professeure, Université Paris-Sud

Directeur de thèse
Richard KULPA
Maître de Conférence HDR, Université Rennes 2

Co-directrice de thèse
Anne-Hélène Olivier
Maître de Conférence, Université Rennes 2

UNIVERSITÉ RENNES 2 – HAUTE BRETAGNE
Unité de Recherche 7470
Ecole Doctorale – Education, Langues, Interaction, Cognition, Clinique

Sous le sceau de l'Université Bretagne Loire

**VISUAL PERCEPTION OF
HUMAN MOVEMENT DURING
WALKING TASK INTERACTIONS**

Thèse de Doctorat

Discipline : STAPS

Volume

Présentée par Sean LYNCH

Directeur de thèse : Richard KULPA
Co-directrice de thèse : Anne-Hélène OLIVIER

Soutenue le 24 Octobre 2018

Jury :

Victoria INTERRANTE	Professeure, University of Minnesota (Rapporteure)
Nicolas BENGUIGUI	Professeur, Université de Caen-Normandie (Rapporteur)
Gilles MONTAGNE	Professeur, Aix-Marseille Université (Examinateur)
Isabelle SIEGLER	Professeur, Université Paris-Sud (Examinatrice)
Richard KULPA	Maître de Conférence HDR, Université Rennes 2 (Directeur de thèse)
Anne-Hélène OLIVIER	Maître de Conférence, Université Rennes 2 (Co-directrice de thèse)

In loving memory of my father.

I am eternally grateful for your guidance and patience,
you always encouraged my life choices and for me to lead my own path.

You were my best friend,
I miss you.

Paul Lynch
(1972 - 2018)

Contents

Introduction	1
1 Background	5
1.1 Visual control of locomotion	6
1.1.1 Perception theories	8
1.1.2 Ecological theory of perception and action	13
1.1.3 Optic array and invariants	16
1.1.3.1 Tau	19
1.1.3.2 Bearing Angle	22
1.1.4 Affordances	24
1.1.5 Experimental methods	28
1.1.5.1 Video	29
1.1.5.2 Motion capture	30
1.1.5.3 Virtual reality	32
1.1.5.4 Eye-tracking	35
1.2 Interactions with the Environment	38
1.2.1 Perception of motion	39
1.2.1.1 Perception of direction	44
1.2.1.2 Perception of speed	48
1.2.1.3 Motion cues	49
1.2.2 Personal space	52
1.2.3 Collision Avoidance	57
1.2.3.1 Collision avoidance characteristics	58
1.2.3.2 Passive obstacle	61
1.2.3.3 Reactive obstacle	65

1.2.4	Human factors	74
1.2.4.1	Gaze	74
1.2.4.2	Visual appearance	78
2	Objectives	81
3	Collision avoidance behaviour between walkers: global and local motion cues	87
3.1	Objective and contributions	89
3.2	Method	90
3.2.1	Participants	90
3.2.2	Apparatus	91
3.2.3	Experimental setup	92
3.2.4	Conditions	93
3.2.5	Task	95
3.2.6	Questionnaire	95
3.2.7	Data analysis	96
3.2.8	Statistics	97
3.3	Results	98
3.3.1	Collisions	98
3.3.2	Crossing order	98
3.3.3	MPD evolution in time	99
3.3.4	Crossing distance	102
3.3.5	Questionnaires	106
3.4	Discussion	107
3.4.1	Qualitative motion adaptation	107
3.4.2	Crossing order	108
3.4.3	Quantitative motion adaptation	109
3.4.4	Local vs. global information	110
3.5	Limitations	112
3.6	Applications	113
3.7	Conclusion	114
4	Influence of path curvature on collision avoidance behaviour	115
4.1	Objective and contributions	116

4.2	Method	120
4.2.1	Participants	120
4.2.2	Apparatus	120
4.2.3	Experimental setup	121
4.2.4	Task	124
4.2.5	Questionnaire	125
4.2.6	Data analysis	125
4.2.7	Statistics	128
4.3	Results	129
4.3.1	Collisions	129
4.3.2	Crossing order	130
4.3.3	MPD evolution	131
4.3.3.1	Timing	133
4.3.4	Crossing distance	137
4.3.5	Orientation angle	139
4.3.6	Questionnaires	144
4.4	Discussion	145
4.4.1	Qualitative motion adaptation	145
4.4.2	Quantitative motion adaptation	146
4.4.3	Rectilinear vs. curvilinear	151
4.5	Limitations	154
4.5.1	Conclusion	156
5	Effect of Virtual Human Gaze Behaviour During Collision Avoidance	159
5.1	Objectives and contributions	160
5.2	Method	162
5.2.1	Participants	162
5.2.2	Task	162
5.2.3	Experimental Design	163
5.2.4	Data analysis	165
5.3	Results and Discussion	166
5.3.1	Collisions	166
5.3.2	Inversions of Crossing Order	167
5.3.3	Crossing Distance	169

5.3.4	MPD Evolution over Time	171
5.3.5	Gaze Behaviour and Collision Avoidance	172
5.4	Limitations	173
5.5	Conclusion	175
Conclusion		177
Bibliography		182
List of figures		225
List of tables		227
Annexes		229
A	Global motion visualisation for detection of deceptive motion in rugby	231
A.1	Introduction	233
A.1.1	Objectives and Contribution	236
A.2	Method	239
A.2.1	Participants	239
A.2.2	Apparatus	239
A.2.3	Stimulus	240
A.2.4	Appearances	240
A.2.5	Perception task	242
A.2.6	Perception-action task	243
A.2.7	Analysis	244
A.3	Perception results	245
A.3.1	Overall performance	245
A.3.2	Expertise	248
A.3.3	Appearance	250
A.4	Perception-Action results	252
A.4.1	Performance	252
A.4.2	Reaction time	254
A.5	Discussion	259
A.5.1	Expertise Performance	259

A.5.2	Appearance Performance	261
A.5.3	Timing	262
A.5.4	Limitations	263
A.6	Conclusion	264
B	Synthèse Française	267
B.1	Introduction	268
B.2	Objectifs	272
B.3	Méthodes	277
B.3.1	Participants	277
B.3.2	Dispositifs	277
B.3.3	Tâches	279
B.3.4	Mise en place expérimentale	280
B.3.4.1	Comportement d'évitement des collisions entre marcheurs : indices de mouvement global et local	280
B.3.4.2	Influence de la courbure de la trajectoire sur le comportement d'évitement des collisions	283
B.3.4.3	Effet du comportement du regard humain virtuel lors d'une tâche d'évitement de collisions orthogonales	286
B.4	Comportement d'évitement des collisions entre marcheurs : indices de mouvement global et local	289
B.4.1	Objectif et contributions de la première étude	289
B.4.2	Discussion	291
B.4.2.1	Adaptation qualitative du mouvement	291
B.4.2.2	Ordre de croisement	292
B.4.2.3	Adaptation quantitative du mouvement	293
B.4.2.4	Informations locales ou globales	294
B.4.2.5	Conclusion	296
B.5	Influence de la courbure de la trajectoire sur le comportement d'évitement des collisions	297
B.5.1	Objectifs et contributions de la deuxième étude	297
B.5.2	Discussion	301
B.5.2.1	Adaptation qualitative du mouvement	301
B.5.2.2	Adaptation quantitative du mouvement	302
B.5.2.3	Rectiligne et curviligne.	308

B.5.2.4	Limitations	311
B.5.2.5	Conclusion	312
B.6	Effet du comportement du regard humain virtuel lors d'une tâche d'évitement de collisions orthogonales	314
B.6.1	Objectifs et contributions de la troisième étude	314
B.6.2	Discussion	316
B.6.2.1	Collisions	316
B.6.2.2	Ordre de croisement	318
B.6.2.3	Distance de passage	320
B.6.2.4	Évolution de la MPD	321
B.6.2.5	Conclusion	323
	Scientific contributions	325

Introduction



Figure 1 - City life, a crowd of people walking in multiple directions and completing several forms of interaction.

While locomotion can be considered an elementary task that is completed seamlessly without conscious thought, the processing within the central nervous system is far from at rest. Navigation through any given environment can involve the stepping over, on, around obstacles, or a combination of all, with the purpose of transporting the body, safely, towards a goal [Winter1991]. Successful navigation is then the ability to orientate the body and interact with the environment, either avoiding or intercepting mobile or fixed obstacles, or avoiding an obstacle to intercept another (i.e., circumventing an individual to meet a friend behind them, or navigating any cluttered environment to

arrive to a goal). Therefore, the study of human locomotion has a vast and enduring area of interest, covering disciplines such as neuroscience, psychology, sports science, medicine and computer science.

The task of interception can be thought of as a thesis or scientific publication, the well-referred bottleneck deduction, the initial stages are broad and numerous while approaching an end-goal and a focus point. For example, nature's predator and prey, the initial interaction is in a changing environment of multiple possibilities with the prey increasing the possibilities through evasive tactics, the end-goal for the predator will be the capture of the prey. Avoidance is then the inverse of such, the initial stages of the task are predefined, and each behavioural adaptation broadens the scope of possibilities. In terms of locomotion, while walking down a busy street (Figure 1), a task can be to not collide with others, the behavioural responses for such may include: to stop completely, change direction, or adjust your current speed. In each task, perception is required for information gathering (where is the body in reference to the current environment), and action is required (neuromuscular coordination and organisation of the body). Forming a perception-action coupled loop of a perceiver and their environment [Warren2006], one must perceive in order to act and act in order to perceive [Gibson1979].

Interactions such as collision avoidance constitute the basic synergies of daily living, coordinating one's movement with another. Given this, human movement is thus not only aimless displacement within an environment. Instead, it is dense with perceivable information for action. Navigating stairwells [Warren1984], passing through doorways [Cinelli2008b], and going around other walkers and obstacles alike [Olivier2012]. The identification of underlying mechanisms, which is the perceptual cues required for correct movement perception, would allow for significant progress to be made in human social behaviour. Consider, for example, a simple interaction with another walker or a more dynamic and complex sporting task; the visual system is particularly sensitive in extracting cues from human movement (Figure 2). For example, emotional states, intent, gender and deceptive motion [Montepare1987, Runeson1983a], of which, these

cues can be extracted from abstract information representations such as point light displays [Troje2002]. Local cues such as gaze can transfer information, where gaze has been characterised as a factor of social interaction [Kleinke1986] and considered a form of nonverbal communication, through emotional arousal from previous experiences or communicative intention [Senju2009]. By perceiving another walker, a human is able to determine future outcomes, interpreting the intentions and anticipate the forthcoming event with possible adaptations to their current state.

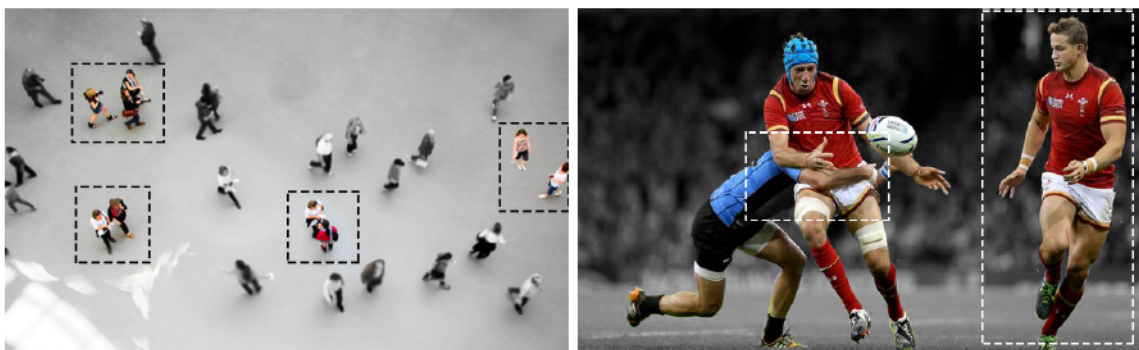


Figure 2 - Two example environments of perception-action coupling. Left) natural city scene with four possible forms of interaction, anti-clockwise from top-left: following, accompanied walking, intercepting (meeting), and collision avoidance. Right) An example of successful interception (player being tackled) and a teammate following in support.

To this end, this thesis aims at answering the following questions: what are the visual cues an individual perceives from the movement of others? What are the models for determining future predicted crossing distances? What are the interpretation mechanisms involved? In working towards answering these questions, the thesis consisted of three studies. The first study focused on the visual cues, namely the nature of visual information, whether the information is extracted from a global representation of motion or local cues within the global representation. The second study then focused on the path of the virtual walker, whether future outcomes are extrapolated rectilinearly or curvilinearly. Finally, the third study worked towards the mechanisms of interpretation,

investigating perceived agency through gazing behaviour of virtual humans. In summary, the combined three studies investigated the influence of visual cues on collision avoidance behaviour. In order to develop the understanding and answer these questions, a simple introductory one-on-one paradigm of orthogonal collision avoidance was studied. To address these questions and maintain control of the environment the works herein were performed using virtual reality. The use of virtual reality is a validated tool for applied psychology as it allows us to manipulate finite details of a given environment and withdraw conclusions of effect from those manipulations. For example, psychophysics, a catching task of a ball in flight under various gravitational forces [Bosco2012] and angular accelerations [Bennett2016].

The thesis is structured in the following manner: Chapter 1 reviews the current literature, specifically, focusing on theoretical foundations, perceiving the environment, interacting with the environment and the coupling of computer science technologies for perception-action investigations. Thereafter, the objectives are summarised in more detail before presenting the three chapters that refer to the studies involved in the thesis. Chapter 3 is the first work completed in relation to the thesis, focusing on the nature of visual information, specifically, investigating whether the information is extracted from global displacement or local motion cues. Chapter 4 being the second work of the thesis and focused on the path constraints of the virtual walker, with the virtual walker maintaining a constant tangential velocity and following a curvilinear or rectilinear path. Chapter 5 is the final study of the thesis, focusing on the social aspects of the interaction, namely, gaze behaviour of the virtual walker. Finally, a general conclusion of the three studies and future perspectives. An additional study on the nature of visual information in a more dynamic setting of a rugby attacker-defender dyad is available in annexe A, which presents a possible field of application from chapter 3.

Chapter 1

Background

"The environment of animals and men is what they perceive. The environment is not the same as the physical world, if one means by that the world described by physics."

— Gibson, James J.. The Ecological Approach to Visual Perception

1.1 Visual control of locomotion

All living organisms must adapt to their environment in order to survive and reproduce, evolution being a by-product of fine-tuning for such goals. The body is adapted to and by its environment; the presentation of nutrition by the environment and the mechanics to move towards the source of nutrition by the organism. Even within this example, movement requires regulation, the ability to detect the environment and to interact with it, that is, perceive and act to find food [Bruce2003]. It is therefore that perception and action are coupled, in that movement is required to perceive, and perception is required for movement.

Perception is the psychological phenomenon connecting us to the sensitive world through our senses. It involves the use of our five senses: hearing, sight, smell, touch and taste, each of which is expressed in a perceptive way; auditory, visual, olfactory, tactile and gustatory perception. Each sense is used for detecting and interpreting the various forms of energy and its changes from the environment, such as light, sound and neural activation [Bruce2003]. However, it is not only the interpretation of these systems, but the anticipation of the consequences of the simulated actions also constrain perception [Berthoz1997].

Any living organism navigating their respective environment must perceive the environment as well as be aware of its current state, answering the fundamental questions of where one is, how one is orientated, where are objects in relation to one, where are objects in relation to each another, are these affordable for action, and what action is necessary [Marshall2001]. The visual system, while not the sole source of information is a privileged channel that animals (birds, reptiles, fish etc.) use to explore and interact with their environment [Prevost2002, Patla2004, Silva2018], providing several sources of important information, including the identification and localisation of objects [Schneider1969, Mishkin1982], focus for fine motor skills or ambience for whole

body movements [Trevvarthen1968], and far and near space vision [Previc1990]. With the vast information and the efficient processing rate, vision can support several major roles during locomotion, answering the fundamental questions of Marshall [2001]: the detection of hazards, the selection of required manoeuvres, the preparation and execution of chosen manoeuvres, and further adjustments, if necessary, through anticipation [Tresilian2012].

The eyes, the peripheral organs of vision and a primary sensory outpost of the brain, function in a complementary and conjugate manner, detecting light that is refracted from objects in the environment of the optic array [Williams1999]. With light rays passing through a transparent lens, replicating an inverted form of the environment to the light-sensitive retina, which in turn translates light rays into nerve signals via receptors, horizontal cells, bipolar cells, amacrine cells and ganglion cells [Williams1999]. The fovea is then a smaller area of the retina that allows the maximal resolution of the environment through fixation [Zeki1993]; therefore the human oculomotor system updates points of interest through fixations and the dense concentration of neural receptors (Figure 1.1). The visual system is then principally for visual perception, transforming, organising and interpreting light to the brain. Where information is obtained through fixations, saccades and pursuit movements of the eyes.

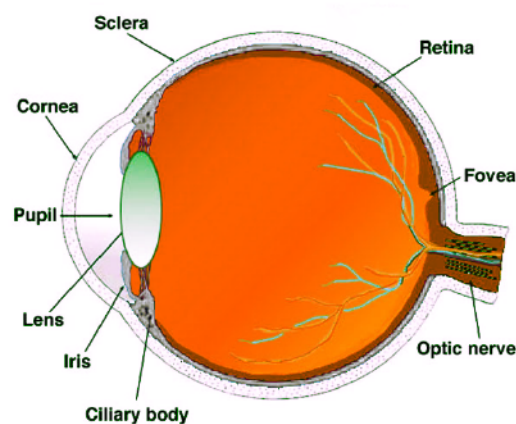


Figure 1.1 - Cross-sectional view displaying the anatomy of the eye.

1.1.1 Perception theories

The modelling and interpretation of visual information require a theoretical framework to explain the relation between perception and action. The theory of mind is a theoretical framework, which considers the ability to attribute mental states and intents of oneself and the intentions of others, essential components of social interactions. The theories of the mind date back as early as the 18th century from the works of Kant and Wundt where Kant's philosophy was a significant influence on the phenomenology and the works of Husserl, Heidegger, Sartre, and Merleau-Ponty, and Wundt founding the first experimental psychology lab in 1879 [Kaufer2015]. A brief taxonomy of the development of the theories of the mind is given in Figure 1.2. One of the earlier distinctions could be the functionalists or eliminativists as one branch and structuralists or representationalists of psychology as a second branch from the theory of mind [Chemero2011, Fodor1988]. Structuralists suggest a state of representation, intention or semantics as essential for cognitive sciences, whereas functionalists dispute semantic notions for representation. Alternatively, functionalists postulate neurological, behavioural or syntactic events that formulate mental states. Continuing from the functionalist branch, the views that are referred to as functionalist come from the American pragmatists or naturalists [Fodor1990]: Charles Sanders Peirce, William James, and John Dewey [Dewey1896, Heft2001, Rockwell2005, Chemero2011]. Thereafter, two further branches extended from functionalists concerns the variety behaviourism, including the ecological approach from the works of Gilbert Ryle, Richard Roty, Stephen Stich, Daniel Dewet, and James Gibson. All those under the functionalist branch, antirepresentationalists, believe mental acts are understandable through their functions (i.e., without appeal to thought or feeling) as opposed to a mirror of nature (i.e., a state of representation).

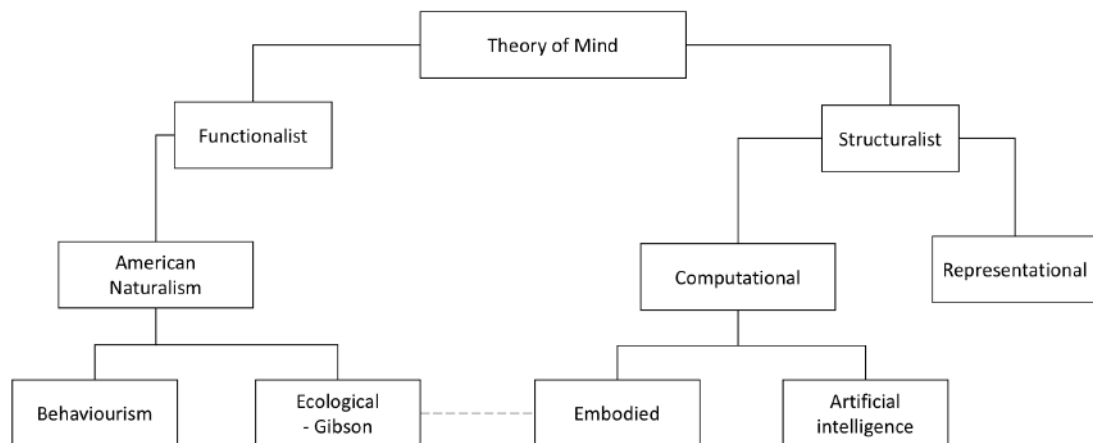


Figure 1.2 - Taxonomy of the theories of the mind, adapted from [Chemero2011].

In contrast, structuralists believe intention, semantics or representations are essential for cognition with the traditional view that mental acts followed the structure of: first, physical stimulation of receptors (e.g., visual stimulation), then, a linear series of mental acts related to the stimulus before, finally, a behavioural response [Titchener1895]. Under the structuralist branch are two sub-branches, computational and representational, the later in accreditation to Jerry Fodor. The representational theory of the mind [Fodor1981] commits to five hypotheses: 1) propositional attitude states (e.g., beliefs and desires) are relational. 2) Amongst these relations are mental representations. 3) mental representations have formal and semantic symbolisation. 4) mental representations have causal roles as a result of their formal properties. 5) propositional attitudes inherit their semantic properties from those of the mental representations that function as their objects [Fodor1981, Chemero2011]. Therefore, cognitive science theories that semantically evaluate internal entities are a variety of the structuralists representational theory of mind as they share these hypotheses in common. Then, a branch from the structuralists theory of mind would be the computational theory of mind, computation (and cognition) being the rule-governed processing of information. Systems within the computational branch and fit with the properties as mentioned above are often re-

ferred as artificial intelligence [Haugeland1985]. In his book, *surfing uncertainty*, Clark provides an excellent example when discussing Dennett's SLICE machine. Clark relates the machine as a representational model, further expressing the device in relation to action and embodiment in his book of *surfing uncertainty*, where he discusses cognition as predictive processing [Clark2015].

Finally, as expressed by the dashed connection of the ecological and embodied theories, we can see the eventual emergence of pluralism (the acceptance that several contending theories are necessary for explanation). Theoretical pluralism is then the theory that allows several incompatible theories to guide each other for progression, each identifying and resolving falsified aspects of each theory [Feyerabend1963, Feyerabend1965, Chemero2011]. Such overlaps can be noted from the work of Dennett [Dennett1969], and Stich [Stich1983]; arguing that cognition is the rule-governed manipulation in a logical manner but with semantic interpretation, difficulties both argued cognition was then a form of nonrepresentational mental gymnastics [Dennett1969, Stich1983]. It is therefore that these have not been explicitly highlighted in the taxonomy as they reside under both functionalism and computational categories. Another example includes the dynamical approach [Temprado2001, Newell1994], which considers musculoskeletal, environmental and task constraints with the perception and action coupling for organised coordination of action (Figure 1.3). These dynamical systems are then situating an agent within an environment, where it has been argued that meaning or cognition cannot be applied without accounting for agents being spatially located (i.e., situated) and have information from the localisation of themselves at a given instant [Barwise1981, Perry1983]. The concept of being situated is also used in the definition of robotics and their interactions with the real world as opposed to the mental gymnastics of representational theories [Brooks1991, Brooks1999]. Returning to the example from Clark and his reference to Dennett's SLICE [Clark2015]; the original device was predetermined representations, Clark mentions that an adaptation which allows action would then be a Robo-SLICE but the effective interaction of current en-

vironments would require a Situated Robo-SLICE [Clark2015]. Developing from being situated came embodiment and the embodied cognitive sciences, incorporating works in robotics, simulated evolution, developmental psychology, perception, motor control, cognitive artefacts and phenomenology [Chemero2011]. However, as per the works of Dennett [Dennett1969] and Stich [Stich1983], situated and embodied systems while representational or cognitive based have used the ecological approach to reduce the cognition of representations, such as action-orientated [Clark1997]. Finally, the works of Chemero, who focuses his book "radical embodied cognition" on changing the direct pathway of embodiment from computational to ecological [Chemero2011]. In his book he defines radical embodied cognitive science as the study of perception, cognition, and action as embodied phenomenon, using an explanatory tool other than mental representations. These theories combine, in part, essences of their counterpart theories to explain the other. Both Dennett and Stich founded in the functionalist string while explaining specific meanings to be semantically organised. Most recent works have considered the dynamical approach that regards limitations of current ability. For example, the range of motion and degree for freedom at hinge joints limits the number of possible outcomes.

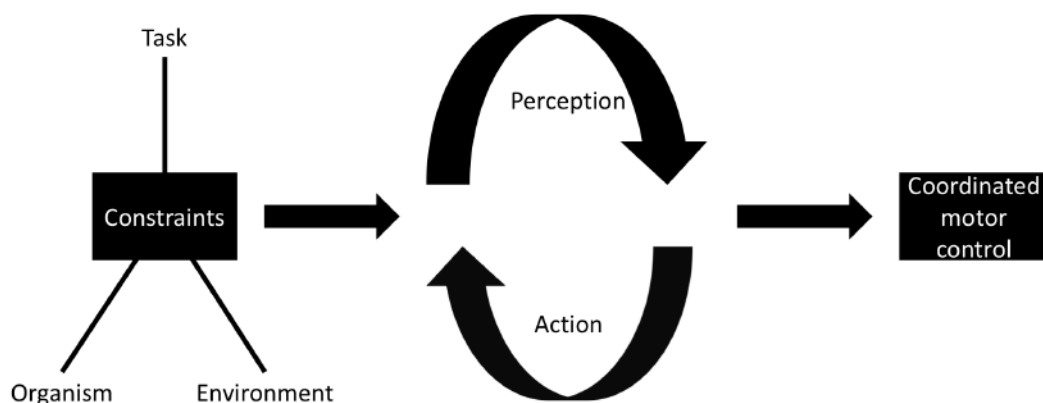


Figure 1.3 - Model of perception and action for neuro-musculoskeletal organisation after considering situated constraints. Adapted from [Temprado2001, Newell1994].

Current debate continues as to whether sensory information is meaningless when it arrives to the eye and later translated into meaningful information through cognitive processing or whether the information being received is already meaningful (Figure 1.4). The first, indirect, otherwise referred to as the top-down, cognitive and computational theory of mind argues that ambiguous stimulation of the senses from information cues requires progressive development into a percept, which is identified and processed by the mind [Helmholtz1925, Marr1982, Neisser2014]. The latter, direct, and otherwise referred to as the bottom-up or ecological approach is the alternative [Bernstein1967, Gibson1979]. The mind is not rejected from the theory. However, perception and action are directly coupled with the environment; what is being perceived is meaningful, and any action is meaningful, the mind needs not interpret all the information. Instead, it relies on biological and neurophysiological processing of the brain. Coupling vision to a whole system rather than a single channel, the environment being perceived with the eyes-in-the-head-on-the-body-resting-on-the-ground as the head and body move within an environment keeping the eyes relative to a surface [Gibson1979]. For the remainder of the thesis, we will focus on the ecological approach. The following sections will discuss the tenets of the ecological approach and present current evidence of how perceived invariants can express behavioural responses.

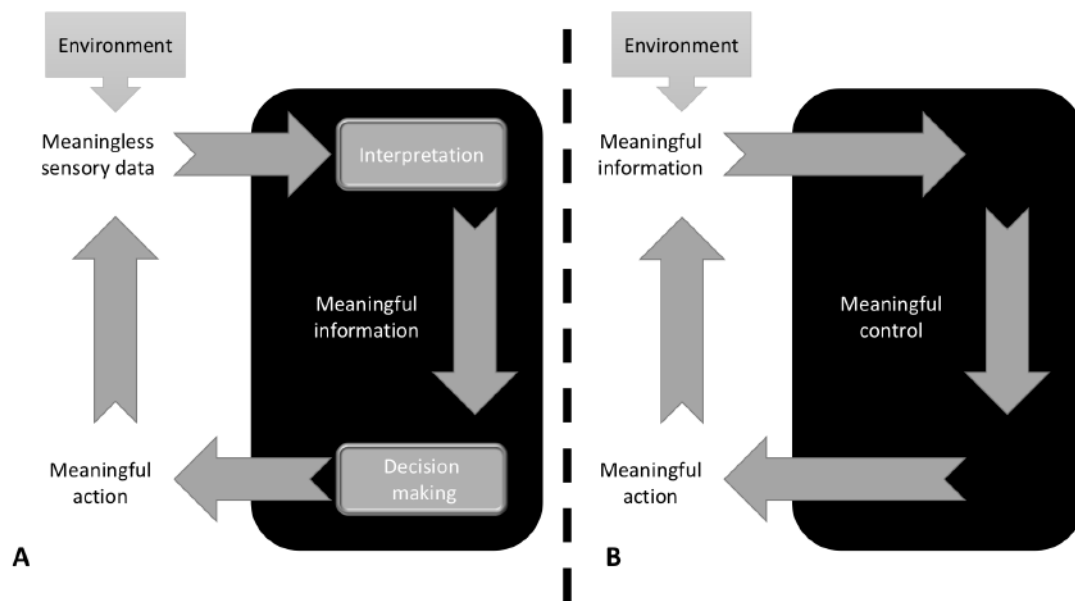


Figure 1.4 - A visual conception of indirect and direct theories of perception and action, adapted from [Williams1999]. A). Indirect approach where meaningless data is entered to the brain, therein it is interpreted and given a meaning for appropriate decision making and a meaningful action. B). Direct approach, information is already received with meaning and a meaningful action is completed without the necessity of interpretation and decision making.

1.1.2 Ecological theory of perception and action

While the roots of ecological direct perception can be found prior to the works of James Gibson, this section will focus primarily on his works and the effects thereafter that have influenced the development of ecological psychology as it is currently known. The birth and growth of Gibson's theory can be found in three major books expanding more than 35 years of his work [Gibson1950, Gibson1966, Gibson1979]. Succinctly, the birth and thus the initial book [Gibson1950], he began with his work on depth perception while working with aircraft pilots during the second world war. Radically changing his views on visual perception, already suggesting that depth and space should instead be emphasised by surfaces of the environment [Bruce2003]. This emphasis of the environment was more successfully expressed and detailed rather extensively in his final book where almost 50% of the book is dedicated to expressing the environment [Gibson1979]. When

referring to the environment he referred to the current and situated surroundings of animals and organisms in which they perceive and behave. Finally, with his last book and widely accepted, Gibson developed three main principles [Gibson1979, Bruce2003, Chemero2011, Kaufer2015]:

1. **Perception is direct.** Information is perceived from the environment is meaningful, we can act without the further necessity to process the information. In claiming so, perception is then not of mental gymnastics through representations and computational cognition, instead, it is antirepresentationalist.
2. **Perception is for action.** Perception is to generate and control action. We perceive the environment in order to be able to act with it. It is from this principle the perception-action coupling is most related.
3. **Perception is of affordances.** Following from the first two principles, it becomes evident that direct perception is for action, that must be guided by information of a sort. Affordances are widely discussed for their interpretation; therefore they are discussed later in order to express the impression taken for this work.

The ecological approach differed from previous theories in that it coupled the organism to the environment, and they were not two separate systems, rather they were considered as one. Perception through the optical array directly transferring information of invariants and variants of the environments; surfaces, structures, layouts and events. Affordances are then the action capabilities readily available and sizeable to the acting agent. Each transfer of information between the current situated environment and the currently available affordances are frame dependent as relevant properties between the two are coupled; the current position of the agent within the environment and the current musculoskeletal organisation of the agent in reference to the environment constrain each other as a synergy [Turvey1986, Williams1999, Kugler2015].

The perception and action coupling infers that from limited invariants of the optical flow, coupled with the parameters of the actionable system forms a control system. That information from the optical flow can directly influence the control of movement in adaptive behaviour, controlled movement of adaptive behaviour, in turn, alters the information from the optic flow [Kugler2015]. William Warren went on to develop this coupling as behavioural laws in the dynamics of perception and action [Warren1988a, Warren1990, Warren2006]; interactions between both agent and environment of physical, informational and task constraints (goal-oriented) form behavioural dynamics (Figure 1.5).

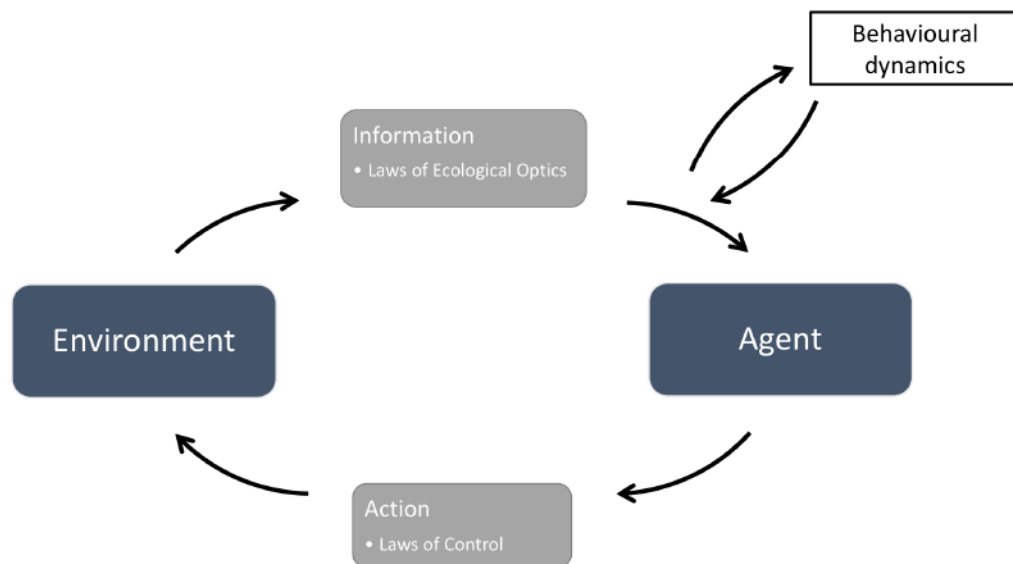


Figure 1.5 - The perception and action loop with the consideration of behavioural dynamics. Adapted from [Warren2006]

1.1.3 Optic array and invariants

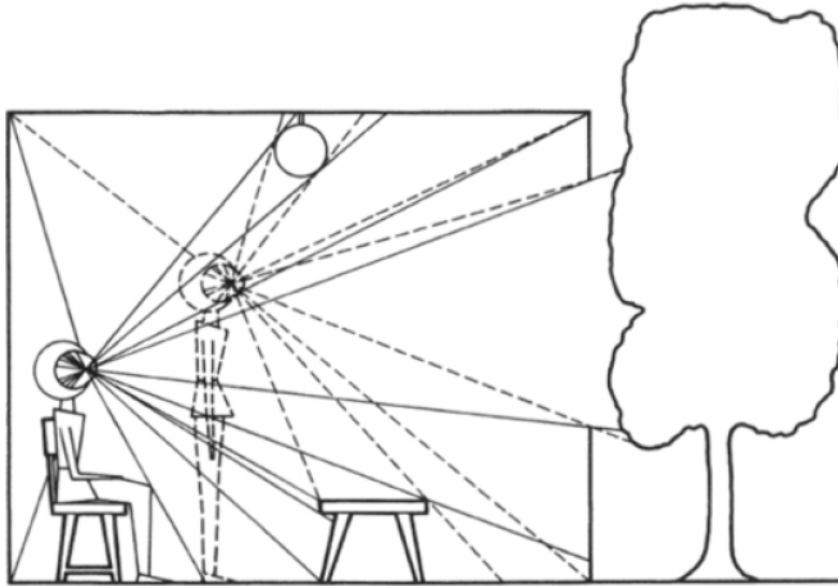


Figure 1.6 - Ambient optic array of a room from two points of observation. The change of optic array can be brought by locomotor movement of the observer, from sitting to standing and vice versa. From [Gibson1979]

Relating the properties of the environment with the distribution of surrounding energy distributions perception is then specific to sensory information [Williams1999]. One major source of information coming from ecological optical energy [Gibson1961], light reaching the eye after the reflection from surfaces (not planes) and objects (attached and detached), each with their defining textures forming cluttered environments [Williams1999, Bruce2003]. Considering the numerous elements of a situated environment, the reflected flow of light varies according to the surfaces, textures, and connections of surfaces. While certain flows are unaltered and maintain their ordered flow, others are perturbed and vary; flows that are unaltered are often referred to as invariants while perturbations and changes of the environment are variants. The combination of variants and invariants supports the perception of motion of external organisms as well as our own [Williams1999]. To describe the ambient optic array in further detail, an

image (Figure 1.6) from the third book [Gibson1979]. A static scene of one observer in two positions: the first, seated position, highlights how the ambient optical rays arrive and present the current situated environment to the observer, the second, is from motion by the observer, where the environment has not changed, but the perspective of the invariants of the room have different light rays reflected from them. Additionally, to express the information provided from textured surfaces and their potential influences on depth perception, an image from [Bruce2003], showing examples of artificial gradation gives the impression of a recession in the distance (Figure 1.7).

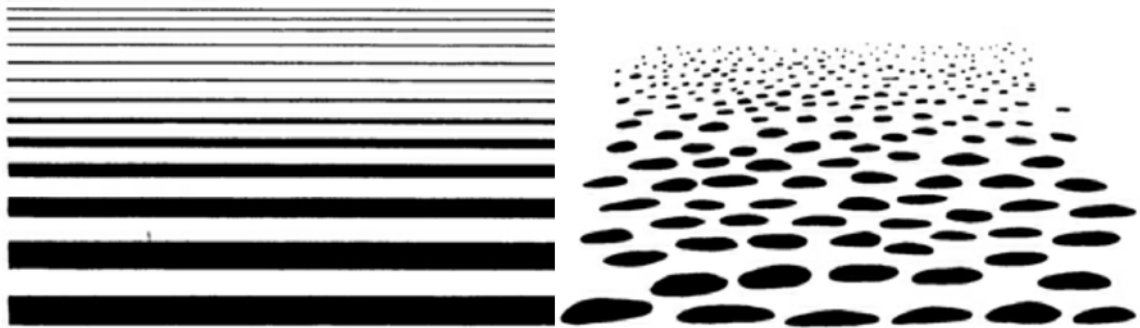


Figure 1.7 - Examples of textured gradation and an impression of distance. From [Bruce2003]

Previously mentioned, the motion caused by an observer changes the perspective and in doing so the light arrays that arrive to the observer. Gibson went on to further explain this in terms of the optic array and within it relativity: as an observer acts and moves through an environment, all surfaces and textures of varying distances present relative motion and the layout of such obstacles. Optic flow is not fixated as unidirectionally (i.e., flow is not solely in one direction), rather, it is dependent on the direction of movement (i.e., moving forwards or backwards). The most commonly referenced example is from his early years of applied work in aeroplane pilots and flying over an airstrip or, a variation of optic flow as the side view from a moving train (Figure 1.8). As he described optic flow, and the information it provided [Gibson1979]:

- ▶ The flow of the ambient optic array indicates motion in the environment and nonflow indicates a stasis within the situated environment.
- ▶ Outflow, as the flow expands from in front and past the observer, indicates approach while inflow, as if coming from behind the observer indicates a backward motion.
- ▶ A centralised point in the outflow, the focus of expansion, indicates the current attention and heading of motion.
- ▶ Changes in the position of the focus of expansion indicates a change in direction.



Figure 1.8 - A representation of the optic array expansion of the horizon (focus on the horizon), in this case from the pilot's field of view (left), from [Gibson1979]. Optic flow from the view of sitting in a train (right), from [Bruce2003].

The coupling between perception and action and the notion that changes in the optic flow can influence motor control has previously been demonstrated [Lee1975]. Using a purpose-built room that allowed a controlled movement of the walls of the room backwards and forwards induced respective sway of children and adults at slow movements of the walls. From this example, the findings presented a case of how invariants (and variants) within the optic flow can influence motor control. While, generally, details of structures can vary widely over space and time, specific properties remain invariant, that is persistence within the optic flow. As in the above example, in the absence of invariant and only subtle fluctuations of the optic flow lead to mimicry of wall behaviour by the observer. Further, invariants are information that an observer may attune to

specify something. Therefore, experimental approaches in ecological psychology should follow three steps [Bootsma1994]:

1. Invariants of the optic flow should be expressed as a mathematical formula
2. The sensitivity to the identified invariants should be analysed
3. The applicability and use of the invariant should also be analysed

Consider how collision avoidance behaviours can be triggered with limited visual information and invariants in the optic flow. As explained by Vicki Bruce, an obstacle in an environment void of any additional visual cues other than itself, void of textured patterns for distance and size information, the motion of itself is sufficient to trigger an avoidance behaviour by the observer [Bruce2003]. For example, if the obstacle were to approach the observer directly in-front, the image of the object would expand on the retina of the observer. When the trajectory is directed towards the observer, the two sides of the obstacle would expand at the same rate. If the obstacle were to pass perpendicular to the observer and not approach, the two edges of the obstacle would not increase in size, but rather, they would translate across the field of view. This information can be used separately or as a combination of the two in the prediction of collision course trajectories. In such a depiction, global motion cues (i.e., expansion of the sides or translation of fixed length sides) of a given obstacle would be deemed sufficient for determining a time to interaction and a location from the observer.

1.1.3.1 Tau

When the trajectory is directed towards the observer, an optical variable that can be used in the determination of time-to-contact (i.e., the time remaining before a collision with the observer would occur) would be Tau (τ), originally developed during a braking task [Lee1976]. Tau demonstrates the changes of how a gap is closing, and the gap is defined as closing as Lee refers to an action-gap that is purposeful actions entailing controlled closure [Lee2011]. These definitions of tau and action-gap were formulated

during the development of general tau theory [Lee1998], after its initial time-to-collision conception [Lee1976] and further development of time to nearest approach [Lee1985]. For a full review of his work and advanced understanding, it is recommended to visit his laboratory's web page perception-in-action and to read [Lee2011].

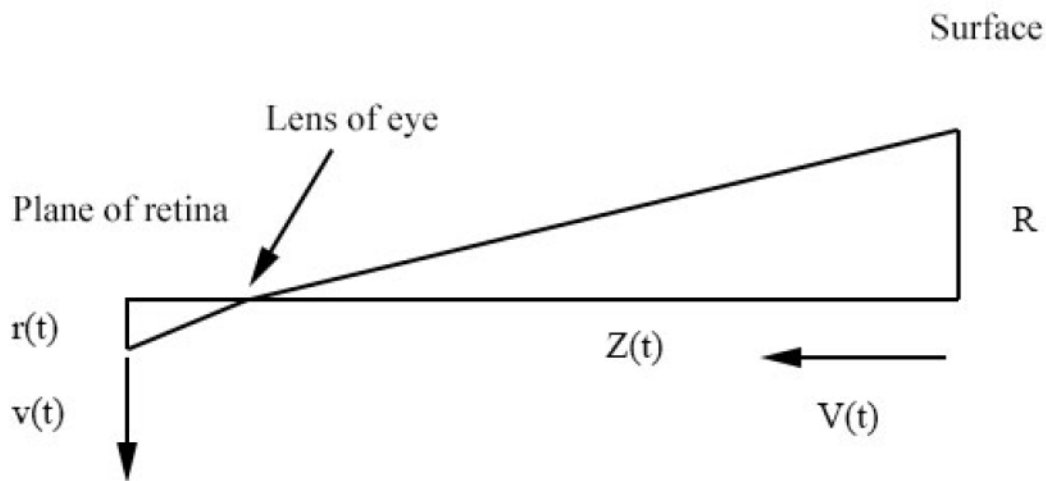


Figure 1.9 - Simplified visualisation of Lee's tau, the optical expansion of a surface (R) as it approaches the eye of the observer. From [Chemero2011].

Tau is directly related to the rate of change in the visual angle of an object (in the absence of prior knowledge of the objects size, distance or velocity), which in turn is related to the time-to-contact. Best visualised as two triangles inverting at the lens of the eye (Figure 1.9), where a surface (R) is approaching an observer at a constant velocity (V). At a given time (t), surface R is a distance away (Z(t)), where surface R is projected at a proportional size on the retina (r(t)). As the distance between the observer and surface R decreases the projected r(t) increases at V(t):

$$\tau = \frac{r(t)}{v(t)}$$

Tau is expressed as a ratio of any given distance at any instant of a point from the centre of expanding optical pattern. Knowing the distance of the as a ratio and its rate of approach tau is equal to $Z(t)/V$, where if V is constant, tau can be simplified as the time remaining until contact [Lee1976, Bruce2003, Chemero2011]. Tau is an optical variable that is directly available on the retina of the eye, while it does not provide absolute distances or calculated velocities it is directly perceivable and requires no further computation.

Lee and colleagues observed many animals in the development of tau theory, one notable study being that of gannet seabirds [Lee1981]. For those unaware, gannets are seabirds that fly 30m above sea level and dive (almost) vertically into the sea to catch a fish near the surface. As noted by Lee and Reddish [1981], the gannets maintained a wide wingspan for greater control of steering while plummeting at speeds of 87 km/h, only to streamline their wings with their body a second from the surface of the water. In such an instance the velocity is not constant, due to gravitational forces, and therefore tau at any instant did not specify a time to contact. However, within their work, Lee and Reddish derived an expression for time to contact in relation to the water surface and successfully fitted a curve from this expression that related to the actual time to contact and duration of the dive.

Another interesting publication studying the theory of tau was the manipulation of the optical variable while attempting to grasp tau [Savelsbergh1991]. In this particular study participants were required to regulate their hand apertures according to different sized balls that would approach them. The environment was designed to limit all visual information (e.g., texture, distance, horizon), participants were in a dark room and interacted with a ball that was lit up. It was reported that participants successfully adjusted their hand apertures to catch different sized balls.

However, it has been argued that tau is not sensitive to acceleration, only provides information of an object in reference to the eye and not to the hand catching a ball

and that tau is not observable for smaller objects; having a greater role in large objects as originally devised, the optical expansion of cars [Andersen2007, Tresilian1999b, Tresilian2012]. Finally, while tau is useful in the determination of time to collision, another limitation is that it does not detect future collision events [Andersen2001].

1.1.3.2 Bearing Angle

As mentioned above, tau has limitations in that human movement and interactions occur on several planes. Tau provides information concerning timing; however, distances and future collision events are additionally fundamental for effective collision avoidance tasks [Cutting1995]. Where they explained, based on the derivative of bearing angle, whether an observer will pass in front, behind or collide with an obstacle or another walker (Figure 1.10). The bearing angle derivative in combination with time-to-contact has been evidenced in a vision-based model for crowd simulations, steering walkers for collision avoidance using these control laws [Ondřej2010].

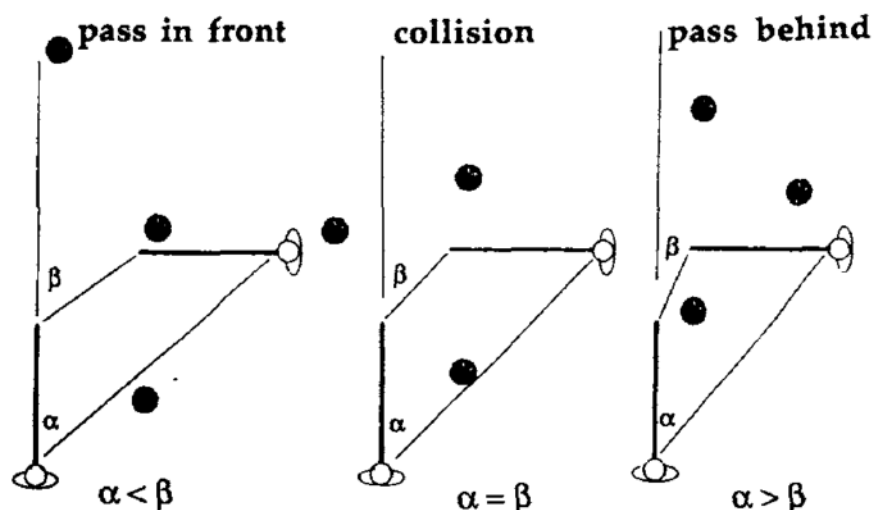


Figure 1.10 - The change or non-change in gaze-movement angles for an orthogonal collision avoidance task. The angle will increase when the observer will in front of another walker, remain constant if a collision will occur, and decrease when the observer passes behind. From [Cutting1995].

A prospective strategy that has gained increasing attention in the recent years is the constant bearing angle strategy. Originally being inspired from the behavioural work on steering [Fajen2004, Fajen2007], the strategy follows a goal of attraction by an observer while interacting with an obstacle moving along a horizontal plane. The constant bearing is the angle between the intended goal direction and the obstacle itself; if the constant bearing angle remains invariant and equal to zero then both observer and obstacle will intercept. Alternatively, an invariant absolute angle greater than zero ensures collision avoidance by leading the intersection or passing second (Figure 1.11). One strategy within the constant bearing angle strategy is a control law linking the rate of bearing angle change to a required acceleration in order to successfully perform the task [Chardenon2004, Bastin2006a, Bastin2006b].

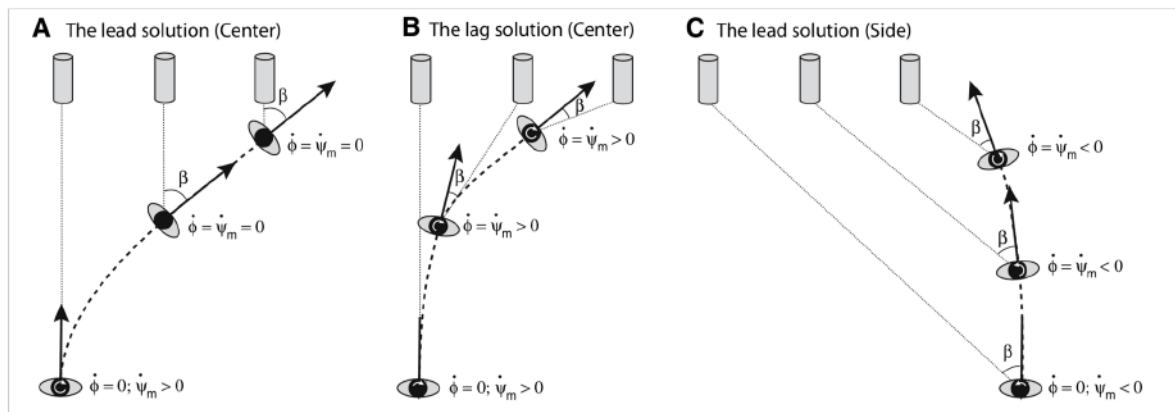


Figure 1.11 - Modelled solutions of interception using a constant bearing strategy: A), A solution that results in the observer intercepting the obstacle as bearing angle is near zero. B), Result in the observer passing behind the obstacle as the constant bearing angle is greater than zero. C), The observer will pass in front of the obstacle as the constant bearing angle is less than zero. From [Fajen2007].

The constant bearing angle strategy has been reported as a robust approach for whole body displacements [Fajen2004], which allows agents an ability to adapt to changes of the task or environmental constraints early on in experimental conditions or at later stages [Chardenon2005]. In this instance, the constant bearing angle has been reported to account for continued displacement adaptations during curvilinear ball flight paths [Bastin2006b]. It has been previously mentioned that the perception and interaction of

curvilinear trajectories are impeded, as opposed to traditional horizontal or rectilinear experimental conditions [Berthelon1993, Craig2006]. Where the work by Bastin *et al.*, [2006b] presented a continual adaptation of acceleration to null the bearing angle.

1.1.4 Affordances

"An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behavior. It is both physical and psychical, yet neither. An affordance points both ways, to the environment and to the observer."

— Gibson, James J.. The Ecological Approach to Visual Perception

As mentioned in the previous section, affordances are widely discussed for their interpretation. Gibson's theory of ecological perception would have prematurely wilted and faded if not for the reply of Turvey, Shaw and Mace in 1981; their paper provides a systematic explanation of affordances [Turvey1981]. The aim here is to highlight previous works that have considered the explanations of affordances through the relation of organism and environment. The notion of an affordance traces back to Gestalt psychologists [Koffka2013]:

"To primitive man each thing says what it is and what he ought to do with it ... a fruit says 'Eat me'; water says 'Drink me'; thunder says 'Fear me'."

— Koffka, Kurt. Principles of Gestalt psychology

Affordances, which are often expressed as opportunities for action were a central theme of Gibson's concept and became a major theme of the work conducted by Eleanor Gibson. In her publication of perceiving the affordances: a portrait of two psychologists,

she mentions how she firmly believes affordances are learned through perceptual learning; the affordance of things, layout and anything an infant encounters. Interactions, then, of the near environment from reaching, handling, sitting, crawling and (eventually) walking of motor skill development is the learning of what the world affords [Gibson2001]. Prior to reviewing previous works concerning affordances, here are several key features as highlighted by [Fajen2009]:

- ▶ **Affordances are real.** Affordances can be directly perceived by an organism and need not be conceived by cognitive processing; sufficient information is available between the actor and the environment.
- ▶ **Affordances are animal specific.** Affordances are defined by the action capabilities of the animal: a book affords lifting and reading to a human while affording climbable to a mouse.
- ▶ **Affordances capture the reciprocity of perception and action.** Gibson recognised perception as a whole system, that is an agent in an environment that can be acted upon; affordances capture this reciprocity as they describe how animals can act with the environment.
- ▶ **Affordances allow for prospective control.** The perception of affordances allows for the organised control of future events as and when they occur. This is discussed further in the examples within the literature; two examples would be the laws of control [Warren1998] and the behavioural dynamics of steering [Fajen2003].
- ▶ **Affordances are meaningful.** As opposed to structuralist philosophy, affordances do not require higher-order processing, they themselves are inherently meaningful and describe what can and cannot be done (i.e., can be bound to the laws of control).
- ▶ **Affordances are dynamic.** As Gibson stated, one must move in order to perceive and perceive in order to move. Therefore, opportunities for action come and go with the movement through an environment. For example, a chair under a desk affords to be pulled from under the desk, thereafter, the chair affords sitting.

A well-known and often cited work in relation to affordances is the work of Warren and stair climbing [Warren1984]. Within the build-up of this work, he mentions the determination of a path that affords locomotion depends upon the analysis of relevant properties of the environment with the relevant properties of the animal and its action system: surface rigidity in relation to body mass, and path width in relation to body dimensions for example. He continues by implying a body-scaled metric for such analysis. The work of the paper itself consisted of three experiments; a perceptual study of whether a step was climbable or not, the energy expenditure related to the size of the step, and choice task of preference and rating of the stairs. The results of this study evidenced the correspondence between organism and environment; judgements of climbable or not differed depending on the height of the participant [Warren1984].

It was reported the affordability of stair climbing could be accomplished through the ratio of standing eye height and leg length. Similarly, as reported earlier in this work, a decline in the frequency of jumping through an aperture was reported when apertures were smaller than $1.3\times$ the width of a frog's head [Ingle1977]. Interestingly, the threshold of $1.3\times$ shoulder width has also been reported for comfortable passage of humans traversing an aperture [Warren1987]. Additionally, it has been reported that the threshold for passage through an aperture without shoulder rotation is adapted with changes to the body (e.g., the carrying of a larger than shoulder width object), or when the aperture is of two poles or two humans [Hackney2014b, Hackney2015b].

Affordances, as becoming evidently clearer, are applicable to numerous tasks; the climbing of stairs [Warren1984], frogs and humans traversing apertures [Ingle1977, Warren1987, Hackney2014b, Hackney2015b], the affordances of gap sizes in the floor [Jiang1994], and surfaces that afford sitting depending on eye height of the perceiver [Mark1990]. An interpretation suggested that affordances are directly related to the requirements of the task, as well as the body and the environment [Proffitt2013]. This suggestion (Figure 1.12) shares similarities to the dynamical approach (Figure 1.3).

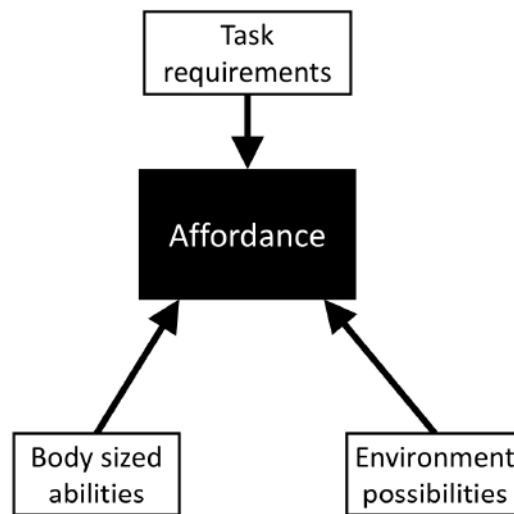


Figure 1.12 - An adaptation of Gibson's conception of affordances, extending from just agent and environment, the demands of the task, or purpose, additionally influences affordances. Adapted from [Proffitt2013].

Since the conception, there are two notable issues worth mentioning: the first as in part expressed by the examples above, in the entirety of the world that we experience, considering all the possibilities for action, we only complete specific actions [Kaufer2015]. For example, while an office chair affords sitting on and a desk affords supporting a computer that affords writing a thesis, the chair and desk also afford climbing and standing on. The former is a regularity while the latter is rare. Due to the numerous possible affordances available at a given moment and the interaction with only one has led to the discussion of further specification and clarity of affordances; namely, describing the extent to which affordances are inviting [Withagen2012, Kaufer2015, Withagen2017]. A second development was that affordances should take into account the variability of human movement [Franchak2014]. Arguing that considering affordances with critical points was to imply that affordances are actionable categories, an action is possible until a critical point is met and then is no longer actionable. Rather, considering human movement variability, affordances have to be expressed as probabilistic functions (Figure 1.13). As one of the primary tenets of the ecological theory of perception and action is of affordances, it is important to understand affordances themselves. Here we

demonstrate that while affordances can generally be accepted as relationships between the agent and the environment, they can be interpreted in a number of alternative ways. In the context of the thesis, we will interpret affordances as general opportunities for action by the agent-environment relationship.

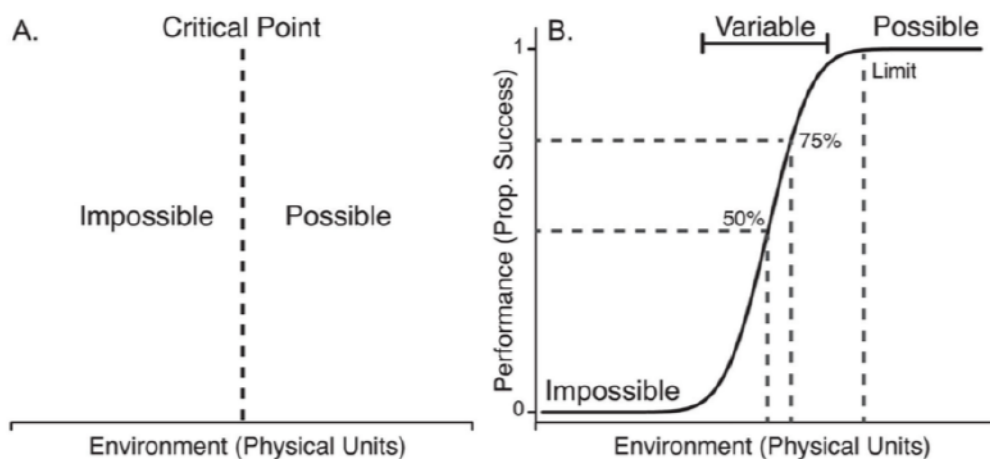


Figure 1.13 - A). Affordances expressed as actionable categories, actionable being possible or not dependent of a critical point. B). Affordances expressed as probabilistic functions, a range of task success variability between actionable or not to allow for variations of human movement. From [Franchak2014]

1.1.5 Experimental methods

The application and manipulation through psycho-physics was an original interest for the study of visual perception and interactions with the environment. While, psycho-physics was already applied in cognitive studies for indirect perception validations, after the radical approach for ecological perceptions [Gibson1979], psycho-physics became increasingly important in the control and understanding of invariants in the optic flow [Bootsma1994].

Methods to study visual perception by means of psycho-physics manipulation have advanced through the years. James Gibson mentioned how he used methods of shadow projection in his early work for depth perception [Gibson1979], Eleanor Gibson developed work of a physical platform and transparent surface for the invisible cliff [Gibson2001]. Similarly, many studies have been conducted in the presence of physical scenes that were manually manipulated for testing visual perception and affordances [Warren1984, Warren1987, Savelsbergh1991, Jiang1994]. Currently, a more favoured tool for experimentation is virtual reality [Pan2018]. This section will cover the use of motion capture, video recording and virtual reality with eye tracking and occlusion techniques for the coupling of visual perception and action.

1.1.5.1 Video

Videos allow applied psychologist to present several images of a dynamic scene, pausing at instances prior, during or directly after an action. This technique allowed the observer to begin immersing themselves to the scene more easily than static slides [Williams1999]. In both approaches, participants are generally required to observe the scene, where their eyes are tracked, or they are requested to verbally report back what they are looking at and what they are thinking. Additionally, video techniques allow for event occlusion and temporal occlusion; event occlusion refers to the removal of regional specific local motion cues whereas temporal occlusion refers to the pausing or removal of video stimuli (Figure 1.14). In visual perception and action in sports [Williams1999], readers are recommended to read [Abernethy1985] for a study using event occlusion and that reports a systematic decline in task performance with the removal of spatial cues where a local cue that significantly impedes performance is inferred to be important for visual perception. Temporal occlusion is then to stop or remove all stimuli, for example, as an attacker in rugby runs towards a defender [Jackson2006]. Within this study, a critical point of change in direction by the attacker was selected as a temporal reference

point, occlusions of the video being cut-off were then set prior, after and during this instant. While the application of video techniques have proven insightful in the development and understanding of visual perception, nevertheless, the application of video footage uncouples perception from action, such uncoupling can lead to biased results [Dicks2010a]. Furthermore, another limitation of video-based experimental methods is the monoscopic view in 2D, where it is argued that a sense of immersion and depth perception is enhanced through stereoscopic stimulus in 3D. It was further suggested that 3D may lead to egocentric spatial referencing (self-centred), whereas 2D may lead to allocentric (world-centred) [Kober2012].

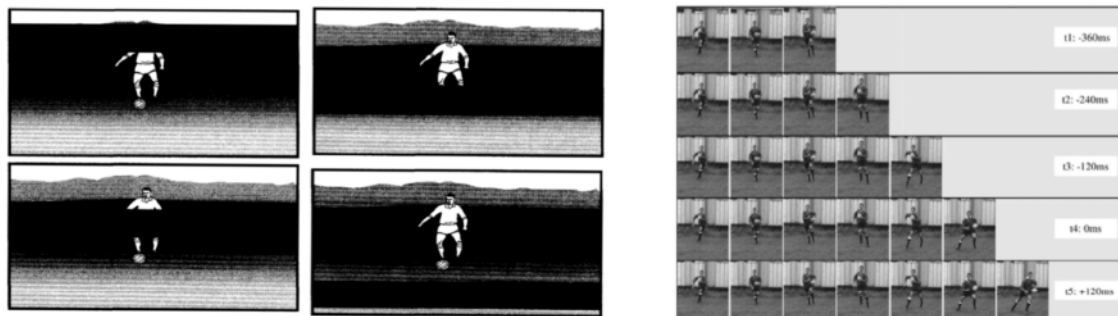


Figure 1.14 - Two examples of occlusion techniques: left, is event occlusion of a soccer player dribbling a ball [Williams1999], and right, is a temporal occlusion of a rugby attacker performing a deceptive or non-deceptive motion [Jackson2006].

1.1.5.2 Motion capture

Motion capturing for visual perception studies has three main components of application. The recording of natural and unconstrained whole body behaviours in response to presented stimuli where an environment is produced with physical stimuli, as mentioned above, and the participants are required to navigate the environment. Such examples would include aperture traversing and approaching mannequins on a rail, capturing the whole body behavioural responses of the participant to varying rates of approach by the mannequin and the presence of an aperture [Cinelli2007, Cinelli2008b].

Further, motion capture is used as a stepping tool for the presentation of stimuli. For example, the visual stimuli can be reduced to a point light display [Runeson1983b]. Participants were able to identify biological motion on-screen and detect deceptive motion from a limited number of white dots on specific anatomical landmarks displayed on a black background (Figure 1.15). Further, motion capture can be used as an input of virtual character animation, providing a more realistic motion than computed algorithms. The captured motion can then be used as part of a perception and action study with occlusion time paradigms [Brault2012].

Finally, real-time motion tracking allows for adaptive and responsive environments; avatars can be embodied or work towards such realistic interactions. For example, virtual characters can be programmed to follow the participants through gaze and head rotations [Nummenmaa2009, Narang2016].

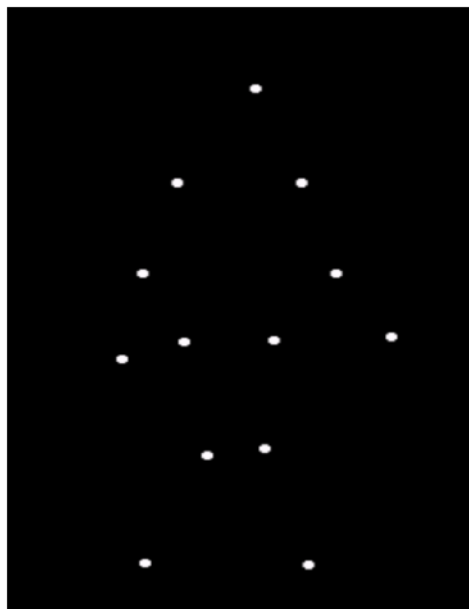


Figure 1.15 - An example point light display of a walker

1.1.5.3 Virtual reality

"Virtual reality is a scientific and technical domain that uses computer science and behavioural interfaces to simulate in a virtual world the behaviour of 3D entities which interact in real time with each other and with one or more users in pseudo-natural immersion via sensorimotor channels."

— B. Arnaldi, P. Fuchs, and J. Tisseau. *Traité de la réalité virtuelle*

Virtual reality is a tool that provides an ability to decouple natural co-varying variables, increasing the control and manipulation of experimental set-ups [Arnaldi2003]. In the recent years, virtual reality has been readily available for consumers, thanks to technological improvements and cost reductions. Virtual reality opportunities include head-mounted displays and computer-assisted virtual environments (CAVE), where a user is immersed in a virtual world (Figure 1.16). The application of virtual reality has proven a novel and powerful tool for ecological perception and action research [Loomis1999, Tarr2002].

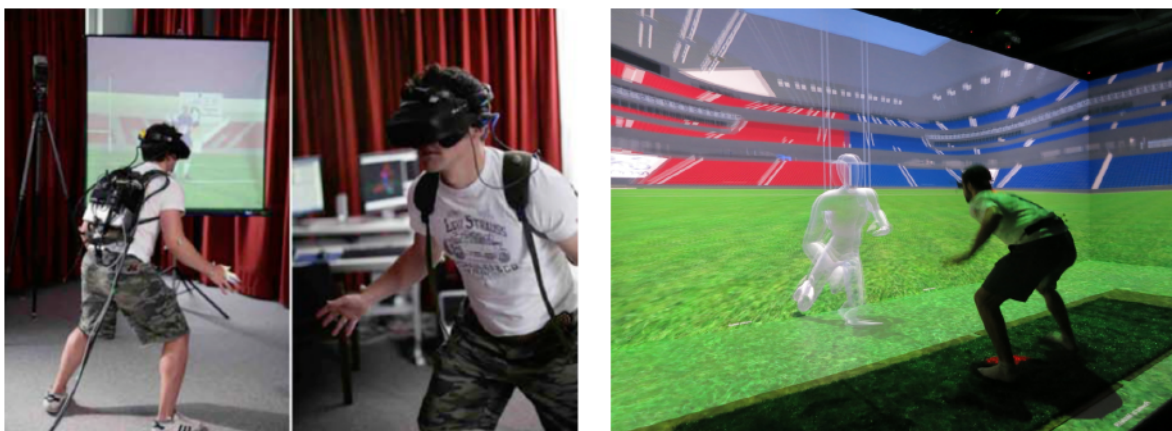


Figure 1.16 - Two examples of immersive technologies: left, a participant using a head mounted display from [Brault2012], and right, a participant from the study within the appendix of this thesis using a CAVE environment.

A brief and succinct history in the development of virtual reality and the concepts of immersion finds its roots with Ivan Sutherland, predicting the immersive virtual world and head-mounted displays [Sutherland1965, Sutherland1968]. Although the first HMD dates back much earlier, it is the prediction of Sutherland where the roots are more grounded [Slater2016]. The systems are most commonly known better resemble the virtual interface environment workstation; a full virtual reality system with head tracking, wide field of view, audio, body incorporation with tracked gloves that allowed virtual interactions through haptics [Fisher1987, Slater2016]. Later, immersive CAVE systems were developed [Cruz-Neira1992, Cruz-Neira1993]. Independent of the system, an effective virtual reality system surrounds the user in a 3D world, where the user's head is tracked in order for the projected images to be updated in relation to the user's head position and orientation. Further, users should have the ability to interact with the environment through the tracking of the user's body, tracked handheld devices, gloves, a joystick or a mouse [Slater2016, Olivier2017].

Immersion describes the technical capabilities of a system, the physics of the system, that provide an immersive experience as defined by three components: 1) 3D stereo vision, 2) surround vision, the external world is excluded from current visual perception, including after head rotations, 3) dynamic control of viewpoint, the user's head position should be tracked to update the projected display in real time [Pan2018]. A subjective correlate from immersion is the sense of presence; when the user perceives the virtual world in a natural way the perceptual system infers that what is being perceived is the current actual surroundings [Slater1997, Slater2016]. The subjective illusion of presence is then the "sense of being there", being within the virtual world [Pimentel1993, Barfield1995, Slater2016].

A detailed review of virtual reality was recently completed [Pan2018], therein, several interesting and additionally comprehensive commentaries discuss the applications (and limitations) of virtual reality for social interactions [de la Rosa2018, Kulik2018]. Virtual reality permits the ability to maximise experimental control of the visual environment,

where one variable may be altered at a time to test its influence. Social features of a virtual avatar would be a prime example, changing the pigmentation to investigate racial biases, or the gender [Slater2014], or, changing the appearance and densities of crowds [Bruneau2015]. Another example would be the control of the interactive situation, how the user interacts with the virtual environment [Cirio2013, Olivier2017] or the behaviour of the virtual character [Grillon2009, Hu2016].

The study of perception and action through immersive technologies (Figure 1.17) is not without its drawbacks [Fink2007, Pan2018, Kulik2018]: variances between reality and virtual reality have been reported for depth perception [Loomis2003], which is not necessarily related to a restricted field of view from head-mounted displays [Creem-Regehr2005]. Systematic spatial estimations may be a result of not being able to see one's own body in virtual reality [Phillips2010]. Alternatively, the memory of the real environment, when both virtual and real environments are identical, veridical distance perceptions seems possible [Interrante2008]. Further, the rate of optic flow from forward gaze-driven speed has also been reported to be underestimated [Banton2005]. Additionally, virtual reality can produce undesired artefacts of the projected environment: mismatching limb locations, latency in movement, or incongruent cues [de la Rosa2018]. Nevertheless, despite the possible variances and drawbacks, virtual reality has been validated for the reproducibility of stereotyped walking trajectories [Cirio2013] that can be found in reality [Hicheur2007], despite interactive methods such as a mouse, keyboard or joystick [Olivier2017]. Where in [Olivier2017] similar collision avoidance behaviours were observed when navigating with a joystick, additionally, the notion of personal space is maintained [Gérin-Lajoie2008, Argelaguet-Sanz2015].

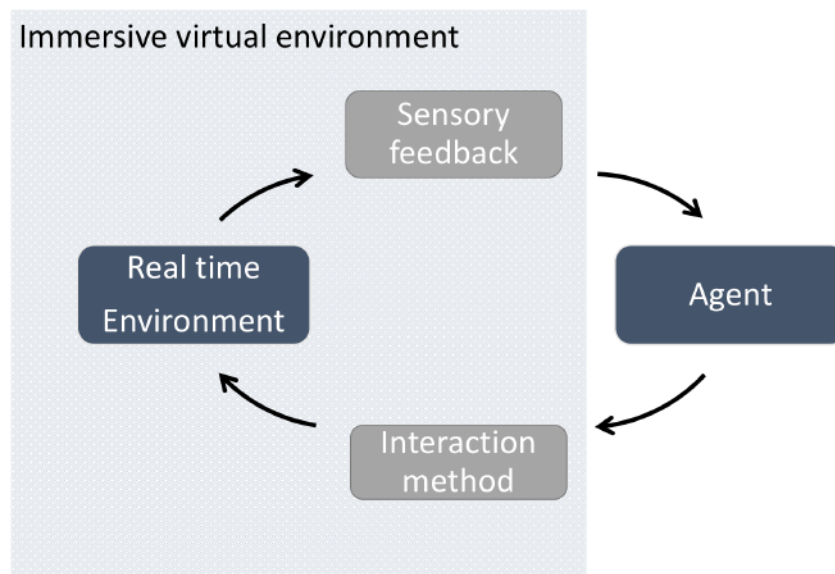


Figure 1.17 - An adaptation of the perception action loop that considers immersive technologies a part of the loop

1.1.5.4 Eye-tracking

The visual system plays a vital role in the pick-up of information, through fixations, saccades and pursuit movements of the eyes observers are capable of negotiating complex and cluttered environments [Marigold2007, Silva2018]. As evidenced by the optical invariants previously mentioned, social interactions can then be guided and modelled based on vision and optical variables [Ondřej2010, Fajen2007]. Therefore, eye-tracking can provide a good indication of where visual information is obtained for motor control [Patla1997, Warren1998]. Similarly to video, through the application of glasses, visual cues can be identified and tested through event occlusion, temporal occlusion and with eye-tracking event identification (Figure 1.18). Event occlusion (and distortion [Rushton2001, Warren2001]) and temporal occlusion are similar paradigms to those explained within video methods, therefore, this section will focus on eye-tracking.



Figure 1.18 - Examples of modified glasses for the study of visual perception. Chin-up glasses that occlude events below the chin (left), Plato temporal occlusion glasses (centre), and ASL eye-tracking glasses (right). Images sourced from supplier websites.

Eye-tracking was traditionally realised by fixating the participant's head to a frame of reference and recording the eye movement responses to a stimulus that is highly dynamic or of static images [Williams1999, Schwarzkopf2013]. Since, the experimental approaches have advanced to remote eye trackers (without head fixation) in front of desktop screens, for example, or wearable trackers, such as figure 1.18. With the advancement of technologies, wearable trackers have become lighter and more frequently included for virtual reality studies and real-world applications [Jacob2003, Schwarzkopf2013, Lappi2015].

The introduction and application of eye trackers with their technological advancements of precision and accuracy aided advances in psychological theories. Most notably, the distinction of perceptual differences between experts and novices in most competitive settings [Williams1999]. Nevertheless, eye-tracking remains with limitations: the physical relationship between the participant and the eye-tracker, either limiting the participant's movements from a remote eye-tracking unit or a head-mounted unit which will require a portable battery pack or frequent charging [Lappi2015]. Additionally, data extraction and interpretation can be tedious and time-consuming. Researchers should be aware of the metrics they wish to extract and interpret (e.g., fixation points, gaze duration, area of interest, and scanning path), as the interpretation of the results can require the experimenter to conduct a "fishing expedition" of several interpretations

in order to extract the most relevant analysis [Jacob2003]. Finally, after a systematic review of 38 research papers on the visual perception and exploration behaviour in soccer using eye tracking technologies identified an influence of experimental domain [McGuckian2018]. That is, the majority of work is based in laboratory settings, and no field work has considered open play settings, where such open play field-based settings are recommended for better understanding visual exploratory behaviours. Further, it was suggested that gaze tracking alone is not sufficient for the full comprehension of visual search strategies, rather, technologies should consider eye-head-body movements and specifically during open play settings [McGuckian2018].



Section 1.1 has detailed the theoretical framework related to the visual control of locomotion, expressing how information exists within the optical flow and how specific information can be invariant. Additionally, several experimental approaches to investigate the perception-action loop have been discussed, showing that virtual reality is a fruitful tool to develop experiments in such a context. The following section will consider the interactions formed with the environment in the specific case of collision avoidance.

1.2 Interactions with the Environment:

Collision avoidance

With the theoretical framework discussed, this section applies the fundamental systems of visual perception during interactions with the environment, focusing on the perception of motion and the strategies used for collision avoidance. Specifically, the aim of this section is to detail the relevant information that may be extracted for successful future collision detection. Therefore the visual systems ability to detect motion; its sensitivity to perceive speed and direction motion adaptations will be considered. Further, this section continues in detailing the motor adaptations of avoidance strategies if a collision is imminent and the preservation of personal space before finally discussing the possible human factors that could further influence the perception of the task. The central focus of this section will be on collision avoidance, predominantly during a locomotor task it is, therefore, necessary to define the types of collision and the possible avoidance behaviours. With a significant amount of literature using similar paradigms of invariants from the optic flow to express interactions with the environment, where necessary, examples from alternative sources have been cited. Cutting *et al.* adeptly explained that collision avoidance occurs frequently each day and in several forms [Cutting1995]:

"We and other animals move through cluttered environments many times each day, often at considerable speed. Most objects in these environments are stationary and need to be avoided if we are to get safely from one place to another. Some objects also move, and these too often must be avoided. Such acts of avoidance are of obvious and considerable importance; to fail to execute them with reasonable accuracy is to risk our daily well-being as well as that of others. What visual information subserves these acts, particularly for mobile-eyed creatures like ourselves?"

1.2.1 Perception of motion

In further developing the understanding of information that could possibly specify collisions, it was proposed that the specification of detecting a collision could be divided into two categories. First, whether a collision would occur or not, irrespective of temporal components; second, the temporal component of when, such as the time to contact where timing can be specified through the optical expansion of tau, however, there is no specification as to whether a collision will or will not occur [Cutting1995]. An example of the decision process was presented in their 1995 article (Table 1.2.1), considering collision detection with a fixed or mobile obstacle and using the differential parallax of optic flow [Cutting1995]. The displacement of an object can cause a parallax through the change of point of observation (e.g., looking at an object with the right eye closed and then closing the left and opening the right eye). Motion parallax is then the displacement of the body for a different point of observation and a new parallax of the object, note the same effect is caused for a moving object moving. The differential parallax is then the relativity between foreground and background displacement parallaxes that was suggested as a visual cue in the determination of crossing order [Cutting1995]. The decision process (Table 1.2.1) used this understanding to express whether a collision would occur or not for fixed and mobile obstacles; if there was no differential parallax with a fixed obstacle then a collision may occur, alternatively, if there was then a collision was not imminent. If the obstacle was mobile, depending on the flow differences of the parallax between foreground and background signified the risk of collision.

Question	Choice
Step 1	
Is the fixated object rigidly attached to the environment?	*If yes, go to step 2 *If no, go to step 3
Step 2	
Are there any differential parallax displacement around the fixated object?	*If no, a collision may be imminent *If yes, a collision is not generally imminent
Step 3	
	*If the objects or textures in the foreground move faster than those in the background, a collision may be imminent.
What is the nature of the differential parallax displacements around the fixated object?	*If the objects or textures in the background move in a retrograde manner, a collision will not generally occur, one will pass in front of the moving object. *If the objects or textures in the foreground and background move at the same velocity, a collision will not generally occur, one will pass behind the moving obstacle

Table 1.1 - A decision tree for the detection of collisions with stationary and mobile objects when traversing linear paths [Cutting1995].

This conception of the two fundamental issues of collision avoidance was further extended by Anderson *et al.* who studied the detection of collisions through constant velocities and rectilinear paths of multiple obstacles [Andersen1999, Andersen2001]. In their 2001 study, they completed several experiments of collision event detection from multiple moving obstacles, focusing on two sources of information. The one being the rate expansion during approach and the second being the angular position of approach (i.e., tau and bearing angle). More specifically, participants observed several obstacles approaching on a rectilinear path at constant velocity with varying time-to-contact, the only perceivable information was manipulated so that the rate of expansion as the distance between obstacles and observer decreased and the angular position consistency. Participants were instructed to identify possible future collisions through a signal detection paradigm [Andersen2001]. The findings of these studies include the capabilities of collision detection and that both the rate of expansion and angular position are used

for collision detection; however, the rate of expansion may have been a more important source of information. Finally, it was suggested for a continuation of the work with consideration to variable speeds and curvilinear paths [Andersen2001].

Previous studies focused on collision detection through the motion of an observer or an obstacle, whereas few studies considered collision detection and the avoidance behaviour between two walkers [Olivier2012]. Based on the assumption of a reciprocal interaction, Olivier and colleagues [2012] proposed a new metric that coupled both walkers trajectories and expressed the evolution of collision avoidance behaviour between the two walkers. At each instant of the interaction, through linear extrapolation of each participants position with their current respective velocity vectors the authors were able to predict the future distance of closest approach between the two walkers, referring to the Minimal Predicted Distance *MPD* (Figure 1.19):

$$P_{pred,1}(t, u) = P_1(t) + (u - t)V_1(t)$$

Where u is a time parameter, and $P_1(t)$ and $V_1(t)$ are the position and velocity vector at instant (t) of participant #1. Through repetition of this process for participant #2, *MPD* was formulated in the following way:

$$MPD(t) = \frac{argmin}{u} ||P_{pred,2}(t, u) - P_{pred,1}(t, u)||$$

With the equation being solved as the argument of the minimum of a second degree polynomial. Where if the solution is positive ($u > 0$), then trajectories are converging, therefore a negative solution ($u < 0$) would mean that trajectories diverge, and finally, a null solution ($u = 0$) indicated the point of minimal distance:

$$MPD(t_{cross}) = dmin$$

MPD is then the prediction of d_{min} for both walkers at position (t) with velocity (t), assuming a constant heading and constant speed. It specifies the future risk of collision at each time of the interaction. Whenever *MPD* values vary in time, it means that walkers performed adaptations of their trajectories.

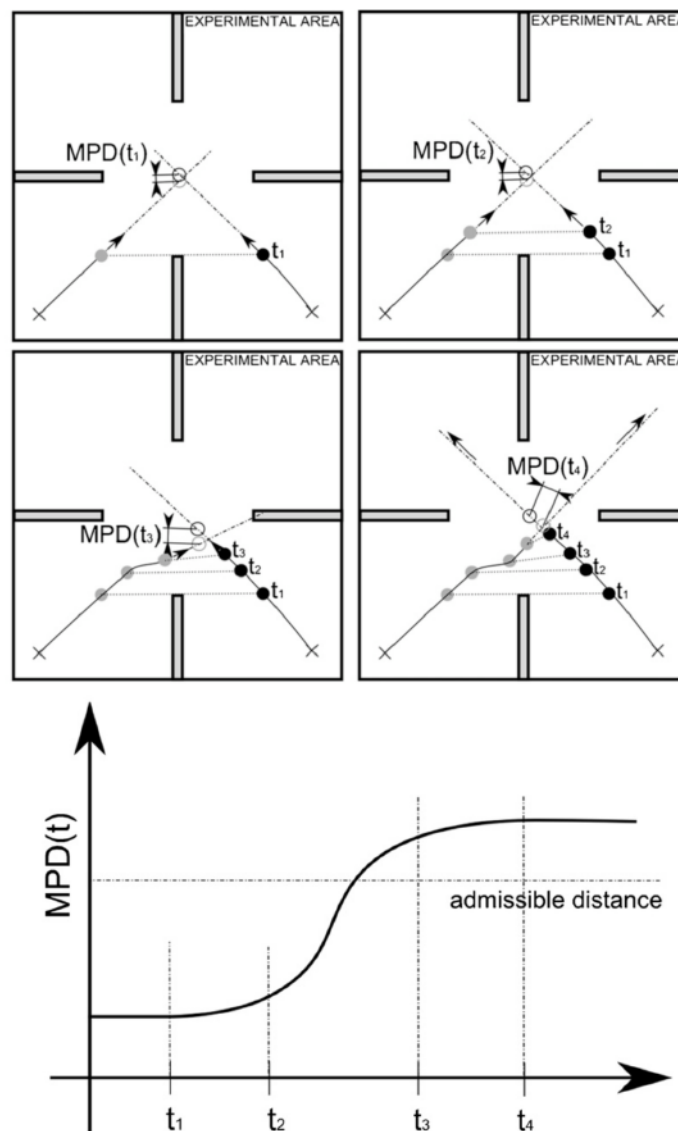


Figure 1.19 - An illustration of *MPD* being calculated at four different times between two walkers on perpendicular paths. Top, a top-down view of two trajectories of two walkers. Each sub box is a captured instant between the two walkers. t_1 is the first time where walkers can see each other due to occluding walls. An adaptation of the walkers' trajectory is illustrated between t_2 and t_3 . Bottom, the evolution of *MPD* over time and the referenced stages of the interaction. From [Olivier2012].

Within their study, the authors set some occluding walls at the start of the walking path so that walkers can reach a steady state before seeing each other. The interaction was then defined between t_{see} , the first instant when both walkers could see each other to t_{cross} the instant when the actual distance between walkers is minimum (i.e., the clearance distance). Results showed that walkers are able to perceive well the future risk of collision because motion adaptation was performed only when necessary, i.e., when $MPD_{t_{see}}$ is below 1m (Figure 1.20). This threshold distance was attributed to the notion and preservation of personal space when avoiding collisions [Gérin-Lajoie2005].

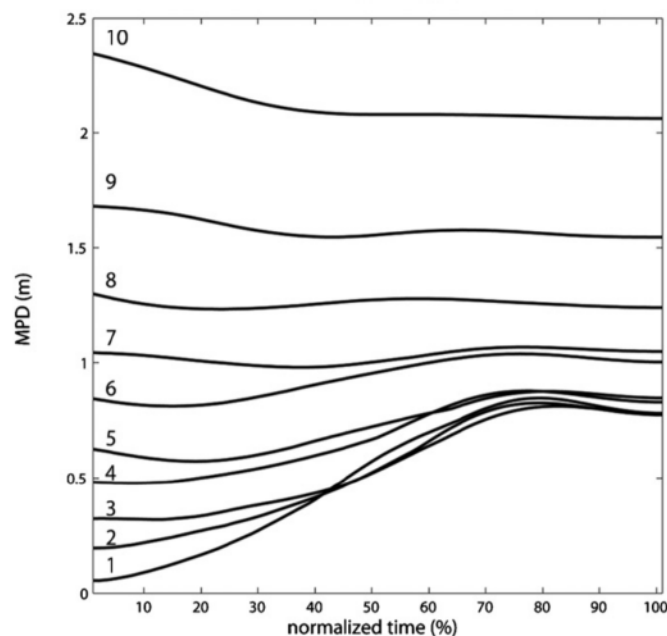


Figure 1.20 - MPD evolution of ten grouped initial MPD conditions over normalised time. 0% normalised time refers to t_1 and 100% of normalised time refers to t_4 . Changes in the MPD are from adaptations made by the interacting walkers. Adaptations are observed for t_1 distances below 1 m. From [Olivier2012].

Further, MPD revealed temporal stages of the interaction, when adaptations are required; three successive phases, from observation to a reaction before final regulation of MPD . From $MPD_{t_{see}}$, the predicted distance of future crossing remained constant. Thereafter, MPD varied as both walkers adapted their trajectories in order to avoid a collision. The final stage is a plateau in MPD as the adaptations of both walkers reduces, and the predicted crossing distance is maintained until actual crossing $MPD_{t_{cross}}$. From

these findings, it was evidenced that distances with a *risk of collision* (distances within the personal space) were predicted by the walkers, further, the task was completed with anticipation as the collision was solved before crossing [Olivier2012].

While, the introduction of *MPD* as a measurable variable is interesting and informative for post-hoc observations of adaptation between two walkers, the nature of the visual information used by the participants in determining the detection of future crossing distances or possible collisions was not explored in this setting. Therefore, we can wonder whether the walkers used a global representation of the other walker or fixated on specific joint articulations or foot placement, or a combination of both, as a local cue of information for effective anticipation of future crossings. Further, the proposed method was based on a linear extrapolation based on a constant trajectory, however, in real-world applications, there are a limited number of cases where a trajectory is exclusively rectilinear and constant [Pierce2013]. We will discuss hereafter the perception of direction, velocity and the consideration of accelerations.

1.2.1.1 Perception of direction

When we move along a rectilinear path, the instantaneous direction of motion coincides with the focus of optical expansion. It has previously been shown that observers can detect the position of the expansion site for the control of locomotion with an accuracy between $1 - 4^\circ$ [Cutting1992, Warren1988b]. However, these judgements appear to not relate directly to the focus of expansion. Rather, information is extracted from the entire field of view and the optic flow surrounding the focus of expansion [Warren1988b]. Further, the detection of direction is rapidly perceived, with reports approximating 400ms [Crowell1990, Hooge1999], evidencing that observers are capable of perceiving the visually specified direction of motion from rectilinear trajectories. Everyday trajectories are not only rectilinear, and in that context, it has been reported that observers are accur-

ate in detecting the direction of curvilinear heading trajectories [Warren1991]. While the detection of one's direction and heading is important, additional information cues for collision avoidance include the detection of an obstacle location, size and heading and its relation to oneself [Rhea2007]. A source of information available for trajectory detection specification could include the change of disparity over time, similar to the differential parallax of optic flow, of an object relative to a fixed background or reference object. An alternative would be the binocular velocity information from an object as it moves in depth, projecting different image velocities to the eyes. Where the visual system would combine the speed and direction of motion by determining the inter-ocular velocity difference changes over time [Harris2008, Pierce2013].

The ability to perceive changes in direction from self-motion or object motion is highly accurate, and this is evidenced from the interception task of rectilinear and curvilinear trajectories of uniform and non-uniform motion [Chapman1968, Bastin2006b, Bosco2012, Delle Monache2015]. However, few studies have previously considered a curvilinear trajectory and collision detection [Berthelon1993], moreover, to our knowledge no studies have considered the perception of curvilinear trajectories between two walkers during a collision avoidance task.

Previous studies have considered the linear extrapolation of current state, and suggested that collision avoidance is completed through anticipation [Olivier2012]. Their study demonstrated that the task is prospectively controlled since *MPD* is linearly extrapolated based on walkers' current state. Further, it is argued, since collision avoidance adaptations are performed before the end of the interaction, the task is anticipated. Additionally, studies have considered curvilinear trajectories during an interception task [Bastin2006b]. Walkers were only able to control their speed to intercept a ball that crossed their trajectory (Figure 1.21). Walkers were instructed to intercept a ball that crossed the path of the walker. The trajectories of the ball were arc lengths from two circles (5 and 10 m radii), and a control rectilinear trajectory. Additionally, the trajectories intercepted the path of the walker at three distances (-1, 0, and +1 m), respectively

requiring the walker to reduce, maintain or increase their velocity to intercept the ball. Finally, the curvilinear trajectories were signed so that the ball followed a final approach in front (positive) or from the side (negative) of the walker. The findings of this study showed that walkers prospectively controlled their behaviour with respect to the visual stimulus for successful interception [Bastin2006b]. To demonstrate this, Bastin *et al.* computed the theoretical time course of bearing angle for each curvature without adaptation and compared these simulated changes with the actual changes performed by walkers. The results showed systematic errors of displacement kinematics, which further supported their hypothesis that walkers use a constant bearing angle strategy to prospectively control interception. A continuation of this work showed that the walkers' velocity was more affected by the curvature of a ball in flight than the manipulation of the rate of expansion [Bastin2008].

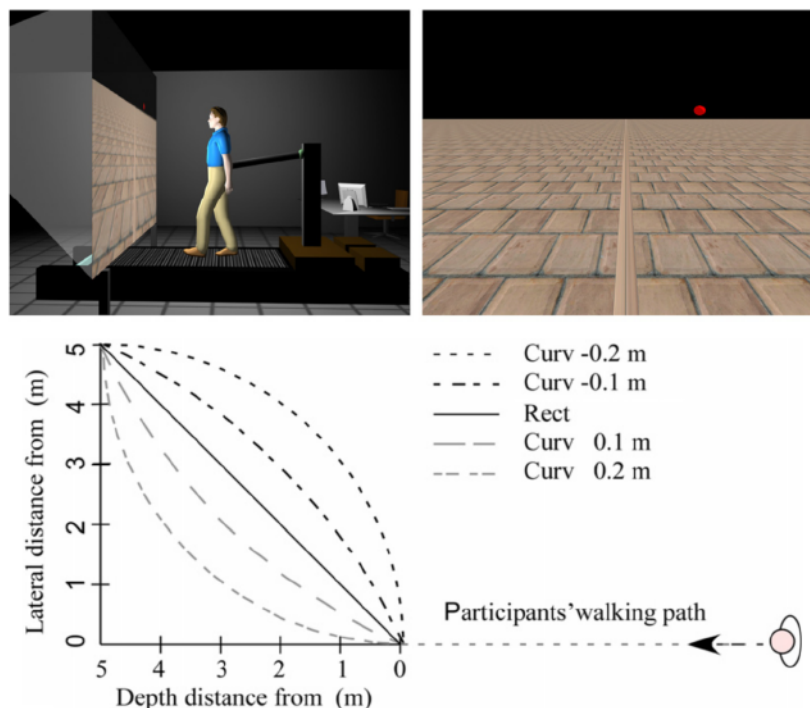


Figure 1.21 - A representation of the experimental setup of Bastin *et al.*, [Bastin2006b]. Top left is a representation of a participant immersed in the virtual experiment while their lateral displacement was fixed by a rod attached to the treadmill. Top right is the first person perspective of the virtual environment. Bottom, is the top-down view of the theoretical environment and the experimental conditions. From [Bastin2006b].

Continuing with the interception task and curved trajectories, more specifically, a goal-keeper intercepting a ball in flight towards a goal. It has been reported that interception of a ball in flight with a spin that causes the ball to follow a curvilinear path as opposed to a rectilinear path causes participants to incorrectly predict the initial path, later prospectively adapting to intercept the ball successfully [Dessing2010, Craig2011, Casanova2015]. Where the influence of the balls spin, trajectory and local cue information was considered in the detection and prediction of future path (Figure 1.22). It was reported that spin direction of a chequered ball pattern was identified at greater distances than plain white balls, and movement initialisation was sooner when intercepting chequered balls. Finally, it was reported that the detection of direction was easier for changes in outward curving balls than inward, this may be associated with the lack of initial heading information that can be perceived during the outward curving trajectories [Casanova2015].

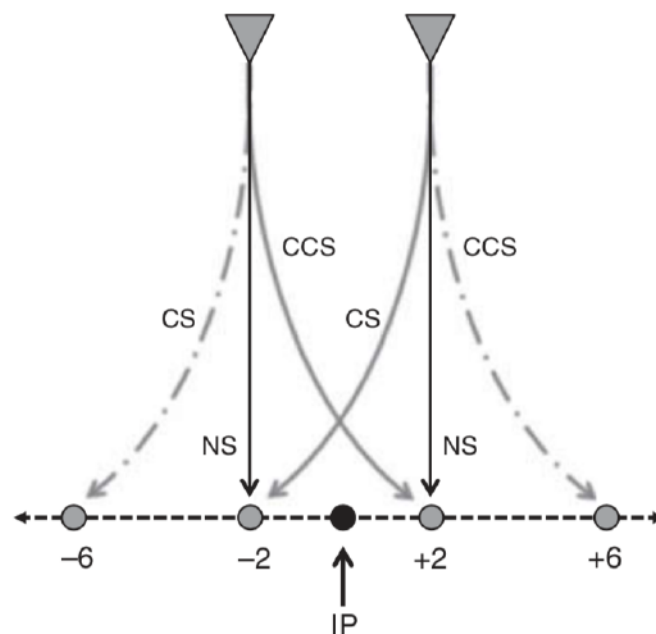


Figure 1.22 - The experimental setup of Casanova *et al.*, [Casanova2015]. chequered and plain balls were fired from the grey triangles and depending on condition, the ball would be without any spin (black lines) or curve towards (solid grey line) or away (dashed grey line) from the participants initial position (IP). From [Casanova2015].

1.2.1.2 Perception of speed

Movement is the change of position over time, where the notation of a position at a given instant that has previously been identified at another position gives the velocity of the movement. Given this, speed and direction information are coupled and cannot be processed independently. Nevertheless, the ability to perceive speed is fundamental in the processing of visual motion and the detection of future collisions. The visual system is sensitive to the perception of speed but rather insensitive to acceleration [Brouwer2002, Watamaniuk2003, Zaal2012]. However, it has been reported that speed judgements can depend on the shape and direction of motion [Manning2018]. Moreover, the detection of acceleration indeed requires an instantaneous change of speed with an approximate difference of 30% [Gottsdanker1956], speed changes lower than this or with gradual increments are poorly detected [Werkhoven1992, Watamaniuk2003].

Previous findings have reported poorer time-to-contact judgements during non-constant velocity (i.e., constantly accelerating) than when compared with constant velocity [Benguigui2003, Tharanathan2006, Tharanathan2009]. Nevertheless, when considering a natural environment without experimental restrictions, stimuli of moving obstacles are rarely constant, and humans are capable to adapt their behaviours to accelerating obstacles. This has lead to several studies identifying and attempting to identify how humans perceive acceleration to adapt their behaviour [Tresilian1999a, Dubrowski2002, Benguigui2003, Bennett2013, Bennett2016]. Where it has been reported that spatial estimation from occluded lateral motion of objects under constant acceleration was consistent with the use of first-order information, further, there was a tendency for underestimation of future position [Montagne2000, Benguigui2003, Bennett2013, Bennett2016].

Constraints associated with judgements of time to contact, temporal, and spatial accuracy included the motor capabilities of the observer and the implied dynamics [Bastin2006a, La Scaleia2014, Stapel2016, Vagnoni2017]. This can be seen through age-related differences, where it has previously been observed that adults are better attuned to temporal information than spatial information [Siegler2013]. Whereas children are more attuned to spatial information and progressively attune to temporal information with ageing [Benguigui2008, Bazile2016].

1.2.1.3 Motion cues

After consideration of the capabilities and limitations of the visual system in the visual perception of direction and speed, the third source of information is the motion cues in which perception is based. Global and local information are often referred to in psychology and the visual control of locomotion, and these definitions occasionally define differences within the optic flow, general layout of an environment or the nature of visual information from an object [Gibson1979, Warren1990, Huys2009, Fajen2003]. However, for clarity, the definition of global and local motion cues here will refer to the nature of information from an obstacle (Figure 1.23).

Global motion cues refer to the object's body as a whole, information that has been interacted upon based on the optical invariants such as bearing angle and rate of expansion [Regan2000, Huys2009, Cañal-Bruland2011, Rio2014]. Local motion cues are then the perception of individual points, joints or pairs that form limbs and provide information such as stepping rate or orientation; cues that distinguish biological motion [Thornton1998, Diaz2012, Masselink2015]. To further elucidate, the application of point light displays allowed for information to be picked up predominantly from biological motion (i.e., local motion cues of joint articulations) with a limited presence of global cues [Johansson1973].

Two exemplary publications evidencing the ability to detect biological motion through point light displays are the works of Cutting and Kozlowski [Cutting1977, Kozlowski1977]. Where they evidenced the ability to identify male gait from female gait, further, while attempting to identify a friend's gait, it became evident that individual gait patterns are detectable but not necessarily the ability to detect their friend. Therefore, this section will focus on the literature that has considered interactions either solely with global motion cues, or the effects of additional local motion cues in the presence of global motion.

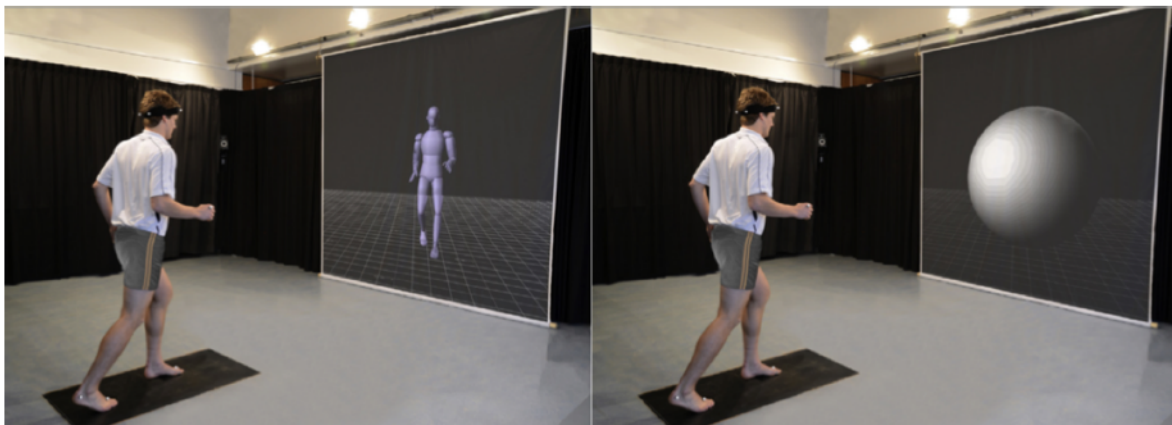


Figure 1.23 - Example representations of motion cues: local motion cues with presence of global shape and form of the biological body (left), global motion cues only in the form of a large sphere (right). From [Meerhoff2014]

Here we will discuss a study about hand aperture regulation with only global motion cues available, thereafter, the introduction of local motion cues are discussed that is applied to a locomotor interception task. Finally, we will discuss a previous study that has considered the temporal advantage of local motion cues from global motion cues during a distance regulation tasks.

Savelsbergh *et al.*, [Savelsbergh1991] showed how hand aperture could be regulated by merely attuning to the global cue of optical size changes. In their study, participants were asked to catch an illuminated ball in a dark room, eliminating ambient contextual information. Nevertheless, participants could directly regulate their hand aperture to successfully catch the ball.

In a competitive setting, Brault and colleagues [Brault2012] used virtual reality to study the salience of local and global motion information and the ability to judge movement direction. Authors showed that the performance of experts was more related to the evolution of honest signals than deceptive ones and more particularly to the global parameter centre of gravity than of local ones. This does not mean that local information is not informative, but it can be more sensitive to deception.

Meerhoff *et al.*, [Meerhoff2014] studied the role of global and local motion information in a non-competitive locomotor setting. Their results suggested that indeed the ability to regulate distance is not perturbed when only global motion was available, but participants provided earlier responses when both local and global motion were available.



While we have detailed here the information that can be used to interact with the environment, there remain several questions unanswered with consideration to the collision avoidance task. Previously, in section 1.2.1 it was evidenced that adaptations between walkers are performed below a threshold and that this threshold can be attributed to the preservation of personal space. Suggesting that collision avoidance behaviour between walkers is not defined by a strict contact between two walkers, instead, the distance of regulation involves a notion of personal space.

1.2.2 Personal space



Figure 1.24 - Three example images of differences in personal space: A), close proximity and within personal space as a coach instructs a player. B), peripersonal space that allows communication and physical interaction between individuals. C), extrapersonal space, no communication or interactions are formed as people keep their distance while waiting a bus. From [Hall1966]

In general, personal space is considered as an area around the body that individuals maintain to interact with others at a comfortable distance during social interaction [Hall1966]. Figure 1.24 depicts examples of personal space variances in daily living. Therefore the notion of personal space preservation during collision avoidance tasks should be considered. The notion of an emotional response to the invasion of personal space has previously been elicited. For example, in a passenger train experiment, it was reported that the density ratio of carriage size and the number of passengers elicited no correlation to stress responses, however, seat density and the number of passengers was highly correlated with stress indices. It was noted that passengers prefer to stand alone than to sit next to a stranger [Evans2007]; a familiar sensation in which we all share is to find an open seat first or the one empty seat barrier between oneself and a stranger. Therefore, it is not without reason to claim that personal space is a protective bubble, which we strive to maintain. This space has been presented as the space of safe passage when presented with an obstacle [Woods2003], where the maintenance of this space during locomotor collision avoidance would suggest temporal and spatial components for future planning and anticipation of navigation for correct locomotor adaptations [Templer1995].

In the previous section it was mentioned that during a collision avoidance task, between two unconstrained walkers, the two walkers would adapt when a predicted crossing distance was less than 1m that coincided with the preservation of personal space. The space around the body is of fundamental importance for the safe navigation and interaction with the environment. Therefore it is necessary to elicit the different zones that surround the body and to understand the role of personal space during collision avoidance. The space around the body has been categorised into three zones [Iachini2014, Iachini2015, di Pellegrino2015]: extrapersonal space refers to the area outside of the current reachable area, exploratory eye movements generally occur in this space. Moving closer to the body, the peripersonal (interpersonal) space is the area in which the agent can directly interact through the grasping of objects. Finally, from the social psychology perspective, a third and smaller space can be found in which an emotional response is reported and often referred as the personal space, the private space that causes discomfort on intrusion [Iachini2014, Iachini2015, di Pellegrino2015]. The notion of two representational differences between grasping and walking distance was initially suggested by Brain *et al.*, [Brain1941], the first expression of personal space as a safety margin was later described in animals; if a predator entered this space, the prey would attempt to flee [Hediger1955].

The work conducted by Gérin-Lajoie and colleagues has been influential in the understanding of personal space and collision avoidance navigation [Gérin-Lajoie2005, Gérin-Lajoie2006, Gérin-Lajoie2008]. Gérin-Lajoie *et al.*, [2005] studied the preservation of personal space during a collision avoidance task with both a static and moving mannequin, and this study was the first to directly quantify personal space during locomotion [Gérin-Lajoie2005]. They quantified personal space during locomotion by defining in the transverse plane in front of the participant a scanning window; a quarter circle composed of 90 vectors in the upper left quadrant of the circle that was centred at the centre of mass of the participant. The vectors were polar coordinates for each Cartesian degree of the circle's quadrant, which were also equal three times the average

step length of each participant. Using this scanning window, that was much larger than the actual personal space, permitted the authors to capture and calculate the clearance distance and its shape. Then, the personal space from the clearance behaviour was recorded as the distance in the transverse plane between the participant's centre of mass and the elbow of the mannequin, taking the shortest distance from each vector of the Cartesian quadrant to contour the personal space. From their findings, the personal space corresponded to an elliptical shape with a longitudinal length of 2.11m and a lateral width of 0.48m (Figure 1.25).

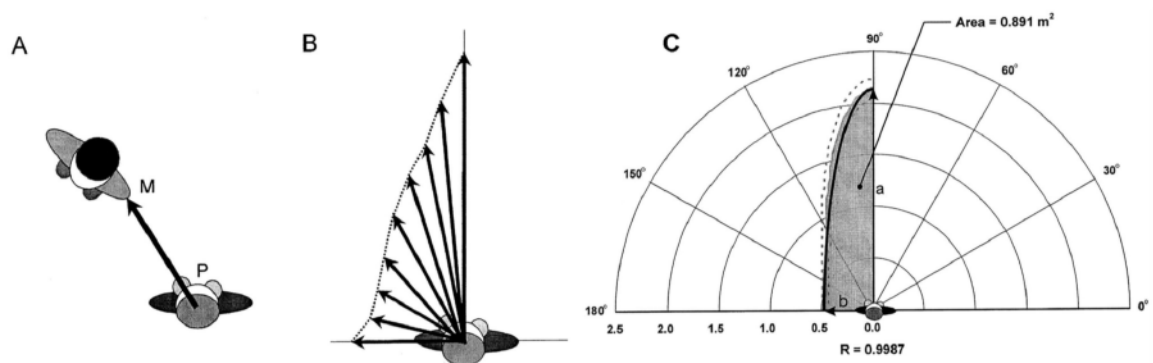


Figure 1.25 - Personal space of the transverse plane between the centre of mass of a participant and the left elbow of a mannequin (P - M). A), expresses the definition of P-M. B), Represents each shortest polar vector of clearance during the avoidance behaviour within the Northwest quadrant of a circle. C), The average personal space calculated and represented as a shaded elliptical shape. From [Gérin-Lajoie2005]

The findings of personal space were congruent with previous estimations, albeit slightly larger [Templer1995]. The differences in size were attributed to variances in walking speed [Gérin-Lajoie2005]. The participants thus systematically preserve an elliptically shaped personal space that varies according to the demand for information processing required by the congested environment. For example, if an auditory message distracts their attention, the personal space expands as the demand for attention increases, where an increase of personal space suggests a more conservative strategy. Also, when the movement of the mannequin is known in advance, subjects have time to plan a fairly large personal space that allows less attention to be given to the mannequin.

Additionally, an influence of age on the personal space, which is normalised to step length, has been reported. Elderly individuals preserved a personal space similar to that of younger people unless distracting phenomena during locomotion are applied, to which the elderly group had a larger personal space than their younger counterparts [Gérin-Lajoie2006]. From these findings, personal space functions as a control criterion of the locomotor system, coupled with between the agent and the environment and used to plan future adaptations. A further understanding was ensued by questioning the influence of walking speed, passage side and the influence of virtual reality [Gérin-Lajoie2008]. For this study, participants passed either right or left of the obstacle, and personal space was recorded for both sides. Further, they were instructed to complete the task with a natural, slow or fast self-selected walking pace. A second experiment was conducted as part of this work, using the same design as the first within virtual reality. It was observed that personal space was larger on non-dominant sides during passage. However, there was no influence of self-selected walking speed.

Virtual reality, as detailed in section 1.1.5.3, has proven a powerful tool for ecological perception and action research [Loomis1999, Tarr2002]. The presence of personal space within virtual reality has previously been validated [Gérin-Lajoie2008], and for social interactions with virtual animations (i.e., objects, robots and humans) and for interactions between walkers [Iachini2014, Argelaguet-Sanz2015, Jung2016, Olivier2017]; personal space was systematically preserved whilst immersed. However, personal space within virtual reality has been reported to be larger than that in reality, although, this could be attributed to the restricted field of view and depth perception [Loomis2003].

Iachini *et al.*, [2014] completed work in virtual reality to study the influence of emotional response for peripersonal and personal space of approaching virtual characters. Within this study male and female avatars were used, and additionally, a global representation of the avatar in the form of a cylinder or a robot was used to remove social biases. The task of the study was to stop either themselves or the character once they were perceived to be at arms reach or at the limit of the comfort zone (i.e., per-

sonal space). The findings of this study highlighted the close relationship between basic visuomotor-spatial processing and complex social processing. Furthermore, variances in the personal and peripersonal space were reported depending on the virtual objects appearance [Iachini2014].

The variance of personal space with obstacle appearance was further verified both within virtual reality and reality [Hackney2015b, Argelaguet-Sanz2015]. Where Argelaguet-Sanz and colleagues [Argelaguet-Sanz2015] reported differences in the clearance distance when passing a human or a box, and this difference was further observed in both reality and virtual reality environments. Moreover, from their results, they observed an effect of obstacle orientation in both reality and virtual reality. They reported larger clearance distances for humans standing perpendicular to the participant's path, however when the human was facing towards or away in parallel to the participant's path the clearance distance was less. The authors attributed the notion of orientation effect to the participant's additional consideration for human obstacle's personal space in the collision avoidance task [Argelaguet-Sanz2015]. The notion of orientation and the perceived distance has also been reported to be larger when a virtual character is facing away and close when facing towards participants [Jung2016].



Figure 1.26 - Personal space variances from the clearance of anthropomorphic and inanimated obstacles in both reality and virtual reality. From [Argelaguet-Sanz2015]

Similarly, Hackney and colleagues [Hackney2015b] observed behavioural differences in aperture crossing, when an aperture is formed of two human poles rather than two cylindrical poles in reality, where the critical point of shoulder rotation is smaller for two human poles. Overall, these studies have evidence that personal space is systematically present and preserved in both reality and virtual reality. However, the physical appearance of an obstacle influences the behaviour of avoidance, which is consistently observed in reality and virtual reality.

1.2.3 Collision Avoidance

A cluttered environment affords many possibilities for action, where some obstacles will be stationary, and some obstacles will move; independent of the obstacle's state, a safe navigation task requires that these obstacles should be avoided [Cutting1995]. For a fixed obstacle, it is clear that the walker must adapt their trajectory to avoid a collision. Therefore, a lot of studies have focused on the understanding of motor control regulation in stepping over an obstacle; for example, analysing lower limb regulation and foot placement [Patla1991], the effect of the properties of the obstacle [Spaulding1991], gaze behaviour [Patla1996] or the effect of ageing [McFadyen2001]. An alternative paradigm of fixed obstacle collision avoidance includes the navigation and circumvention of obstacles; further analysing avoidance behaviours [Gérin-Lajoie2005], effects of age [Gérin-Lajoie2006], or comparing the avoidance behaviour between real and virtual environments [Gérin-Lajoie2008]. A final example of fixed obstacle collision avoidance is the aperture crossing paradigm [Warren1987]; the analysis of body and limb regulation [Wilmot2010], considering the effect of ageing [Hackney2011, Hackney2013, Hackney2014b], analysing agent specific affordances [Hackney2014a] and environment specific affordances [Hackney2015a, Baker2017, Hackney2018]. In accordance with the framework of this thesis, the following section will focus mainly on collision avoidance with moving obstacles and the kinematics of the avoidance behaviours.

1.2.3.1 Collision avoidance characteristics

We can distinguish several aspects from the literature of collision avoidance with moving obstacles: first, we can identify the behaviour of the obstacle being avoided. Second, we can identify three types of collision between two walkers (Figure 1.27), towards, away and glancing [Rymill2005]. Finally, we can also identify different kinds of avoidance behaviour (Figure 1.28), circumvention of a fixed obstacle, path adaptations by both walkers, speed changes by both walkers, and a combination of path and speed changes by one walker [Lettich2016]¹.

1. Mobile obstacle behaviour

- ▶ **Passive.** A mobile obstacle can be passive (e.g., a confederate) where the obstacle will follow a predefined trajectory and not deviate its course with regard to any other participants of the task [Gérin-Lajoie2005, Cinelli2007, Cinelli2008a, Vassallo2017].
- ▶ **Reactive.** A mobile obstacle can be reactive, for example, two unconstrained walkers where both are allowed to interact and adapt to the situational demands [Olivier2012, Olivier2013]. Another example would include an environmentally aware robot that reacts according to another walkers trajectory [Vassallo2018]

2. Types of collision

- ▶ **Towards** (Figure 1.27A). When two walkers are walking towards each other on the same path (e.g., a narrow corridor), both are on a head-on collision course. Without adaptation walkers will walk straight into each other or have an overlap of the bodies [Honma2015]
- ▶ **Away** (Figure 1.27B). This situation involves one walker behind another, where the trailing walker is gaining on the first. Without adaptation from

¹Note that these distinctions have been categorised for collision avoidance with large obstacles that cannot be stepped over or passed through, that is these obstacles and collision avoidance categories are for obstacles resembling the dimensions approximate of the human body.

either the trailing walker will collide with the leading walker. Such examples of this type of collision include automotive driving, a focus of the early work by Lee [Lee1976, Lee2011], where drivers are required to regulate their distance. Additionally this has been investigated for perceptual tasks and following the leader tasks [Rio2014, Meerhoff2014].

- **Glancing** (Figure 1.27C). When two walkers have intersecting paths and the two walkers are likely to meet at the point of intersection at the same instant, there will be a collision [Olivier2012, Olivier2013].

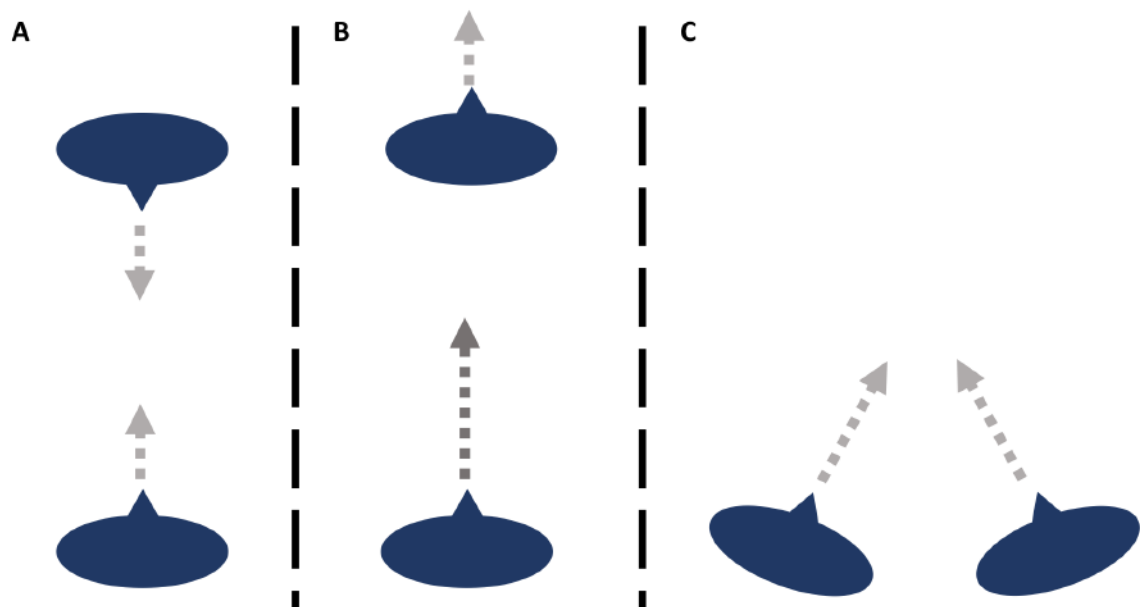


Figure 1.27 - Three types of collision can be identified: A), A head-on collision from two walkers follow paths towards each other. B), A trailing walker is faster than the leading walker (size of arrow represents velocity vector), catching up with the leader and will collide without adaptation. C), Two walkers on intersecting paths may arrive at a point of intersection at the same instant and thus collide. Adapted from [Rymill2005]

3. Types of collision avoidance

- **Circumvention** (Figure 1.28A). A typical paradigm of circumvention includes a walker on one side of an obstacle and a goal for them to walk towards on the opposite. The obstacle acts as a repeller to the trajectory the walkers takes, and the goal acts as the attractor [Fajen2003, G  rin-Lajoie2005, Fink2007].
- **Adaptation of a single walker** (Figure 1.28B). In the situation of passive confederates, all adaptations of collision avoidance are based on those of the participant [Basili2013, Huber2014, Vassallo2017]. In the scenario depicted in figure 1.28B, the task of the walker would be to join the general heading of the confederate.
- **Path adaptation of both walkers** (Figure 1.28C). For interactions between two mobile and reactive obstacles or walkers, each can adapt their path to ensure a mutual completion of collision avoidance [Olivier2013]
- **Speed adaptation of both walkers** (Figure 1.28D). Alternatively, or in combination with adaptations of path, two walkers can adapt their speed, decelerating or accelerating.

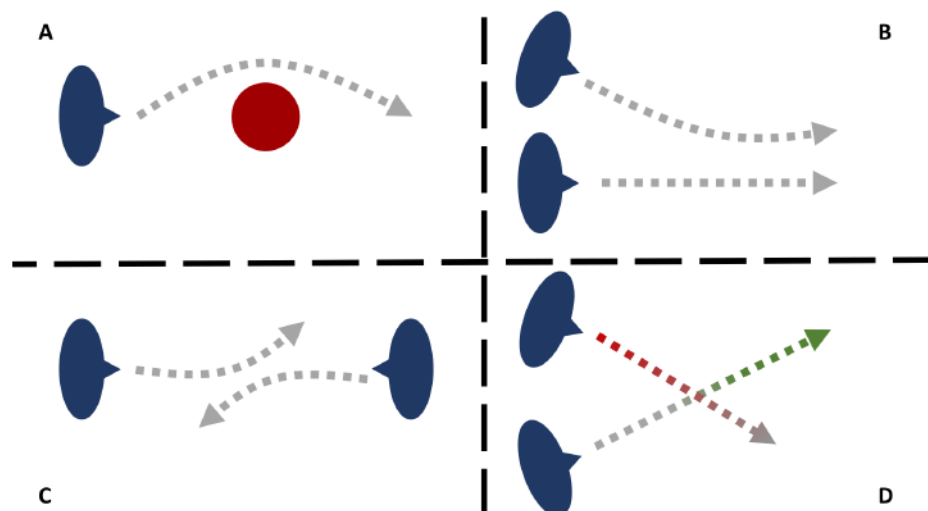


Figure 1.28 - Collision avoidance behaviour can be identified in four categories: A), circumvention of a fixed obstacle. B), adaptation of a single walker. C), both walkers adapt their path. D), both walkers adapt their speed. Adapted from [Lettich2016]



With a clear definition of the factors of collision avoidance with moving obstacles, we can begin to discuss the current observations from the literature. The following two sections are titled by the behaviour of the mobile obstacle: section 1.2.3.2 will focus on the works of [Gérin-Lajoie2005, Cinelli2007, Cinelli2008a] and collision avoidance with passive obstacles, and section 1.2.3.3 will focus on the works of [Olivier2012, Olivier2013, Basili2013, Huber2014, Knorr2016, Vassallo2017, Croft2017]. Indeed, by definition, the work of Basili *et al.*, Huber *et al.*, Vassallo *et al.*, and Croft *et al.* have passive obstacles. However, for a better understanding of a glancing collision avoidance task, these works share the same orthogonal paradigm within their experimental setup; therefore these studies will be discussed collectively in section 1.2.3.3. Whereas the works of Gérin-Lajoie *et al.* and Cinelli *et al.* share similar experimental designs of collision avoidance while interacting with a passive mannequin on a fixed rail.

1.2.3.2 Passive obstacle

Gérin-Lajoie *et al.* conducted a study with which a mannequin was attached to a rail [Gérin-Lajoie2005]. The behaviour of the mannequin varied from being fixed in a position on the path of the participant, or moved along the rail and intersected the path of the rail, and several *catch* trials where the mannequin started and stopped at predefined positions (Figure 1.29). The rail in which the mannequin was mounted intersected the path of the participant at a 45° angle. The results of this study showed that collision avoidance is anticipated differently according to the dynamics of the obstacles, whether the obstacle is fixed, mobile or not present. Adaptations were reported in the anterior-posterior control of movement, which was attributed to the control of timing, specifically gaining time for avoidance behaviour. Of the three experimental conditions, the gait speed decreased with the presence of the mannequin and further decreased with

the motion of the mannequin, this could be attributed to the increased visual processing demands required for the successful completion of the task. Furthermore, this study presented different anticipation behavioural responses depending on the experimental condition. The trajectory from the centre of mass revealed that participants drifted laterally for the conditions when the mannequin was going to obstruct the path of the participant and its final position was known in advance. Whereas, no mediolateral drift was observed when the mannequin was not present. Moreover, the observed anticipation behaviour was facilitated for the most natural avoidance behaviour, which was to pass behind the mannequin [Gérin-Lajoie2005]. In contrast, when the final position of the mannequin was unknown, the anticipatory behaviour observed was that participants delayed their mediolateral displacement. The delayed onset of mediolateral displacement could be associated with increased demand for online visual feedback to assess the evolution of the task. Finally, independent of anticipatory behaviour and gait speed of approach by the participants, the final clearance distance as the participant passed the mannequin did not show any significant differences irrespective of known and unknown final positions and whether the mannequin was stationary or moving. These results are interesting since participants adapted their anticipatory behaviour and their gait speed to interact with the mannequin and ensure a collision-free passage, however, these adaptations resulted in a standard safety margin when avoiding a mannequin.

Similarly, Cinelli and Patla also used a paradigm of a mannequin attached to a rail (Figure 1.30), looking at the avoidance of a mobile obstacle arriving towards the walking subject at different speeds [Cinelli2007, Cinelli2008a]. In both studies, participants were instructed to walk along a rectilinear path where a mannequin rested 12m from the participant's starting position, during the advancement of the participant an optical switch was used to trigger movement of the mannequin after an initial displacement of 2.5m by the participant. In the first study, they were interested in how a participant would avoid a head-on collision based on the two fundamental questions of where and when will a collision occur. Further, they questioned whether constraints in the travel

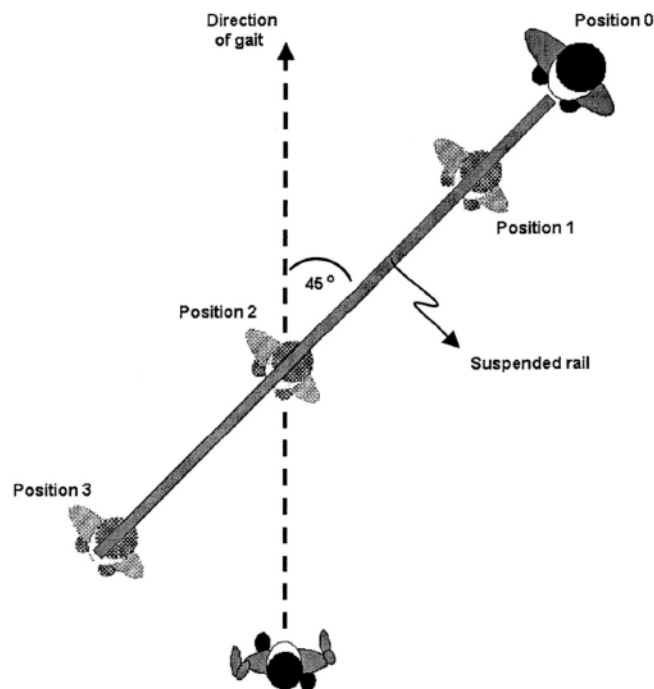


Figure 1.29 - Experimental setup of a mannequin attached to a rail that intersected the path of participants and 45°, several start and stop positions were used to cause uncertainty of behaviour. From [Gérin-Lajoie2005]

path would influence avoidance behaviour. Considering the restrictions of a mannequin being fixed on a rail, their study manipulated the time-to-contact through a range from $0.8\text{m}\cdot\text{s}^{-1}$ to $2.2\text{m}\cdot\text{s}^{-1}$ mannequin velocities in increments of $0.2\text{m}\cdot\text{s}^{-1}$. To further study the effects of spatial constraints on avoidance behaviour, the second part of their first study introduced a door frame with a 90cm aperture 3.5m from the optical switch. The introduction of the door frame was for the decision processing of participants; deciding to pass through or give way to the mannequin based on time-to-contact information. The authors showed that trajectory adaptations without the spatial constraints of a door frame were initiated at similar times independent of mannequin velocity, however, the speed of lateral displacement correlated with the approaching velocity. With the use of a spatial constraint, the results showed that participants initiated a lateral change prior or at the door frame, with a significant difference of initiation in the travel path between the two fastest and the slowest condition [Cinelli2007].

The second study was then furthering their initial findings; using the same experimental set up as in their first study, the mannequin had three possible velocities ($0.8\text{m}\cdot\text{s}^{-1}$, $1.4\text{m}\cdot\text{s}^{-1}$, and $2\text{m}\cdot\text{s}^{-1}$), and the door frame was placed in one of nine positions that coincided with a time-to-contact position either before, at or after the door frame for each velocity. As per their first study, approach velocity did not affect avoidance behaviour timing, and spatial constraints did. Where a change in heading occurred prior to passing through the door frame, even if they could pass safely through and change heading after passage. The authors attributed this response to the existence of a safety zone, although spatial references may improve relative velocity judgements [Cinelli2008a].

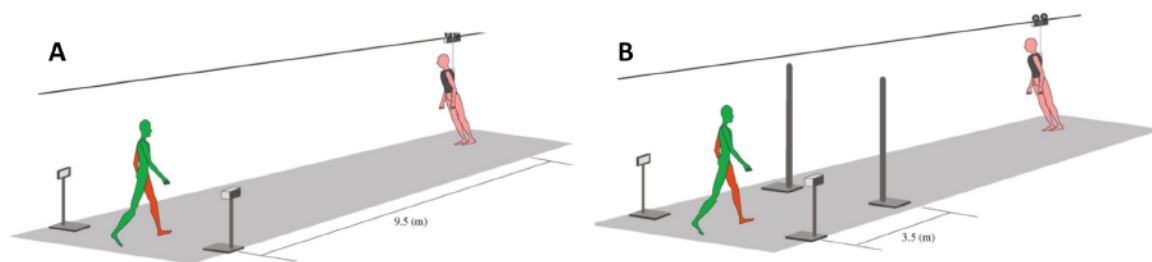


Figure 1.30 - Experimental setup of a mannequin attached to a rail approaching a participant. A), a goal directed task of head-on collision avoidance without spatial constraints. B), spatial restriction in the form of a door frame present. From [Cinelli2007]



These studies have developed and presented an understanding of anticipation and avoidance behaviour while avoiding a mannequin that approached towards participants. However, while these studies have been insightful and their experimental setup allows for reproducibility between trials. The presence of the rail, with which the mannequin was attached, provided visual information of the mannequins restricted path and thus future position could be predicted. Hence, the following section will focus on the collision avoidance behaviour between walkers where the predictability of future position can be reduced.

1.2.3.3 Reactive obstacle

Previous studies have focused on locomotion trajectories and adaptations while interacting with passive or fixed obstacles, whereas Olivier and colleagues [Olivier2012] considered two walkers that could adapt their behaviour without limitation; walkers were instructed to reach a goal and avoid collisions. They proposed a new metric to express the evolution of the collision avoidance behaviour between two walkers, coupling the avoidance behaviour between both walkers under the assumption that the task is completed under the reciprocal interaction of both walkers. In their experimental setup, participants shared a surface area of 15m² and were positioned in adjacent corners; when instructed to walk to their opposite corner they would complete a glancing type collision task as their orthogonal paths would intersect. In order to control the respective position of each walker at the instant of intersection, starting signals were displayed in each of the four corners of the area. Participants were initially occluded from perceiving each other, allowing a steady state walking speed to be obtained. Moreover, there were six participants per experimental session, reducing the predictability of who the walker will interact with and from which direction they will arrive (Figure 1.31).

Based on the evolution of the coupled metric of collisions avoidance (MPD), detailed in section 1.2.1, the authors described three stages in the interaction (Figure 1.32): observation, reaction, and regulation. Each stage was computed from the time derivative of MPD , and the authors compared the MPD between each instance of evolution when the sign of the MPD derivative changed. The observation stage is then considered when MPD is constant from $MPD_{t_{see}}$, a significant difference of MPD from $MPD_{t_{see}}$ was then considered the reaction stage, and finally, a plateau or slight decrease of MPD from $MPD_{t_{cross}}$ was considered as the regulation stage. The regulation before crossing was suggested as an anticipation of the task as the slight decrease in MPD demonstrated that the task had been solved prior to crossing [Olivier2012].



Figure 1.31 - A picture of the experimental setup of two unconstrained walkers avoiding a glancing collision. From [Olivier2012]

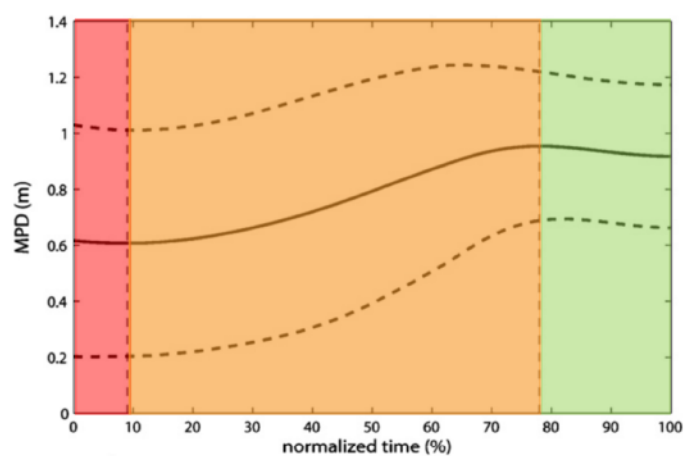


Figure 1.32 - The mean evolution of MPD when predicted crossing distance at $MPD_{t_{see}}$ was below 1m. Three successive stages can be observed during the interaction: observation (red), reaction (orange), and regulation (red). Adapted from [Olivier2012]

The interaction with fixed obstacles towards a goal (i.e., circumvention avoidance behaviour), has shown how walking trajectories are stereotypical and repeatable, and thus predictable [Fajen2003, Gérin-Lajoie2005, Fink2007]. Olivier and colleagues began to consider the avoidance strategies used, where they only considered the adaptations of speed, path, or a combination of the two to express the effect on the overall task and to weigh the walker contributions [Olivier2013]. Since, several studies have considered the role of crossing order, the influence of avoidance behaviours in terms of speed and path, or the combination of both [Basili2013, Huber2014, Knorr2016]. In order to quantify the deviation selected studies have focused on the progression of the environment, a participant completes a goal-orientated task without any interferer in the path, augmenting this, participants are required to complete a circumvention task where the interferer acts as a static obstacle. Finally, a glancing collision avoidance task is completed with the interferer passively interacts with the environment and the participant [Basili2013, Huber2014]. Huber *et al.*, [Huber2014] extensively considered different types of collision and the associated avoidance behaviours. Their experimental set up considered six scenarios, two fixed environment conditions and four conditions of an interferer intersecting at various angles (Figure 1.33). In addition, participants were requested to complete the task under three different self-selected speeds (slow, steady state, fast):

- ▶ **No interferer.** A baseline condition where participants walked towards a goal in an environment free from interference.
- ▶ **Static interferer.** The interferer remained static in the middle of the participant's rectilinear path, acting as an obstacle that requires circumvention. In this situation, the interferer was directed at the starting position of the participant.
- ▶ **45° interferer.** Both the participant and interferer walked rectilinear paths. In this scenario, the initial starting position of the interferer was at a 45° angle from the left of the participant. Note that from this angle of approach the interferer would walk in the same direction as the participant.

- **90° interferer.** The same orthogonal setting as [Olivier2012, Olivier2013], which more closely resembled [Vassallo2017] as the interferer was passive during the interaction.
- **135° interferer.** Similar to the 45° scenario, the interferer was positioned 135° from the participant's left, placing the interferer in front of the participant.
- **180° interferer.** The interferer started at the goal position directly in front of the participant and was directed to the starting position of the participant as their goal. This scenario resembles a head-on (i.e., towards) collision type task.

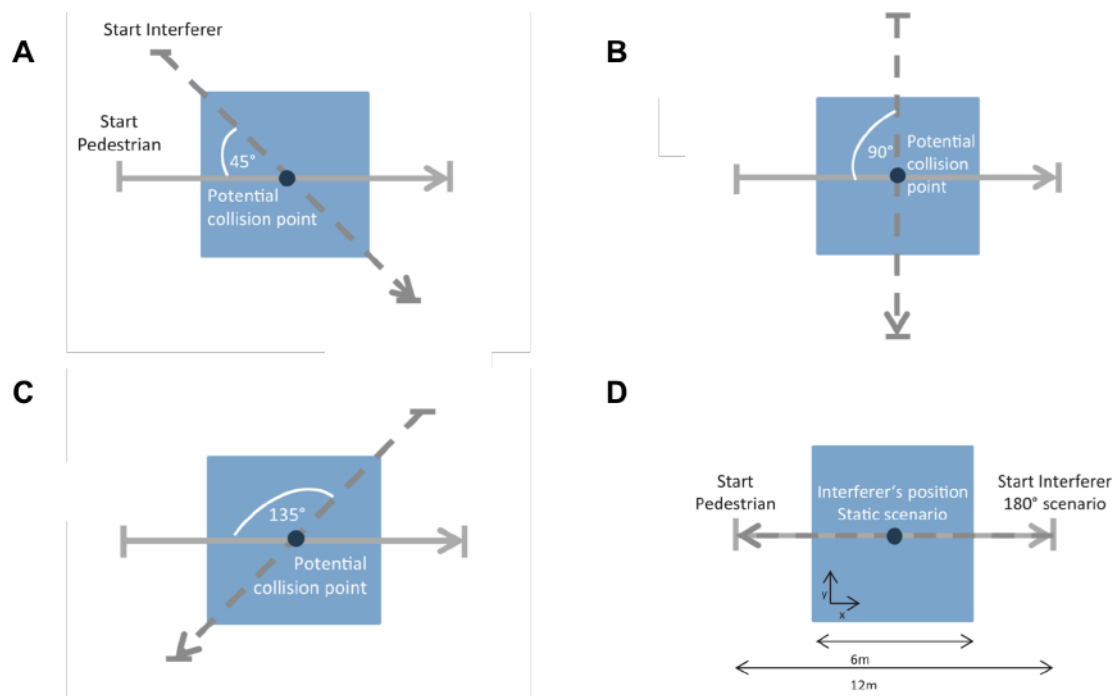


Figure 1.33 - The experimental setup of the different scenarios from [Huber2014]. In each sub-figure the arrows represent the walked distance, the blue boxes are the motion captured zone, and the centred dots are the points of intersection and the position of the interferer during the fixed scenario. A), 45° angle of approach scenario, B), 90° angle of approach scenario, C), 135° angle of approach scenario, D), 180° angle of approach scenario.

The goal of their study was to determine whether and how walkers adapt their path and speed while interacting with an interferer from different angles of approach at three different self-selected speeds. The results showed that the avoidance behaviour was dependent on the participant's walking speed and the angle of approach by the interferer. Generally, it was observed that participants performed adaptations to their path for all conditions where the interferer was present. However, only in the conditions where the path of the interferer was 45° or 135° were adaptations of speed and path observed during the avoidance behaviour. Additionally, the adaptations observed during the acute angles of interaction were initiated with the same time-to-contact. It was hypothesised that considering the interferer was instructed to generate a future predicted collision event at the same location for each trial, and participants could plan their trajectories for more optimal avoidance behaviours. However, the recorded variability between conditions suggested that the interaction is an on-line based feedback process of local planning². Such behaviour had previously been reported, determining that locally planned trajectories are not optimal as a lower cost efficient trajectory was available [Basili2013].

Developing from their first study, Olivier and colleagues [Olivier2013] continued exploring the interaction between two unconstrained walkers; investigating the effect of crossing order, and exploring the avoidance strategies (i.e., adaptations in path, speed, or both), however in this study the authors were interested in the effect of the adaptations on the task rather than the adaptations themselves. Here the authors evidenced the reciprocity of collision avoidance, and the task was solved collaboratively. Further, they suggested the roles in which each walker was predicted to intersect the path first or second, impacted the contribution made and the avoidance strategy used. Walkers that were predicted to cross second were reported to have contributed more to the avoidance behaviour than the walker predicted to cross first. Furthermore, the roles assigned at $MPD_{t_{see}}$ were not inverted, that is, the walker predicted to cross first would

²Local planning refers to the predictive future collision avoidance behaviour. The participant treats a moving obstacle as a static one in each planning time step [Basili2013]

indeed cross first, not adapting to allow the walker that was predicted to cross second to actually cross first. Knorr and colleagues [Knorr2016] continued this work to elicit the effect of the possible limitations previously mentioned by Olivier and colleagues [Olivier2013]; possible human factors such as gender, height and psychological traits that could influence the assignment of roles during a collision avoidance task. Knorr and colleagues found no effect of human factors in the assignment of crossing order roles. However, they determined that the roles were assigned early on during the interaction [Knorr2016].

The notion of crossing order and inversions gained further interest from a later study, using a similar paradigm to Olivier and colleagues [Olivier2012, Olivier2013], participants completed an orthogonal crossing task with a passive wheeled robot [Vassallo2017]. The robot would follow a fixed rectilinear trajectory at a constant velocity of $1.4\text{m}\cdot\text{s}^{-1}$, and was programmed based on the captured velocity of the participant during the occlusion stage to ensure three conditions: fully collide by arriving at the intersection point at the same instant as the participant, arrive at the intersection slightly before or after the participant to create a partial collision course, or pass with a large distance that would cause no collisions. The crossing order and risk of a potential collision were controlled by using the previously proposed metric *MPD* [Olivier2012]. The results of this study showed a consistency in the capabilities of predicting future collisions with a robot, similarly to the observations of Olivier and colleagues. Additionally, the task was solved with anticipation, a plateau or reduction of *MPD* during the final regulatory stages of the interaction. However, when crossing a passive mobile robot, there were a significant increase in the number of inversions from the initial crossing order (i.e., changes in the predicted crossing order with actual crossing order). Previously, the number of inversions were negligible [Olivier2012, Olivier2013], however, in this study, an observed 29% of trials were inverted. A threshold of 0.8m was reported for those predicted to cross first but finally adapted to cross second. An adaptation that causes an inversion in crossing order was considered inefficient, it was therefore considered that this behaviour was an

extreme adaptation to the preservation of personal space. Further, they suggested that this response could be explained through the level of perceived danger from the robot as well as the lack of experience in collision avoidance with wheeled robots [Vassallo2017].

This phenomenon of inversions was further explored in a follow-up study [Vassallo2018]; using the same paradigm as their first study, now with avoidance behaviour by the robot for trials with a risk of collision was implemented. The behaviour was implemented in such a way that when the robot was 2m away from the intersection point, the robot would deviate its path to one of two fixed alternative paths, passing in front of or behind the participant. Note that the behaviour was only implemented when there was a risk of collision and only these trials were considered for analysis. Through the implementation of the robot avoidance behaviour, the number of inversions significantly decreased to 8% with a new threshold of 0.39m. Further, the behaviour of avoidance by the participant and the interaction between the two were reportedly comparable to human-human interactions [Vassallo2018].

The aforementioned studies have focused on the coupling and uncoupling of two walkers, either describing the interaction between the two as a minimally predicted distance or through observations of speed and path adaptations that can involve non-optimal adaptations to avoidance trajectories. Further, the interaction has been reported to include three stages (i.e, observation, reaction, and regulation). While it has been widely accepted that walkers are capable of perceiving the task, and successfully detect and avoid future predicted collisions, previous studies have only hypothesised and suggested future work to investigate the nature of the visual information. Croft *et al.*, [Croft2017] conducted an eye-tracking study to determine what was being observed and whether or not it influenced the avoidance strategy. The collision avoidance task was set as an orthogonal crossing, where a participant was either constrained to walk along a narrow path to a specific goal point or walk an unconstrained path to any point past the intersection (Figure 1.34). Additionally, within their experimental design, they analysed interferer maximum velocity, path constraint and whether or not the participant gazed

at the interferer with Bayesian logistic regression to identify predictors of final crossing distance. The participant was required to avoid any collisions with an interferer that was instructed to walk at a steady state or fast constant velocity and to adjust starting time as to assure future predicted collision events. The findings of this study showed no influence of the path constraints on avoidance behaviour, rather, the credible predictors were the gazing behaviour of the participant and interferer velocity. Participants that gazed earlier and fixated longer at the interferer during the interaction showed a tendency to pass second, similarly when the interferer walked with a fast velocity. While initial fixation and duration of fixation were effective predictors of crossing order, it was reported that gazing at the interferer was not always necessary as location and relative motion could be sourced from peripheral vision [Croft2017].

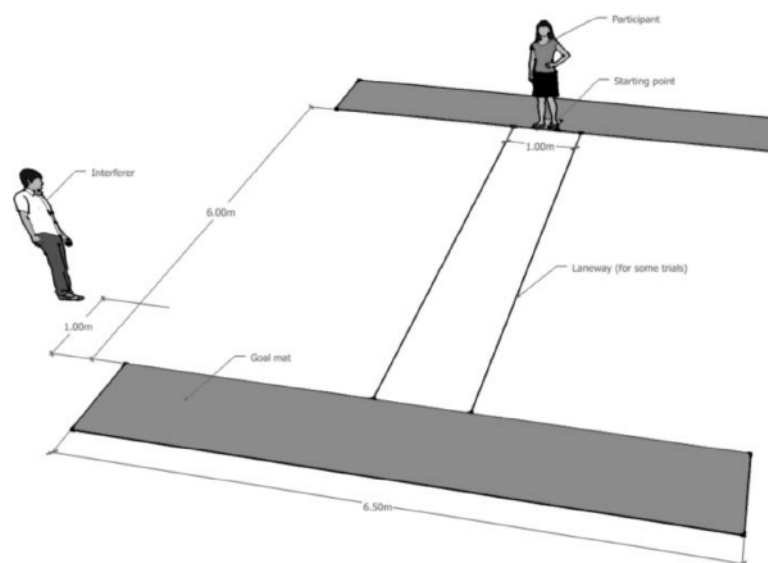


Figure 1.34 - The experimental setup of an orthogonal crossing with and without path constraints by [Croft2017].



To conclude, as an individual moves and interacts with their environment there are visual cues such as time-to-contact and bearing angle that may be sources of information in determining the future position of an obstacle. As the interaction between a walker and an obstacle advances, the prediction of a future collision avoidance can be determined rather early [Olivier2012, Olivier2013, Knorr2016, Croft2017]. During this observational stage of the interaction, roles are assigned for crossing first or second. It was originally suggested the roles were a product of non-verbal communication [Olivier2013]; however, it has been argued that these roles may rather be defined due to situational characteristics and human factors such as age, height, and personality trait had no influence [Knorr2016].

Although it was shown that gazing behaviour was a credible predictor for a walker interacting with a confederate, however, it remains unclear whether the gazing behaviour between two unconstrained walkers indeed influences collision avoidance behaviour. Further, in more crowded environments multiple walkers may have to be interacted with at the same time [Meerhoff2018b]. This raises the issue that a walker has to be sensitive to which aspects of the environment are the most threatening [Meerhoff2018a]. Therefore, the following sections will consider the human factors that include the effect of gaze and visual appearance, which may influence collision avoidance behaviour.

1.2.4 Human factors

This section will discuss the influence of gazing behaviour and human factors that may influence collision avoidance behaviour. Further, to express the influence of gaze and a sense of being looked at, several papers cited will consider the influence of gaze on immersion in virtual reality. During social interactions, gaze can be interpreted as one of several core processes: mutual and averted gaze, gaze following to joint attention and shared attention (see [Pfeiffer2013] for a social-cognitive review). As mentioned previously, gaze has been associated to a form of non-verbal social communication between two unconstrained walkers and as a credible predictor of crossing order while interacting with a confederate [Olivier2013, Croft2017]. During daily experiences of walking among other people and cluttered environments, we generally accept that gaze plays an important role in the negotiation of collision avoidance. For two unconstrained walkers, for example, mutual gaze between them forms a mutual awareness, however, if one walker does not gaze at the other but rather is concerned with their direction or distracted with their personal device, it is the gazing walker who is aware of the interaction and thus avoids the other.

1.2.4.1 Gaze

When two individuals gaze towards each other, mutual eye contact between the two implicitly influences the perception each has of the other [Kuzmanovic2009]. Further, mutual gaze has been characterised as a main factor for social interaction [Kleinke1986]. The social interaction of mutual gaze is considered as a form of nonverbal communication, through emotional arousal from previous experiences or communicative intention [Senju2009]. For example, Caruana *et al.*, [Caruana2017] used virtual faces and gaze direction to form joint attention towards a goal. Participants interacted with a vir-

tual face both character and participant gazed at one of three houses to indicate which house was being robbed (Figure 1.35). Bailenson *et al.*, [Bailenson2005] highlighted the positive aspects of mutual gaze during interaction in terms of coordination-regulation and immediacy-arousal.

The effect of mutual gaze has been demonstrated considering both real-real humans, humans and objects, and real humans-virtual characters social interactions [Vázquez2017, Bailenson2003, Kuzmanovic2009]. Indeed, authors reported an increase of activity in the superior temporal sulcus, a region of the brain involved in the perception of gaze in a mutual gaze task with a virtual character [Pelphrey2004]. Even if gaze is fundamental in social communication, it is also closely linked to associated body motions and orientation. For example, Marschner *et al.*, [Marschner2015] reported that emotion was evoked through the sum of mutual gaze and body orientation. Participants did not feel gazed upon if the character was gazing while orientated away from the agent.



Figure 1.35 - A screenshot of a joint attention task. Houses with blue doors were for participants to gaze at and find a burglar and houses with red doors were for the virtual character. From [Caruana2017].

The influence of gaze and eye contact during walking tasks have predominantly been investigated in towards type collisions (i.e., head-on, direct gaze towards the participant or averted gaze, looking away from the participant). For example, in walking tasks, Bailenson *et al.*, [Bailenson2003] reported that walkers gave more personal space to virtual characters who engaged in mutual gaze (Figure 1.36). During head-on collision avoidance, the gaze direction of an oncoming walker is an important determinant cue for future path intention [Varma2017].

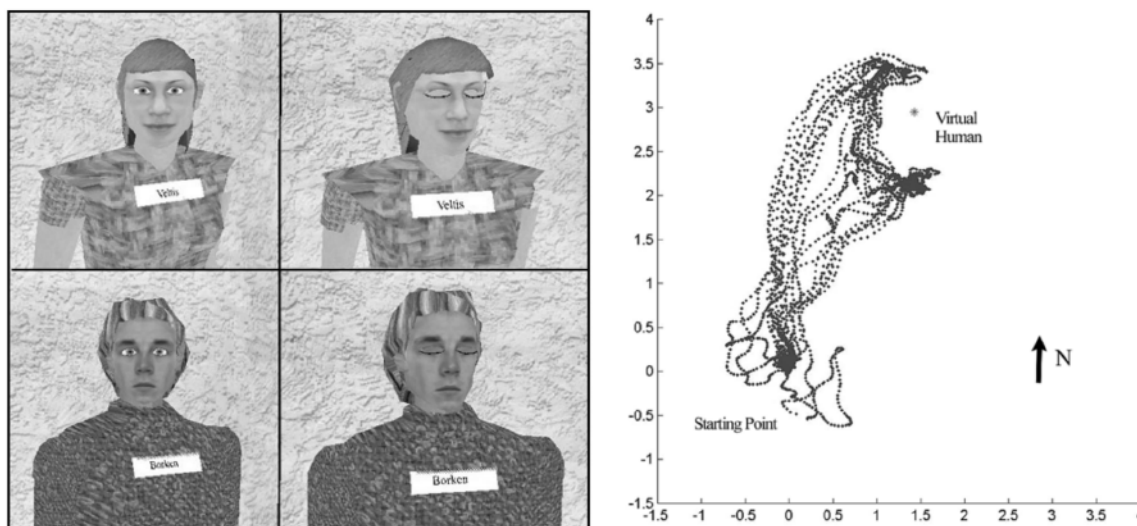


Figure 1.36 - Left: Pictures of female (top) and male (bottom) avatars with gazing behaviour (left) or without (right). Right: trajectories from 10 participants that approached the virtual avatar from behind and then moved to in front of the avatar before returning to the starting position. Note that both axes are distance in meters. From [Bailenson2003].

Nummenmaa *et al.*, [Nummenmaa2009] reported that participants used gaze as a cue to avoid collision: they orientated their path to the opposite side of the character's gaze. In this study, they did not report the effect of mutual gaze. Additionally, Narang *et al.*, [Narang2016] reported the presence of a character's gaze towards a human walker improved the sense of immersion in a crowded simulation. Finally, preliminary work has been completed during a collision avoidance task for crowd simulation [Hu2016]. The authors reported the subjective feedback of participants after crossing paths with

a virtual character with or without gazing behaviour (Figure 1.37). The initial findings of this preliminary work are promising, with participants reporting a sense of being acknowledged and further self-reporting that they adjusted their responsive behaviour as a result.

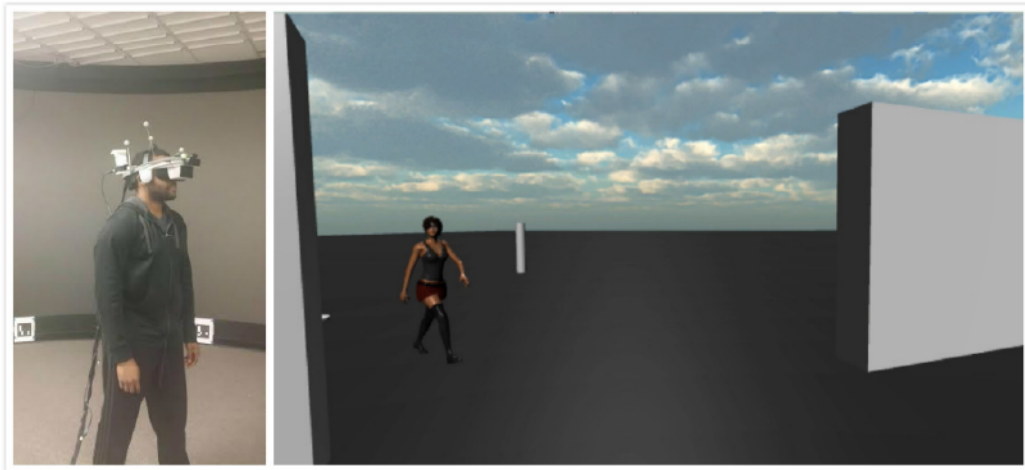


Figure 1.37 - A preliminary study combining reciprocal collision avoidance and gaze behaviour. Participants advanced towards a goal and were gazed at by a virtual walker if there was a risk of collision. From [Hu2016].



Gaze can indeed be an informative cue for the successful non-verbal communication between two walkers. However, it has been shown that the collision avoidance task can be successfully completed with robots that do not possess a visual system for the output of social information [Vassallo2017, Vassallo2018]. Further, it has been reported that the human factors (e.g., age, height and personality trait) do not influence the assignment of crossing order roles, rather, the situational characteristics during the observation stage do [Knorr2016]. To develop this understanding it is necessary to discuss the impact of an obstacles visual appearance for interaction and avoidance.

1.2.4.2 Visual appearance

To start, during infancy, it has been reported that the visual appearance of an object moving laterally and the motor repertoire of the observer can significantly influence the predictability of future location. To elaborate, infants that could only crawl, toddlers that had recently began to walk, and adults observed three scenes: an infant crawling, a toddler walking, and a chair moving from left to right. Using an eye tracker, participants followed the object as it moved with their gaze, as the objects moved from left to right they would pass behind a spatial occlusion. The results showed that crawling infants could only successfully determine the future location and instant of appearance while viewing an infant viewing, toddlers could predict for both an infant crawling and a toddler but not for an inanimate object. In contrast, adults were fairly accurate with all tasks, notably the inanimate object being the least accurate [Stapel2016].

Similarly, the visual appearance of an obstacle has been reported to influence the behaviours of participants. A general observational study of several social interactions (e.g., walking a narrow corridor or in a shopping mall), reported that a pedestrian's height influenced the outcome of social interactions; walkers were giving way to taller walkers [Stulp2015]. However, this was not reported during a collision avoidance task within a laboratory [Knorr2016]. Nevertheless, the effects of the visual appearance of an obstacle have been reported for other tasks, namely, head-on interactions and the influence of appearance on personal space (Figure 1.38).

Iachini *et al.*, [2014] conducted a study that required participants to stop an approaching virtual obstacle (two gender-specific avatars, a humanoid robot or a geometric cylinder) at either a peripersonal reachable distance or at the limits of a comfort zone (i.e., within personal space). The findings highlighted the close relationship between basic visuomotor-spatial processing and complex social processing. Additionally, the findings showed a greater distance was preferred while interacting with a cylinder than human

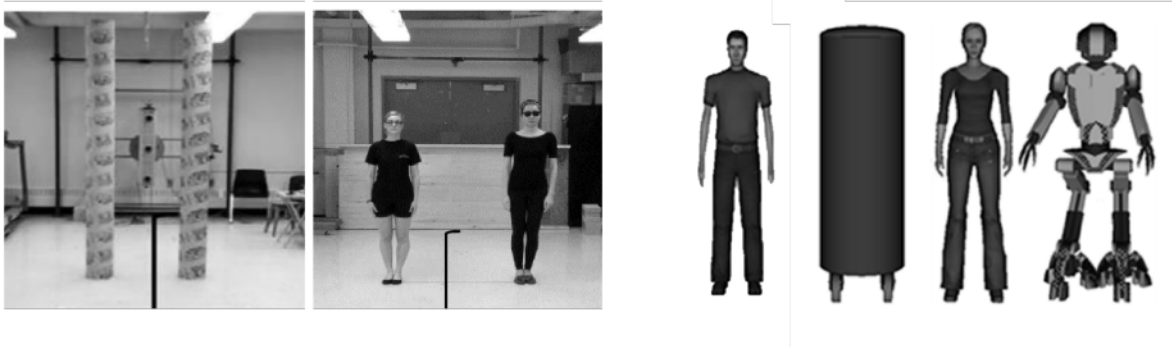


Figure 1.38 - Examples of variation in the visual appearance. Left, from [Hackney2015b], an aperture of two poles or of two persons. Right, four avatars, male, female, a humanoid robot and a cylinder from [Iachini2014].

shaped avatars [Iachini2014]. Similarly, when interacting with obstacles approaching head-on or from 40° to the left or right of the participant, larger clearance distances were observed when the obstacle was a cylinder and smaller distance for avatars [Silva2018].

However, in an aperture passage task, participants rotated their shoulders to allow more space between two human poles sooner than when traversing two cylinder poles [Hackney2015b]. Previous aperture studies have reported a critical point (i.e., the ratio of individual shoulder width) of 1.3m while traversing fixed obstacles such as poles. However, in this case, the critical point increased to 1.6m. Distances below the critical point recorded rotations of the shoulders.

Finally, similar findings were reported in a CAVE setup that compared clearance distances in virtual reality with reality. Participants walked along the length of the cave and avoided either a human or a box in both reality and virtual reality. Focusing on the human factors of the study, the clearance distance in both conditions was higher for human-like obstacles than for inanimate obstacles [Argelaguet-Sanz2015].

Chapter 2

Objectives



Figure 2.1 - An overview image of two paths intersecting and the possible visual cues available (from left to right), a global representation of a walker, a full body walker, two abstract representations of a walker, and two representations of head and gaze orientation by a walker.

This thesis and the works associated with it are focused on interactions with the environment, where we aim to develop further understanding of the underlying perceptual mechanisms that can be involved during a collision avoidance task between two walkers. A review of the literature has evidenced that locomotion and its optic flow supports the safe transportation and navigation of the body through an environment efficiently, with the latter being incorporated as part of the locomotor task. Information that could possibly specify future collisions include the answering of two fundamental questions, whether or not a collision will occur and if so, when will the collision occur. In answering these two questions, walkers adapt their trajectories to possibly maintain their personal space and avoid future predicted collisions. Thus, to answer these two fundamental questions, invariants found within the optic flow can detail the motion of the observer, the obstacle or both, through global motion cues such as the differential parallax and rate of expansion on the retina. Where the visual system has proven powerful in the detection of changes in direction for both self motion and obstacle motion, further, while global motion cues are based on constant velocities and the visual system is limited in perceiving acceleration, humans remain capable of adapting their behaviours to interact with accelerating obstacles. Additionally, it has been shown that biological motion is dense with local motion cues that can be used to identify differences of gender and specific individuals from a limited number of lights fitted on anatomical landmarks. Where the local motion cues may provide additional temporal advantages during interactions, global motion cues are suggested as a source of more honest signals.

Collision avoidance between two walkers has gained interest in the recent years, in the development of coupled metrics to express the evolution of the interaction, whether it is with passive or reactive obstacles, gaze tracking or various rectilinear angles of approach. Further, the behavioural adaptations observed in reality can be seen in virtual reality, simulating locomotion through optic flow with numerous interactive methods. However, the nature of the visual information that is being perceived; the influence of global and local motion cues on the detection of future collision avoidance, the

human factors that are involved during the interaction such as gaze behaviour and the influence of curvilinear paths require further investigation. **Thus the objective of the thesis is to further develop the understanding of the underlying perceptual mechanisms involved in the prediction of future outcomes during an orthogonal collision avoidance task.**

The visual appearance of an obstacle has a significant influence on the nature of visual information available and thus the behavioural outcome. For example, when traversing apertures of poles or humans in reality, it has been reported that a larger aperture or greater distance from humans is required for safe passage. Whereas during a collision avoidance task, differences of avoidance behaviour are reported while interacting with a passive or reactive wheeled robot. Additionally, in virtual reality, personal space and peripersonal space (i.e., arms reach) are smaller for approaching virtual humans than for virtual robots or cylinders. These notable differences suggest the importance of an object's appearance and its influence on behavioural responses. These differences in behaviour may well be attributed to differences in the visual information available. It has previously been shown that global motion alone is sufficient for successfully completing a task, however, local motion cues provided a temporal advantage. Therefore, the first study of the thesis focuses on the nature of visual information of a virtual obstacle during a collision avoidance task. To do this, the visual appearance of the obstacle is manipulated to limit the visual cues available. **This work aims at determining whether relevant cues are based on global movement or from local segment movements (i.e., stepping rate of the legs).**

After completion of the first study, the thesis progresses towards the second study, which works towards the path taken by the virtual walker and the evolution of interaction made by the participant. Regarding the literature of collision avoidance, during an orthogonal interaction, a linear extrapolation of the current velocity vector provides a minimally predicted distance at crossing. Calculating this predicted crossing distance for each time step provides an evolution of the interaction between the two walkers

and evidences three stages of interaction (i.e., observation, reaction and regulation) with anticipation. Additionally, this evidences that during an orthogonal crossing the task may be linearly extrapolated by the walkers to predict the instance of crossing. However, during an interception task of a ball following a curvilinear path, it has been evidenced that the task is completed prospectively through constant changes in the bearing angle. Work has varied the paradigm of collision avoidance between two walker with alternative angles of approach, and with confederates or wheeled robots. For each case, the task involved a participant being instructed to walk towards a goal and avoid any obstacle that may be on a collision-prone trajectory. The paired walker, confederate or robot were instructed similarly (follow a rectilinear path towards a goal), confederates being instructed to either match the speed of the participant, always ensure a predicted future collision or were trained to walk at fixed speed. Further, when navigating cluttered environments, in which we reside, a path may well be curvilinear as opposed to rectilinear. As evidenced by ball sports and interception tasks in the literature, there is the ability to intercept an object following a curvilinear path. However, the visual system has been reported as insensitive to accelerations for both temporal and spatial future estimations. **To this end, study two investigates a curvilinear path of a virtual walker and computes the evolution of minimally predicted distance at crossing. The aim of this work is to gain insight in the nature of perceived path, specifically, whether or not an observer can perceive and predict the future risk of collision from curved trajectories.** Previously it has been evidenced that a future risk of collision correlates with the linear extrapolation of velocity vectors, however, whether this remains true for curvilinear paths or a more complex model that considers accelerations has yet to be explored.

Finally, interactions between two unconstrained walkers presented several findings, firstly the linear extrapolation of position and heading of both walkers presented the predicted crossing distance, when this distance is below a threshold value the two walkers adapted to ensure a safe passage. Secondly, without verbal communication between the

two walkers both assigned roles in that one would pass first and the other would pass second. Further investigation into the assignment of crossing order roles suggested that the roles are attributed to the current position during the observational stage, that there is no influence of human factors (e.g., age, gender, and height) or personality traits (e.g., introvert and extrovert). Thirdly, no inversion of the assigned roles were reported, that is during the observation period the two walkers assigned roles to cross first or second and maintained that role to cross first or second. Whereas, while interacting with a passive robot, inversions are reported, which was considered an over adaptation response. Furthermore, the final crossing distances observed between a walker and a robot are larger than those observed between two walkers. The literature review has emphasised a possible effect through non-verbal social communication, passive behaviour, or a combination of both. Considering the task detailed to participants the most likely form of non-verbal communication would be expressed through the eyes and facial expressions. Where it has previously been evidenced that when two individuals gaze at each other, the two implicitly influence the perception each has of the other, with a mutual gaze forming a social interaction through emotional arousal and intention. Gaze has already proven to increase the sense of immersion in virtual environments. However, most studies considering a gaze behaviour have focused on head-on interactions. Studies have begun to consider the influence of reciprocal avoidance behaviours during a collision avoidance task with promising results. **Study three is then a continuation in the similar direction, introducing gaze as a non-verbal cue during collision avoidance, within this study we included trials with or without reciprocal avoidance behaviour to study the effects of gaze behaviour further.**

Chapter 3

Collision avoidance behaviour between walkers: global and local motion cues

Associated publications:

- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Crétual, A. and Olivier, A.-H. *Collision avoidance behavior between walkers: global and local motion cues*. IEEE Transactions on Visualization and Computer Graphics, In Press, 2017.
- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Crétual, A. and Olivier, A.-H. *Collision avoidance behavior between walkers: global and local motion cues*. 2018 IEEE Virtual Reality, Reutlingen, Germany, 18 - 22 March, 2018.
- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Crétual, A. and Olivier, A.-H. *Effect of local limb cues in the prediction of global motion during collision avoidance*. ACAPS 2017 - 17ème Congrès de l'Association des Chercheurs en Activités Physiques et Sportives, Dijon, France, 29 - 31 October, 2017.
- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Crétual, A. and Olivier, A.-H. *Global Motion Provides Sufficient Information for Successful Collision Avoidance*

During a Locomotor Task Within Virtual Reality. AFRV 2016 - L'Association française de Réalité Virtuelle, Augmentée, Mixte et d'Interaction 3D, Brest, France, 11 - 13 October, 2016.

3.1 Objective and contributions

This study focuses on the visual cues that convey relevant information for accurate estimation of others' global motion, specifically, whether these visual cues are extracted from local body parts or from global perception of the body motion. To manipulate the visual aspect while strictly preserving the kinematics of interactions (i.e., relative motion of the obstacle with respect to participants), we developed an experiment in virtual reality. Virtual reality is a novel approach that has proven to be a powerful tool for ecological perception and action research [Loomis1999]. Advantages of virtual reality include the ability to decouple natural co-varying variables, increasing experimental control and manipulation of finite detail. Perception and action through virtual reality is not without limitation [Fink2007]. It has indeed been demonstrated that there exists variance in depth perception [Loomis2003], which is not necessarily related to the restricted field of view that is often referred to when using head mounted displays [Creem-Regehr2005]. Additionally, in virtual reality forward gaze-driven speed is underestimated compared to actual speed [Banton2005].

Despite these notable differences within virtual reality, behavioural responses conform to reality. Walkers who perform a goal-directed locomotion task in reality replicate their trajectory in virtual reality [Cirio2013]. Specific to collision avoidance, validation of behavioural response has been reported in the preservation of personal space [Gérin-Lajoie2008] and interactive methods whilst using large immersive displays have been developed [Olivier2017]. Virtual reality has proven to be a significant tool in exploiting complex situations such as competitive sports [Brault2012], motion control [Fink2007] and crowd simulation [Bruneau2015]. Thus virtual reality is a robust and reliable tool for further developing the understanding of collision avoidance.

The virtual reality experiment sets a dynamic obstacle on a collision trajectory with a participant. The visual appearance of the dynamic obstacle is changed between trials.

A control situation, the dynamic obstacle is a walking virtual character. In this case, we are able to compare results obtained using virtual reality with real data recorded during interactions between two real humans.

The work has the following contributions:

1. We experimentally investigate the nature of the visual information used by a walker, specifically within a collision avoidance task. We demonstrate that global motion is a sufficient source of information to successfully predict future crossing distances and therefore avoid obstacles while local motion contains additional details that contribute to more accurate and repeatable predictions.
2. From these results, we provide recommendations of computational resources, and considerations of computational budget reduction, for the design of virtual reality platforms to perform human locomotion studies in the context of interactions.

3.2 Method

3.2.1 Participants

Sixteen healthy participants (11 males, 5 females), aged 26.43 ± 5.53 years (mean \pm SD) participated in this study. All participants had normal or corrected-to-normal vision and no history of disease or impairment which could have affected their ability of participation. A written informed consent form was obtained from all participants prior to experimentation and the study was in accordance with the standards of the Declaration of Helsinki.

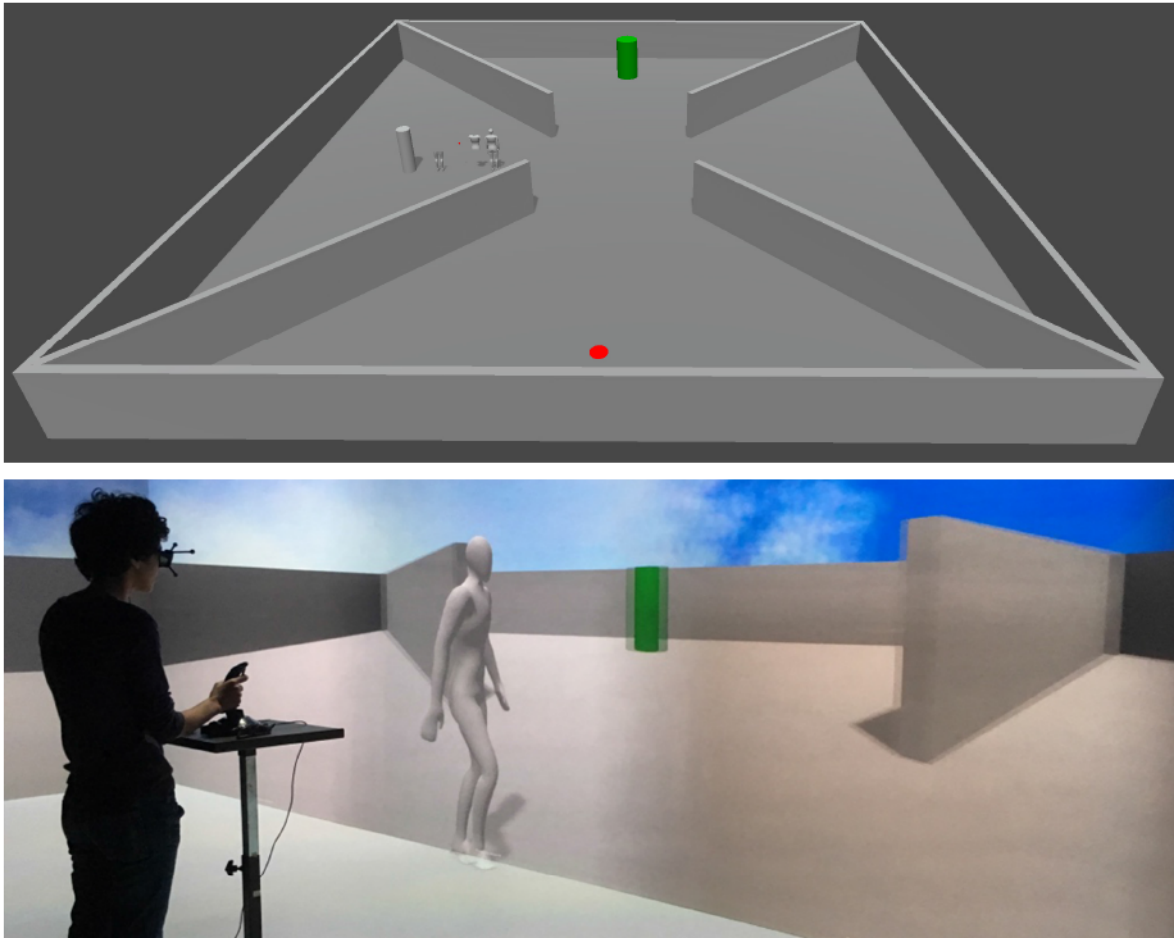


Figure 3.1 - Top). Overview of the virtual environment used for the experiment, a red starting position, a green goal to aim towards and the variety of obstacle appearances at an obstructed starting position on the left. Bottom). Third-person perspective of a participant whilst avoiding the full body control situation with the green goal for the participant in the background.

3.2.2 Apparatus

Experiments took place in a 4-screen Computer Assisted Virtual Environment (CAVE), which was 9m wide, 3m high and 3m deep. It was equipped with 13 projectors with 15MPixels resolution in total. 3D environment display and character animation (Figure 3.1) were designed in the Unity game engine. Multi-surface rendering was performed by the MiddleVR plugin. Active stereoscopy was achieved with Volfony ActiveEyes Pro Radiofrequency wearable glasses. Glasses were tracked by an ART tracking system made up of 16 cameras. A joystick was used by the participants to move in the virtual

environment. The associated control law for the virtual speed was the one used by Olivier et al. [Olivier2017]. The joystick neutral position would produce a baseline displacement of $1.4\text{m}\cdot\text{s}^{-1}$ with zero angular velocity, which resembles a typical normative walking speed [Bohannon1997]. Any action on the joystick thereafter produces an adaptation of the virtual trajectory. The longitudinal axis controlled speed linearly from $0.8\text{m}\cdot\text{s}^{-1}$ to $2.0\text{m}\cdot\text{s}^{-1}$, and the lateral axis controlled angular rotation speed linearly from $-25\text{deg}\cdot\text{s}^{-1}$ to $+25\text{deg}\cdot\text{s}^{-1}$.

3.2.3 Experimental setup

Using a Latin square design, experimentation was partitioned into five randomised blocks of appearance (Figure 3.2). Within each block of appearance, obstacles would advance from the participant's occluded right or left. We also controlled the potential danger of the interaction to assess whether the visual appearance of the obstacle has an effect on the perception of the situation. The obstacle's starting position controlled the future risk of collision determined by $MPD_{t_{see}}$, which is the instant the participant can first see the obstacle [Olivier2012]. A total of 5 crossing distances were chosen for the experiment, varying the risk of collision: two high risk distances, where a collision would occur if no adaptation is implemented (0.1 and 0.3m), an intermediary distance (0.6m) that would require no adaptation, according to what is actually observed between two pedestrians, but an inversion is reported while interacting with robots [Vassallo2017], and finally two low risk distances, where no collision would occur if no adaptation is implemented (0.9 and 1.2m). Furthermore, we controlled the initial crossing order at $MPD_{t_{see}}$ where the obstacle would pass the participant either in front or behind at these randomised risk of collision distances. For each conditional visual appearance block, participants were given a short familiarisation period consisting of five trials of varying risks of collision with the specified conditional appearance.

Within each block of visual appearance, these conditions were presented randomly to participants. As a result, each participant performed 100 trials ($5 \text{ appearances} \times 2 \text{ crossing sides (left-right)} \times 5 \text{ MPD}_{t_{see}} \times 2 \text{ crossing orders}$).

The duration of the experiment per participant, including familiarisation and questionnaire completion was one hour.

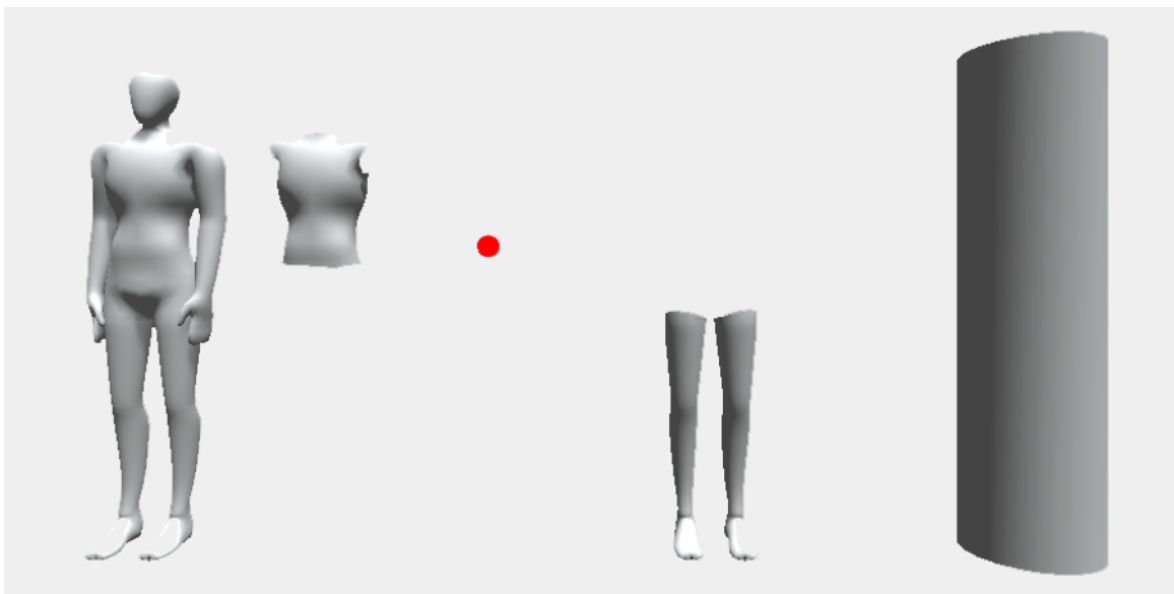


Figure 3.2 - Visual appearances used as visual cues of local and global appearances from left to right, full body, trunk, COG, legs and cylinder

3.2.4 Conditions

We aim at investigating the role of global versus local information about obstacle motion in a collision avoidance task. To this end, we manipulated the visual appearance of the moving obstacle by using the following conditions, as illustrated in Figure 3.2:

1. Full body: A mobile mannequin with a shoulder width of 37cm and hip width of 27cm, was rendered without a face to avoid any influence of emotion and gaze. Furthermore, the motion was animated as a neutral repeated gait cycle.
2. Legs: Considering foot placement is a direct contact to the ground, the feet and legs alone may provide perceptual local information for successful collision avoidance. Thus, all upper body local information was removed with only foot placement and leg motion remaining. Only positioning and stride could be perceived; segmentation of the legs was below the hips to remove any hip orientation information.
3. Trunk: The trunk being the largest visible aspect of the human body we chose to use this segmentation, without legs or arms, in order to remove any swing rate information and present only orientation. Further, the hip was excluded once again from the segmentation as a stride rate could otherwise be perceived through hip oscillations.
4. Cylinder: To remove all orientation and step information, a cylinder fully encompassed the full body control in a static position. The cylinder was then encoded with the same trajectory and velocity profile as the full body condition.
5. Sphere: With recent findings of Brault and colleagues [Brault2012] suggesting a strong correlation between centre of gravity (COG) and interception during a deceptive sporting task in terms of success, we chose to remove all encasing information and use a small sphere (8cm diameter) as an appearance of COG. This was also to remove all orientation and stride information, and similar to the trunk but unlike leg segmentation, it was free from ground contact.

Note that condition 1) serves as a control condition. Conditions 2) and 3) study the role of local motion cues conveyed by the human limbs and torso. Finally, conditions 4) and 5) remove completely the local motion cues, and display global motion cues through different geometrical representations of the obstacle.

3.2.5 Task

Participants were immersed in a virtual environment (Figure 3.1), where they were instructed to stand at a designated location depicted in the immersive environment floor. The task was to navigate through the environment, using a joystick, to reach a goal (a green cylinder) at the opposite end of the room. They were instructed to avoid potential collisions with any virtual obstacle that would appear in their path. The virtual obstacle was moving along a trajectory perpendicular to participants' own trajectories. We set occlusion walls in the environment to control the moment at which participants could perceive the virtual character ($MPD_{t_{see}}$). This allowed participants to reach the baseline speed simulating a steady state of comfortable walking before interaction. Throughout experimentation all virtual obstacles were non responsive, with a constant velocity and trajectory. The participant's initial steady state and the virtual obstacle's speed was set according to the study of normative walking speed at $1.4\text{m}\cdot\text{s}^{-1}$ [Bohannon1997]. Where the speed of the virtual obstacle remained constant throughout, participants could adapt their speed and trajectory after $MPD_{t_{see}}$ using the joystick.

3.2.6 Questionnaire

We collected demographic information and measured simulator sickness with the Kennedy-Lane SSQ questionnaire [Kennedy1993] before and after the experiment. At the end of each block, participants filled a subjective questionnaire. Participants answered the following questions using a 7-point Likert scale from 1 (strongly disagree) to 7 (strongly agree):

- ▶ I am satisfied with the ease of completing this task
- ▶ I am satisfied with the support information when completing this task
- ▶ The virtual obstacle motion was natural
- ▶ The interaction with the virtual obstacle was natural

At the end of the experiment, participants were asked to rank obstacle visual appearance according to the task by order of preference (from best to worst).

3.2.7 Data analysis

Trajectories of the virtual object were recorded from the moment the agent could see the virtual object ($MPD_{t_{see}}$). Post-processing the interaction response of the agent was performed using customised MATLAB scripts (Mathworks 2015b). Using trajectory and velocity of both participant and virtual object, we can calculate minimal crossing distance, inversion of crossing order and collisions, if any. Where minimal crossing distance was defined as the shortest distance between the participant and virtual obstacle centers, crossing order was classified as the participant passing the obstacle as first or second and an inversion would be when the initial order was altered by the participant as part of their collision avoidance strategy. A collision was acknowledged when minimal crossing distance was less than the sum of both participant's and obstacle's radii. We also computed MPD evolution in time throughout each trial. MPD was normalised to the period of interaction, that is, from the instant that the participant could see the virtual object, $MPD_{t_{see}}$, to the instant of crossing, $MPD_{t_{cross}}$. To characterise the evolution of MPD during the interaction phase, we computed its time derivative. For each curve, we identified all the instants corresponding to a change of sign of MPD time derivative and we computed the corresponding MPD values. Then, we applied Wilcoxon signed rank tests to compare the MPD values which encompass these changes of sign to characterise the evolution of MPD (no change, increase, decrease).

3.2.8 Statistics

We set the level of significance to $\alpha = 0.05$. A Kolomogorov-Smirnov test was performed to evaluate whether data followed a normal distribution. The dependant variables were: final crossing distance, number of collisions, number of inversions as well as the responses from the questionnaire. We evaluated the effect of obstacle visual appearance and initial $MPD_{t_{see}}$ on these dependent variables using a Friedman non-parametric test and post-hoc Wilcoxon sign ranked test with a Bonferroni correction. We compared the evolution of MPD of each of the appearances to the control condition (full body) using statistical parametric mapping (SPM) [Friston2007]. With the SPM analysis, time-series data of different trials can be compared taking the variability at each time-step into account. Finally, the distribution of questionnaire responses were analysed using a Friedman non-parametric test with regards to the perception of immersion, interaction with the virtual obstacle and ability of task completion.

3.3 Results

3.3.1 Collisions

A total of 35 collisions occurred (upon 1600 trials in total); of those, obstacle appearance had no significant effect on the rate of collisions ($\chi^2(4)=6.218$, $p=0.183$). Full body, legs, trunk, cylinder and COG appearances had a median collision rate of zero percent. The reported no significant difference was consistent after considering crossing order, with a zero median rate of collision for all visual appearances.

3.3.2 Crossing order

Similarly, from a total of 145 inversions there was no significant overall effect of obstacle appearance on the rate of inversion of crossing order ($\chi^2(4)=5.857$, $p=0.210$). Full body, legs and cylinder had reported medians of 10% occurrences, trunk and COG had reported medians of a 7.5% occurrences. We then considered trials separately, where participants initially were set to cross first (i.e., $MPD_{t_{see}}$ was positive) and second (i.e., $MPD_{t_{see}}$ was negative). Results showed a significant influence of obstacle appearance for predicted crossing first trials ($\chi^2(4)=18.478$, $p<0.001$). Post-hoc analysis showed an inversion from a predicted crossing first to finally crossing second whilst interacting with the cylinder (20%) was significantly different ($p<0.05$) from COG (10%), trunk (10%), legs (5%) and full body (5%). The remaining analyses have had trials with inversion omitted due to the lack of overall effect. Further, while there was a significant difference of inversion with regard to crossing order and visual appearance there was no effect on final crossing distance ($p>0.05$).

3.3.3 MPD evolution in time

Figure 3.3 (top) illustrates average *MPD* evolution during the interaction phase considering absolute values. For all conditions of obstacle appearance, we can visually observe a similar shape of *MPD* curves throughout the interactions. A pairwise Wilcoxon sign ranked test based on *MPD* time derivative (Figure 3.3 bottom) showed for each condition a first stage where *MPD* was maintained constant without significant changes of its values (in blue), a second stage where *MPD* was significantly increased (in green) and a final stage where *MPD* was significantly decreased (in yellow). *MPD* remained constant ($p > 0.05$) for cylinder, trunk, legs, full body and COG up to 6%, 3%, 10%, 6% and 11%, respectively. Thereafter the respective increases in *MPD* ($p < 0.05$) lasted up to 76%, 79%, 80%, 79% and 79%. A further reduction of *MPD* occurred until completion of the task ($p < 0.05$).

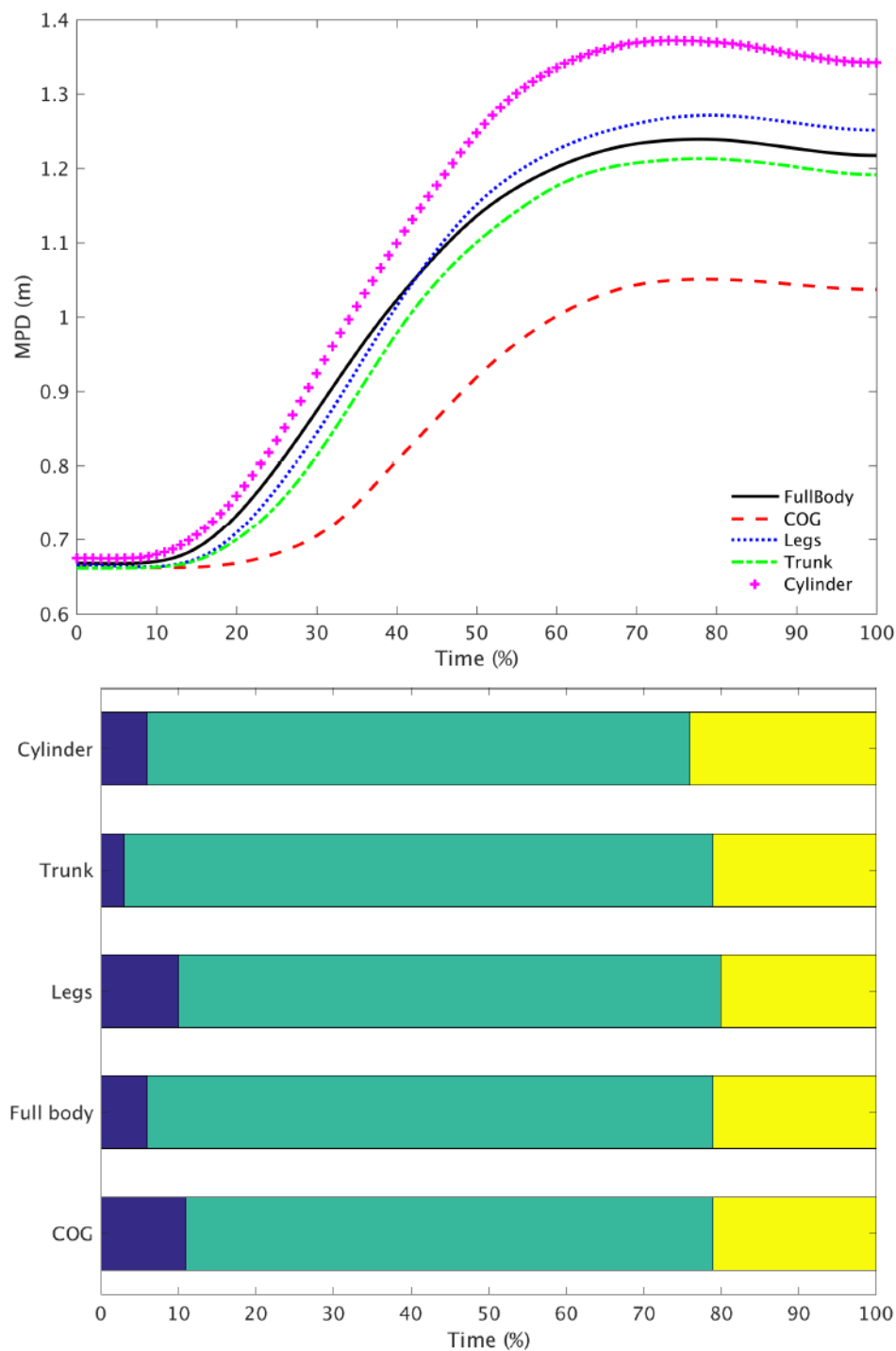


Figure 3.3 - Top). Mean *MPD* curves for each visual appearance condition. Bottom). Three distinct stages within the *MPD* evolution; An initial stage where there is no difference in *MPD* (blue/left), thereafter an increase in *MPD* (green/middle) before a final decrease in *MPD* (yellow/right).

Figure 3.4 illustrates the SPM comparison between each visual appearance of the obstacle with respect to the full body reference one. Within each subplot, a significant difference with the full body reference appearance is highlighted along time between a green vertical bar (first instance of significance) and a red vertical bar (terminus instance of significance). Quantitatively SPM analysis showed significant differences in both COG and cylinder conditions when compared to the full body control ($p < 0.05$). For COG condition, in comparison to full body, the significance first instance occurred earlier within normalised time (22%) than cylinder (47%). Furthermore, the gradient of the slope was observably less in COG than the full body control and cylinder being steeper than the full body control.

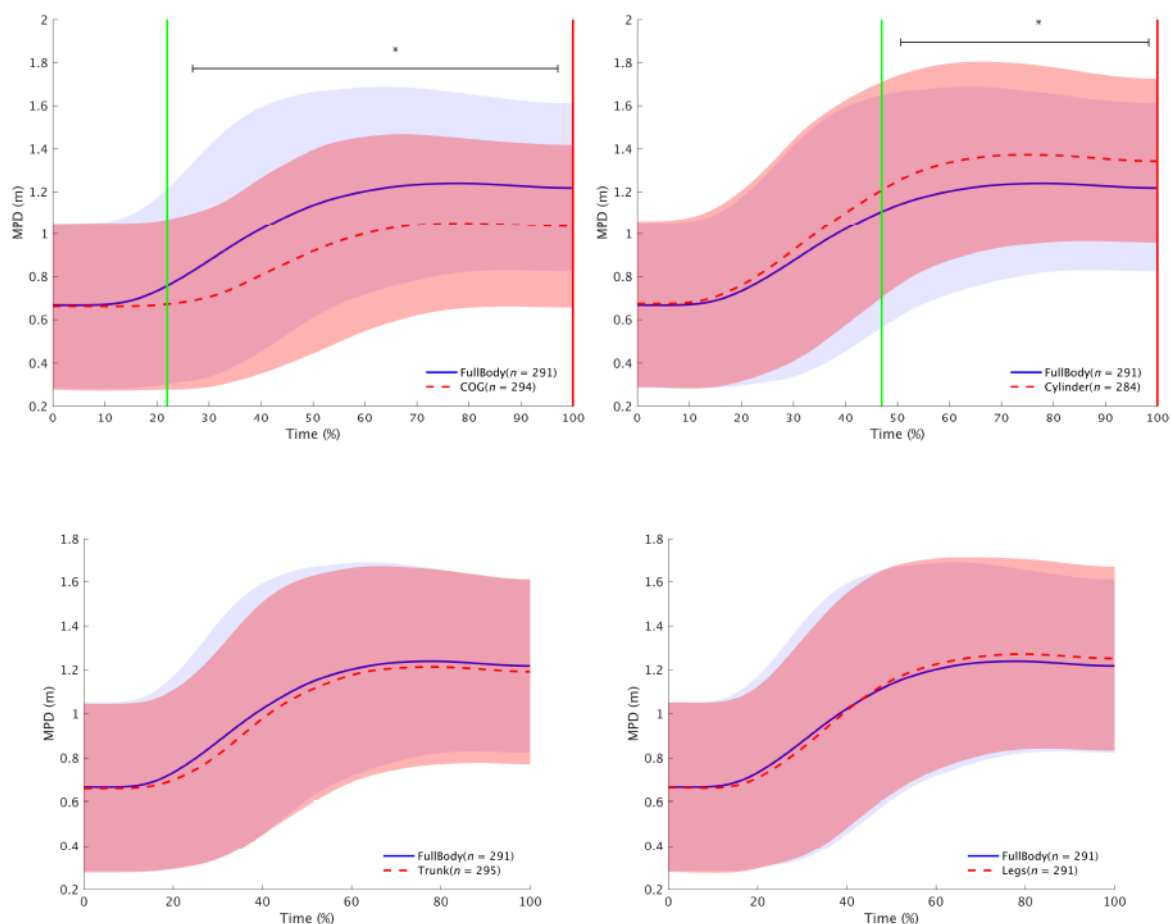


Figure 3.4 - SPM evolution analysis of normalised *MPD*, comparing the evolution of crossing distance of COG (top left), cylinder (top right), trunk (bottom left) and legs (bottom right) to the full body control.

3.3.4 Crossing distance

Table 3.1 reports median values of final crossing distance (MPD_{tcross}) of each visual appearance for each initial risk of collision condition (MPD_{tsee}). Wilcoxon signed rank tests showed that there was a significant difference between MPD_{tsee} and MPD_{tcross} for all visual appearances through all risks of collision ($p < 0.001$). Each comparison showed that MPD_{tcross} was greater than its corresponding MPD_{tsee} . There was no threshold where an adaptation of avoidance or reduction of final crossing distance did not occur; participants implemented avoidance strategies for all MPD_{tsee} conditions. Obstacle appearance (Figure 3.5) significantly affected final crossing distance ($\chi^2(4) = 223.392$, $p < 0.001$). Post-hoc analysis showed that both global motion obstacles COG (0.96m) and Cylinder (1.24m) were significantly different from each other and to their local motion counterparts ($p < 0.05$). There was no significant difference between the local motion appearances ($p > 0.05$): full body (1.17m), trunk (1.16m) and legs (1.20m).

Table 3.1 - Median values of $MPD_{t_{cross}}$ depending on the obstacle visual appearance and $MPD_{t_{see}}$. p values are the results of the Wilcoxon signed rank tests between $MPD_{t_{cross}}$ and $MPD_{t_{see}}$. A significant difference means that an adaptation of the trajectory to increase the future crossing distance has been performed.

$MPD_{t_{see}}$	COG			Cylinder			Full body			Trunk			Legs		
	Median	Z	p	Median	Z	p	Median	Z	p	Median	Z	p	Median	Z	p
-1.2	1.28	4.937	p<0.001	1.69	4.937	p<0.001	1.56	4.937	p<0.001	1.36	4.937	p<0.001	1.59	4.937	p<0.001
-0.9	1.18	4.937	p<0.001	1.49	4.937	p<0.001	1.46	4.937	p<0.001	1.41	4.937	p<0.001	1.44	4.937	p<0.001
-0.6	0.97	4.937	p<0.001	1.47	4.937	p<0.001	1.28	4.937	p<0.001	1.24	4.937	p<0.001	1.45	4.937	p<0.001
-0.3	0.86	4.937	p<0.001	1.28	4.937	p<0.001	1.13	4.937	p<0.001	1.17	4.937	p<0.001	1.08	4.937	p<0.001
-0.1	0.81	4.937	p<0.001	1.20	4.937	p<0.001	0.90	4.937	p<0.001	1.14	4.937	p<0.001	1.00	4.937	p<0.001
0.1	0.73	4.937	p<0.001	1.04	4.937	p<0.001	0.95	4.937	p<0.001	0.88	4.937	p<0.001	0.81	4.937	p<0.001
0.3	0.68	4.937	p<0.001	1.01	4.918	p<0.001	0.92	4.937	p<0.001	0.81	4.937	p<0.001	0.90	4.937	p<0.001
0.6	0.87	4.937	p<0.001	1.19	4.937	p<0.001	1.02	4.937	p<0.001	0.91	4.937	p<0.001	0.96	4.937	p<0.001
0.9	0.90	4.619	p<0.001	1.24	4.937	p<0.001	1.07	4.937	p<0.001	0.99	4.937	p<0.001	1.13	4.937	p<0.001
1.2	1.20	4.450	p<0.001	1.22	4.245	p<0.001	1.20	4.450	p<0.001	1.20	4.937	p<0.001	1.20	4.937	p<0.001

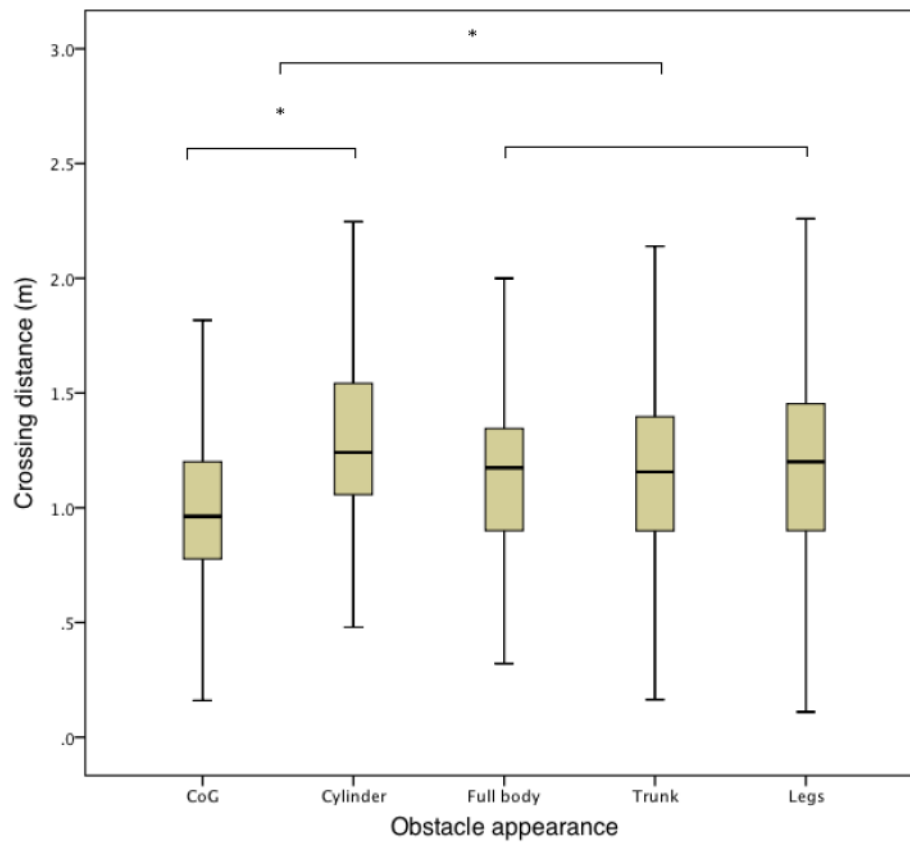


Figure 3.5 - Overall effect of each visual appearance on the crossing distance.

Crossing order had a significant influence on the final crossing distance when considering all conditions globally ($Z = 15.278$, $p < 0.001$) (Figure 3.6) or separately (Figure 3.7). Participants allowed more space with the obstacle when crossing second (1.24m) than when crossing first (1.04m).

Figure 3.7 shows the significant effect of crossing order on final crossing distance, which was consistent for all visual appearances ($p < 0.05$).

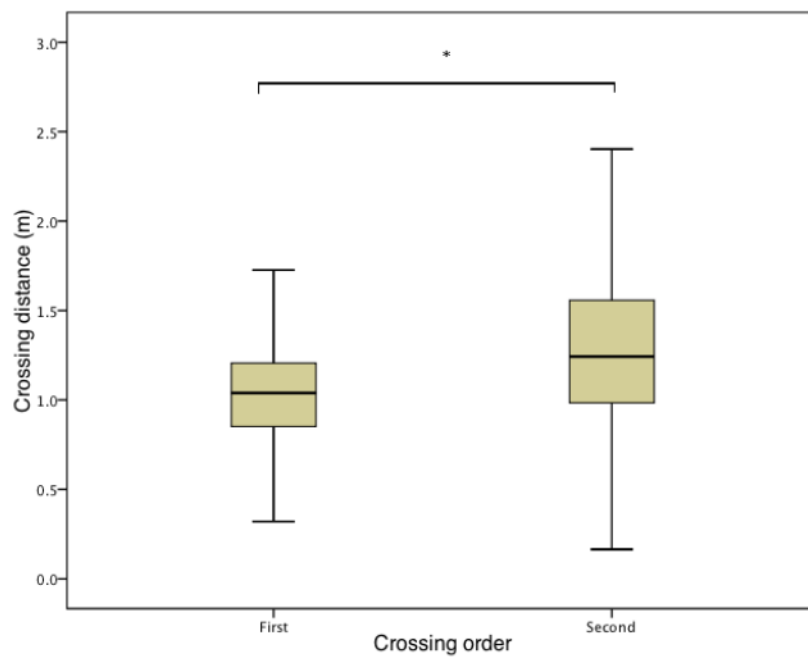


Figure 3.6 - Crossing distance differences between conditions where the participant crossed first or second.

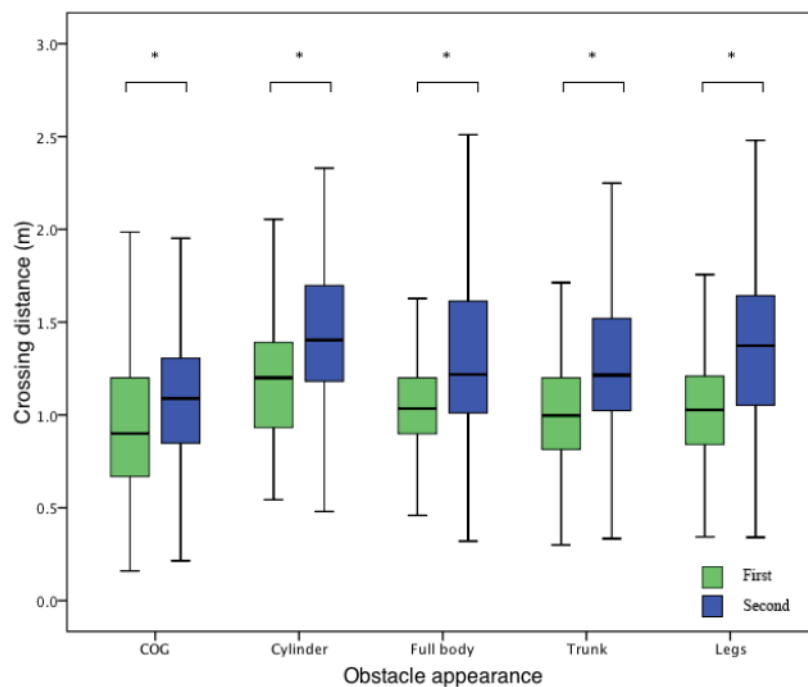


Figure 3.7 - Crossing distance for each condition of obstacle appearance, each conditional appearance plotted according to crossing order. Participants passing first allow a smaller distance (green) than when crossing second (blue).

3.3.5 Questionnaires

There were no reported cases of motion sickness from the Kennedy-Lane questionnaire from pre- and post-immersion. Additional questioning included the ranked preference of the obstacles, from 1 being most favoured for interaction and 5 being least favoured for interaction. The distribution of ranking was not significantly different ($\chi^2(4)=9.257$, $p=0.055$). Further, there was no significant effect of obstacle visual appearance on the distribution of response with regard to the questions concerning obstacle motion, interaction, ease of the task and information availability ($p>0.05$). Open question responses concerning the interaction with the various obstacles were not extensive or exhaustive but included comments concerning the immersion such as, "a sensation of being a ghost floating through space", "difficult to look down at the legs", "personal space was biased due to the joystick", and "difficult to observe just a red point". Finally supplementary comments consisted of the appearances themselves, suggesting additional reality effect could be created through an avoidance behaviour of the virtual obstacle.

3.4 Discussion

The aim of the present study was to investigate the nature of information from obstacle motion that is used during interactions between walkers. We designed an orthogonal collision avoidance task within virtual reality, similar to Olivier and colleagues [Olivier2012] who formed a method of describing interpersonal interaction in real conditions. We focused on global and local motion cues by manipulating visual appearance of obstacles. We evaluated the influence of this manipulation on the adaptation strategy, focusing our analysis on *MPD*, the predicted distance of closest approach.

3.4.1 Qualitative motion adaptation

All obstacle appearances led to qualitatively similar motion adaptation. Almost no collision and few inversions of crossing order were observed. The collision avoidance behaviour presented three distinct phases of avoidance: observation, the participant was perceiving the obstacle but not currently acting upon it; reaction, the participant modified their trajectory to increase the future distance of closest approach; regulation, once a safe crossing distance had been obtained, the distance was kept constant or even slightly decreased. All collision avoidance trials were solved by anticipation. These results match those observed in real life conditions [Olivier2012], as well as in virtual environments with a virtual walker [Olivier2017]. The manipulation of visual appearance showed no effect on human ability to successfully complete an orthogonal collision avoidance task: humans successfully avoided collisions independent of the global or local obstacle appearance.

In contrast to [Olivier2012, Olivier2013] and [Vassallo2017], who reported no trajectory adaptation above a 1m future crossing distance, this study presents no such

threshold of risk of collision (i.e., initial *MPD* values). As illustrated in table 3.1, we always observed an avoidance adaptation of the trajectory, this is in accordance with [Olivier2017]. The absence of an upper threshold within our experimental setup could be in part explained by a change of distance perception in virtual reality [Loomis2003, Lampton1995, Plumert2005], as well as the increased personal space whilst immersed [Gérin-Lajoie2008, Argelaguet-Sanz2015].

3.4.2 Crossing order

After considering the initial crossing order, results showed an effect of obstacle visual appearance on the number of inversions of the crossing order. Similar to a previous study involving a wheeled robot [Vassallo2017], we noted inversions (from 5% to 20%) of the crossing order for trials where a participant was predicted to cross first and finally crossed second. The rate of inversion was greatest for cylinder and least for full body and legs conditions. Similar experimental setups with varying obstacle appearances produced varying behavioural responses. The works of [Olivier2012, Olivier2013] reported no inversion between two humans in real conditions, a crossing order emerged at $MPD_{t_{see}}$ and remained. However, Vassallo and colleagues [Vassallo2017] reported inversions of crossing order after $MPD_{t_{see}}$. The role of inversion was interpreted as an extreme behavioural response for the preservation of personal space, stating an inversion is an energy inefficient response on the predicted trajectory. They suggested that this response could be explained through the level of perceived danger from the robot as well as the lack of experience in collision avoidance with wheeled robots. Immersion within virtual environments reduces physical danger, further, goal-directed behavioural responses within virtual reality have previously been validated [Cirio2013, Olivier2017]. Considering the findings reported here and previously, we may hypothesise that underpinning nonverbal social communication aides participants in maintaining crossing

order after $MPD_{t_{see}}$. Additionally, obstacle size and behaviour uncertainty may further influence the rate of inversion.

3.4.3 Quantitative motion adaptation

Our results reported a significant difference of final crossing distance whilst interacting with global motion visual appearances. Crossing distance was greater whilst interacting with the cylinder (1.24m) and smaller whilst interacting with the COG (0.96m) in comparison to the full body counterpart (1.17m). We note that within an orthogonal collision avoidance setting, variation in visual appearance from the control full body visual appearance did not affect avoidance strategy.

The evolution of MPD over time during the interactive stages of the collision avoidance task showed a significant difference from the full body condition for both global motion appearances (i.e., COG and cylinder). After 22% of $MPD_{t_{see}}$ to $MPD_{t_{cross}}$ normalised time had passed, participants followed a trajectory that resulted in a smaller crossing distance in the COG condition compared to the full body. In contrast, after 47% of normalised time had passed, participants followed a trajectory that resulted in a larger crossing distance from the cylinder. In relation to the three distinct phases of avoidance, COG had the longest MPD normalised time observational period of 10% (Figure 3.3). Thereafter, a significant difference in the evolution of MPD with full body was observed from 22% (Figure 3.4). While obstacle avoidance was successfully performed with the COG appearance (8 cm sphere), suggesting that bearing angle change provided sufficient information for dynamic obstacle avoidance, the observation period before initiating a response was significantly longer, and the final crossing distance was significantly smaller, than for the larger obstacles. This may suggest that optical expansion also played an important role in timing the avoidance response: the optical expansion of an 8 cm object reaches threshold much later than that of a large

object. These results imply that obstacle avoidance may not be controlled by bearing angle change alone, despite being effective in emerging self-organisation within crowds [Ondřej2010].

The cylinder, however, reproduced a similar observational period as the full body, a significant difference occurring from 47% where the participant is likely to have over-adapted due to the larger final crossing distance. This finding is in agreement with [Iachini2014] who reported a larger interaction distance whilst meeting a cylinder in comparison to a human body. They linked their findings with the social aspects of the interaction. However, in our case, our findings can be interpreted by: the difference in the social dimension of interactions with a cylinder or a character, or some uncertainty in the perception of the cylinder size and motion.

3.4.4 Local vs. global information

Participants filled out a questionnaire concerning their subjective experience with each obstacle appearance. They ranked the visual appearance in the order of preference for interaction. Interestingly there was no single preference. This impartial response was further supported by inter-block Likert questionnaires that also showed no bias to obstacle appearance.

Knorr and colleagues [Knorr2016] reported that age, height, gender and personality social factors do not influence the behavioural responses of a collision avoidance task. The subjective preference reported here corroborates the behavioural responses of Knorr et al. [Knorr2016]. However, Knorr et al. did not report an analysis of subjective preference. Surprisingly, the behavioural responses we observed to global- and local- motion information appearances contradict these findings. Our results showed that depending on the obstacle appearance, participants would avoid the obstacle at a different

distance. These findings thus suggest that avoidance behaviour is not bound to a subjective preference of visual appearance, rather, the visual appearance changes a participant's perceived action-opportunities as evidenced by its behavioural response. That is, the larger surface area encompassed by the cylinder affords a larger crossing distance, whereas, the COG has a smaller volume and therefore affords a smaller crossing distance.

Meerhoff et al. [Meerhoff2014] studied the role of global and local motion information in a non-competitive distance regulation task. They showed that even if the ability to regulate distance was not perturbed, when only global motion was available, participants managed to gain a temporal advantage (i.e., earlier responses) when both local and global motion were available. It could thus be hypothesised that local motion information allows for a more accurate estimation of another person's movements, but the usability of this information depends on the nature of the interaction (competitive or non-competitive). In our study, we found that the cylinder conditions induced a larger final crossing distance. However, our COG results contrasted with the findings of [Meerhoff2014], which may be explained by the size of the object. Meerhoff and colleagues [Meerhoff2014] used a spherical object with the same diameter as the height of their full body control condition, whereas we adopted a smaller sphere to represent the COG. Given this smaller size, it could have given the participants a sense of being able to cross at a smaller distance, despite the hypothesised uncertainty from the lack of local motion information. Furthermore, within our analysis, we had considered behavioural responses to an obstacle's centre and to an obstacle's envelope, that is the obstacle's closest circumferential point to the participant. The analysis of behavioural response to obstacle envelope was omitted as there was no difference from obstacle centre. However, collision frequency was significantly increased whilst treating COG within an invisible full body. This further supports that action-opportunities are bound to directly perceived visual appearances within the optic array.

3.5 Limitations

Some limitations of our work can be considered with respect to the behaviour and the visual aspect of the obstacles. Our experimental setup included the passive behaviour portrayed by the virtual obstacles, as used in Olivier et al. [Olivier2017]. The passive behaviour was required to standardise the experiment while exposing participants to the same conditions. Abstract appearances such as our global motion appearances and abstractions of local motion information may be considered as passive obstacles, whereas users may have expected a reaction from the full body control obstacle. However, users were informed about the passiveness of each virtual obstacle and that they should not expect cooperation which should have reduced any bias of passivity. It would be of interest to observe behavioural responses of walkers with active responsive virtual obstacles. Implementing an active response may present greater walker behavioural response differences between global and local motion appearances, where local information may provide additional trajectory adaptation information that would otherwise be lost by the smooth convex shape of the cylinder.

Identifying characteristics such as emotion, gender based walking patterns and gaze were omitted from the full body control. The inclusion of such characteristics would have been additional confounding variables. Omitting these characteristics may have decreased the sense of presence and increased the passivity of the virtual character and thus formed the behavioural responses more closely related to our global motion appearances. The extent of influence of social traits in virtual reality is still advancing [Knorr2016, Marschner2015, Jung2016].

3.6 Applications

From our findings, we suggest guidelines of consideration for future applications of human behavioural responses and interactions within virtual reality. At the pairwise interaction level of behavioural responses we recommend continuation with full body human appearances. Quantitatively local motion was more reproducible in comparison to global motion variances. Studies of increased complexities in virtual reality, including multiple interactions, such as immersion in a crowd, are limited by the need for computational performance. The maintenance of animation details such as foot placement accuracy, directional gaze, emotional state expressions and gender can be computationally cumbersome and thus negatively influence latency. A preservation of computational resources may be apropos the nature of global motion rather than the local details, e.g., foot placement.

Our results showed that task ability is not qualitatively impaired during interaction with global motion appearances: a three stage behavioural response is exhibited throughout all visual appearances that is also observed in paired human collision avoidance [Olivier2012]. Such an understanding poses prospects to future applications that should consider implementing embodied virtual characters with the three stages of avoidance, observation, reaction and regulation. Furthermore, within this work we observed no subjective preference to visual appearance. Our findings are in agreement with this subjective analysis. That is, appearance bore less importance; rather perceived action-opportunity within the optic array may be of greater importance. Thus, complex simulations should focus computation power towards the displacement of global motion and preserve energy costs associated to visual appearance. A standardised full body encompassing a global motion is sufficient. Finite details of foot placement, gaze, gender and emotional state are of lesser importance.

3.7 Conclusion

We have investigated a passive virtual character's motion with global only and local visual motion cues during an orthogonal collision avoidance task. Our findings showed that the nature of visual appearance indeed affected the final crossing distance. Global motion appearances of COG and cylinder were smaller and greater respectively from local motion appearances. Qualitatively all visual appearances reproduced similar motion adaptations. Participants anticipated future collisions through observation, reaction and regulation responses. Furthermore, visual appearance had no effect on the number of collisions or inversions of the crossing order. We associate the variance of crossing distance to the perceived action-opportunities of the walker, the afforded surface area of the virtual obstacle, rather than the visual appearance dichotomy of global and local information. In summary, global motion provides sufficient information for successful collision avoidance, however, local motion variants reproduce more accurate and repeatable responses.

Chapter 4

Influence of path curvature on collision avoidance behaviour

4.1 Objective and contributions

This study investigated the influence of a virtual walker's path for the accurate estimation of future potential collision detection between two walkers. Specifically, we investigated whether a curvilinear path influenced the timing and the avoidance behaviour between two walkers with respect to a rectilinear path. Humans interact in dynamic environments on a daily basis, responding to what each environment affords. For example, public and crowded spaces afford humans to regulate their interpersonal distances to avoid collisions. In the case of a pairwise collision avoidance interaction, the environment may afford to pass first (in front) or second (behind) of another walker, with or without collision avoidance. In the case of rectilinear trajectories, the collision avoidance behaviours have been extensively reported [Olivier2012, Olivier2013, Basili2013, Huber2014, Knorr2016, Olivier2017]. Further, it has been shown that the perceived action-opportunities of the walkers might be afforded based on a minimally predicted distance [Olivier2012, Olivier2013].

The Minimal Predicted Distance (*MPD*) linearly extrapolates instantaneous speed and orientation, which represents the closest predicted distance two walkers will pass if no adaptation is performed by either walker (i.e., based on constant speed and trajectory). Additionally, *MPD* quantifies the notion of *risk of collision*, where adaptations of *MPD* are observed when the future predicted crossing distance is below contact distance; a threshold of 1m was reported [Olivier2012]. Additionally, during the evolution of *MPD*, three distinct phases were identified: observation, reaction and regulation. These findings showed that for a rectilinear trajectory *MPD* may be used in the prediction of future risk of collision. When the risk is low, no avoidance behaviour is observed, however when the risk is high, avoidance behaviour is observed. However, in real conditions, humans do not always follow rectilinear trajectories at constant speeds. This raises two questions, first is whether or not a collision avoidance task with curvilinear trajectories can be as well performed, as previously shown for rectilinear trajectories. Second,

whether or not *MPD* is a pertinent affordance for a collision avoidance task with non-linear trajectories.

Figure 4.1 presents an example of linear extrapolation of a constant velocity during two different trajectories (5m and 10m). Within this figure, the red line presents the extrapolation of future crossing distance if the constant acceleration of the curve is accounted for. The blue and orange line represent the linear extrapolation for the respective 5 and 10m trajectories. In this example, the actual risk is that a collision will occur and the participant will pass second. However, the linear extrapolation suggests that the participant is initially predicted to cross first. Furthermore, the linear extrapolation does not predict a risk of collision when the trajectory is with a 5m radius. Therefore, if *MPD* is linearly extrapolated, it would be expected that participants will change their crossing order more frequently and collide more often.

The visual system has previously been shown as sensitive to directional changes of self-motion and object motion in both rectilinear and curvilinear paths [Bastin2006b, Bastin2008, Bosco2012, Delle Monache2015], and sensitive to the perception of speed but rather insensitive to acceleration [Watamaniuk2003, Zaal2012]. It has previously been shown that walkers' velocity can be prospectively controlled using a constant bearing angle strategy while intercepting a ball that follows a mediolateral trajectory along a 5m and 10m radius curve [Bastin2006b]. Prospective control uses continuous information for action regulation. In contrast, predictive control is an adaptive behaviour from an initial perceptual variable and the further updates of a stimulus do not effect the regulation of action [Katsumata2012]. It was further shown that the walkers' velocity was more affected by the curvature of a ball in flight than the manipulation of the rate of expansion [Bastin2008]. However, the works of Bastin *et al.* the ecological validity may have been affected as the walkers were constrained to a single axis of displacement. Moreover, participants performed an interception task, it is uncertain to what extent these findings apply to pedestrian navigation in collision avoidance task.

Experimentally manipulating the trajectory of a passive walker to follow a curvilinear path without a visual aid and to repeat the curvilinear path with a constant acceleration to ensure a constant velocity at the tangent of the curvilinear path in real life is difficult and reproducibility would be a limitation. Virtual reality is a novel approach that has previously been used to study locomotion and interactions [Bruneau2015, Lynch2017, Olivier2017] as it has been proven as a powerful tool for ecological perception and action research [Loomis1999]. Although virtual reality is not without limitation (see [Pan2018] for a review), behavioural responses observed in virtual reality conform to reality for goal-oriented locomotion tasks [Cirio2013], despite varying interactive methods [Olivier2017]. Additionally, regarding collision avoidance tasks, the preservation of personal space and similar avoidance behavioural responses have been reported [Gérin-Lajoie2008, Argelaguet-Sanz2015, Olivier2017]. Therefore, we have developed and performed the experiment in virtual reality.

This work aims to examine collision avoidance behaviour on curvilinear trajectories in virtual reality. Specifically, we address the question whether collision avoidance of walkers on curved trajectories is perturbed (i.e., wrong adaptations leading to a collision). Where it has been evidenced when the future distance of closest approach is below a 1m threshold of linear trajectories, walkers adapt their trajectory in anticipation of collision avoidance. In this setting, the prediction of future risk of collision follows the assumption of constant velocity. However, in the case of a curved trajectory, there is a constant acceleration to constantly change the direction, and it remains unclear whether this is accounted for in the prediction of future collisions (c.f., figure 4.1). Alternatively, when considering the nature of the curve, if indeed the collision avoidance behaviour is perturbed, behavioural responses may rely on visual cues such as, the orientation of the walker, with respect to the observer. Therefore an additional analysis of the walker's orientation would be of interest. We hypothesise that collision avoidance behaviour will indeed be perturbed by curvilinear trajectories, which would indicate that walkers use a linear extrapolation assuming constant velocity to anticipate future collisions.

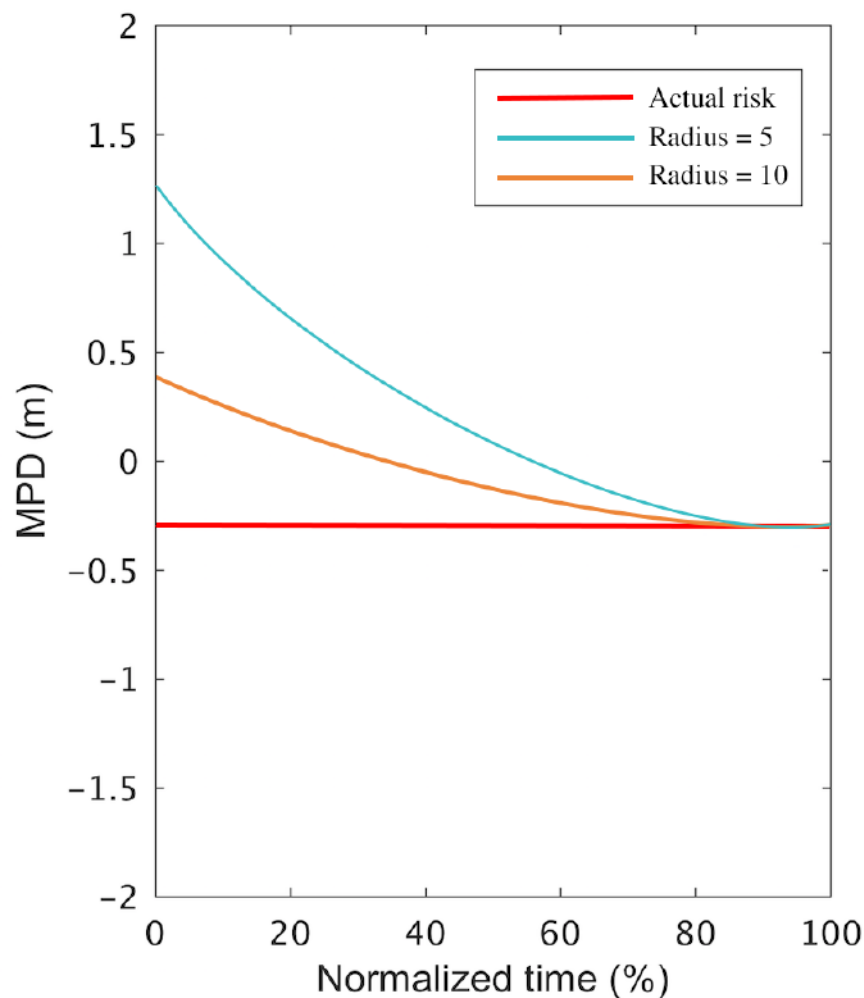


Figure 4.1 - An example of constant velocity *MPD* predicting future risk for curved trajectories. The blue line would be the extrapolation of a trajectory following a 5 m radius curve. The orange line would be the extrapolation of a trajectory following a 10 m radius curve. The red line indicates the actual progression of risk without adaptation. In this example, the actual risk is that a collision will occur and the participant will pass second. Linear extrapolation of *MPD* suggests the trajectory with a 5m curve has no initial predicted risk, and 10m does. Moreover, both linear extrapolations predict the participant to cross first, and the actual risk is that the participant will cross second.

4.2 Method

4.2.1 Participants

Twenty-two healthy university faculty and student members (13 males, 9 females), aged 27.59 ± 4.11 years (mean \pm SD) participated in this study. All participants had normal or corrected-to-normal vision and no history of disease or impairment which could have affected their ability of participation. Written informed consent form was obtained from all participants prior to experimentation and the study was in accordance with the standards of the Declaration of Helsinki.

4.2.2 Apparatus

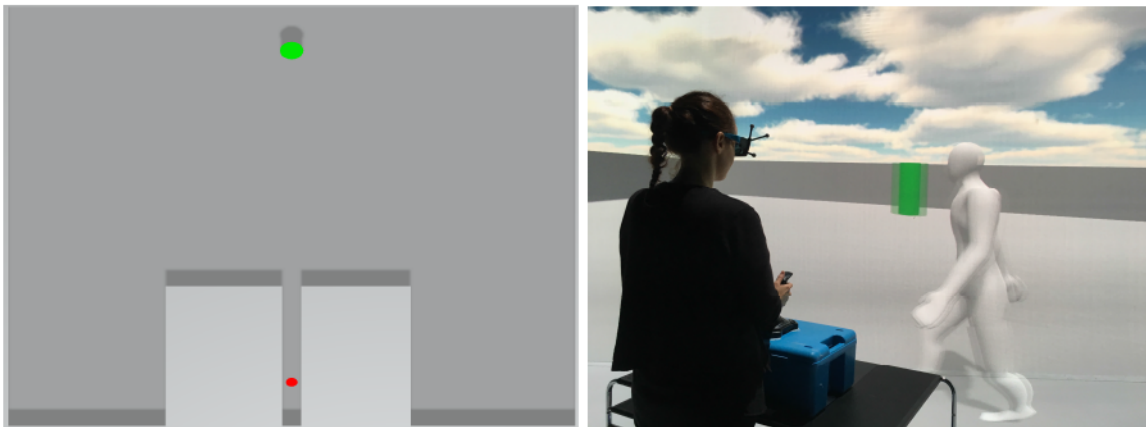


Figure 4.2 - Layout of the virtual environment: Left, a top-down view of the environment, the starting position is highlighted as a red point, the goal is highlighted by a green cylinder, and virtual walker was visible after exiting the corridor. The corridor served to block the view of the environment. Right, a third person perspective of a participant interacting with a virtual walker after exiting the corridor.

Experiments took place in a Computer Assisted Virtual Environment (CAVE), which was 12m wide, 4m high and 4m deep. It was equipped with 4 Christie Mirage 4K 3D projectors. 3D environment display and character animation (Figure 4.2) were designed in the Unity game engine. Multi-surface rendering was performed by the MiddleVR plugin. Active stereoscopy was achieved with Volfony ActiveEyes Pro Radiofrequency wearable glasses. Glasses were tracked by 6 Vicon Bonita cameras. A joystick was used by the participants to move in the virtual environment. The joystick functioned with a control law that was previously validated to study collision avoidance interactions between walkers [Olivier2017]. The neutral position of the joystick produced a baseline displacement of $1.4\text{m}\cdot\text{s}^{-1}$ with zero angular velocity, which resembles a typical normative walking speed [Bohannon1997]. Any action on the joystick thereafter produces an adaptation of the virtual trajectory. The longitudinal axis controlled speed linearly from $0.8\text{m}\cdot\text{s}^{-1}$ to $2.0\text{m}\cdot\text{s}^{-1}$, and the lateral axis controlled angular rotation speed linearly from $-25\text{deg}\cdot\text{s}^{-1}$ to $+25\text{deg}\cdot\text{s}^{-1}$.

4.2.3 Experimental setup

Participants began each trial from a starting position within a corridor, which prevented them from perceiving the virtual walker's starting position. As the participant exited the corridor, a virtual walker advanced from the right or left of the participant. We controlled the potential danger of the interaction to assess whether the radius of approach has an effect on the perception of the situation. To do this, displacing the virtual walker's starting position determined the risk of future collision at $MPD_{t_{see}}$, which is the instant the participant can first see the virtual walker [Olivier2012]. A total of four crossing distances were chosen in order to vary the risk of future collision: two high-risk distances (0 and 0.3m), an intermediary risk distance (0.6m) and a low-risk distance (0.9m). In the high-risk collisions, a collision occurred if the participant did not adapt their

trajectory. In the intermediary and low-risk distances, the participant did not necessarily have to adapt to avoid a collision. It is worth noting that at the intermediary distances humans have been observed to not adapt in human to human interactions; however, in human to robot and human to virtual (moving) obstacle interactions, humans tended to adapt and invert the crossing order [Vassallo2017, Lynch2017, Lynch2018]. Further, we regulated the initial crossing order: the virtual walker would cross either in front or behind the participant at these randomised distances (except for $MPD_{t_{see}} = 0\text{m}$). Finally, the virtual walker advanced using a fixed path trajectory, a total of three paths were chosen (Figure 4.3): two curvilinear paths with a fixed radius of 5m or 10m, and one control rectilinear path. The tangential velocity (i.e., the linear velocity along the curvature of the path) was set at $1.4 \text{ m}\cdot\text{s}^{-1}$, the same velocity as the participant's baseline velocity and the velocity of the virtual walkers on the linear trajectory. All the curved paths were signed negative (in-front) and positive (behind) for direction from where the virtual walker advanced:

- **N5** The virtual walker advanced from in front of the participant, approaching them, with a 5m radius curvilinear path.
- **N10** Similarly to N5, the virtual walker advanced from in front of the participant, approaching them, with a 10m radius curvilinear path.
- **P5** The virtual walker advanced from behind the participant, approaching them, with a 5m radius curvilinear path.
- **P10** Similarly to P5, the virtual walker advanced from in front of the participant, approaching them, with a 10m radius curvilinear path.
- **INF** Given an infinite radius the path of the virtual walker was rectilinear, a control condition. To balance the experimental conditions, INF was repeated twice, as per signed curve approach.

In total, each participant performed 168 trials ($6 \text{ paths} \times 7 \text{ MPD}_{t_{see}} \times 2 \text{ crossing sides (left-right)} \times 2 \text{ repetitions}$). All conditions and their repetitions were presented in a fully randomised order. Prior to experimental trials participants completed six familiarisation trials of randomised conditions, participants familiarised with the virtual walker's behaviour and their own motion adaptation capabilities of the joystick. The duration of the experiment per participant, including familiarisation and questionnaire completion was approximately one hour.

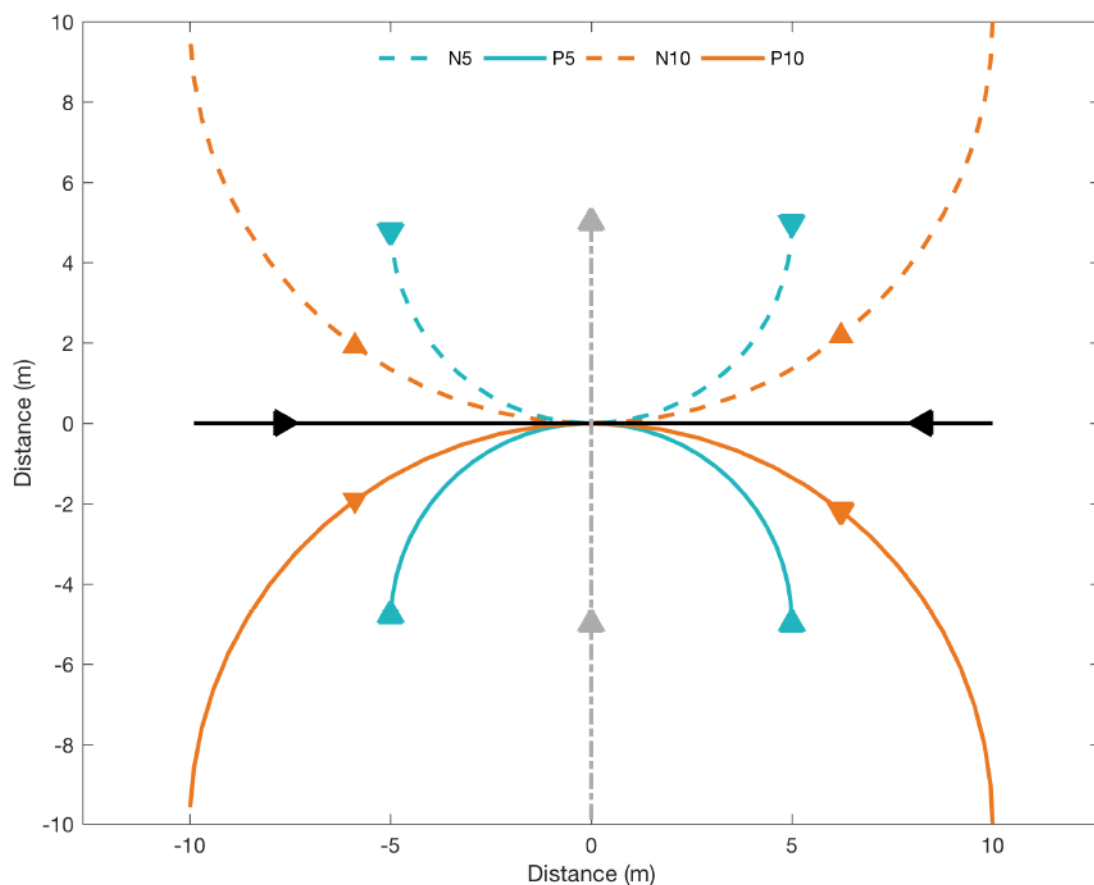


Figure 4.3 - Examples of the presented curves from the setup. The grey line is the hypothetical trajectory of the participant without adaptation, the black line is the rectilinear trajectory of the virtual walker, blue lines are the trajectories of the virtual walker with a 5m radius, orange curves are the trajectories of the virtual walker with a 10m radius. Solid lines are for trajectories from behind the participant, dashed lines are from in front. The virtual walker approached from left or right

4.2.4 Task

Participants were immersed in a virtual environment (Figure 4.2) and were instructed to stand at a designated location depicted in the immersive environment floor. The task was to navigate from their starting position (red circle), through the environment, using a joystick, to reach a goal (a green cylinder) at the opposite end of the 20m² virtual room.

Each participant was instructed to avoid potential collisions with the virtual walker that would appear in their path while advancing towards their goal. The virtual walker's trajectory was one of the randomly assigned paths (Figure 4.3) in combination with a randomly assigned risk of collision at $MPD_{t_{see}}$. To control the moment at which the participant could see the virtual walker we placed the participant in a corridor that occluded them from the environment (Figure 4.4). This allowed the participant to reach the baseline steady state speed of $1.4\text{m}\cdot\text{s}^{-1}$, which resembles a typical normative human walking speed [Bohannon1997]. Throughout experimentation, the virtual walker was passive, non-responsive with a constant tangential velocity ($1.4\text{m}\cdot\text{s}^{-1}$), following a predetermined path. Participants could adapt their speed and trajectory after exiting the corridor, the moment of $MPD_{t_{see}}$, using the joystick.

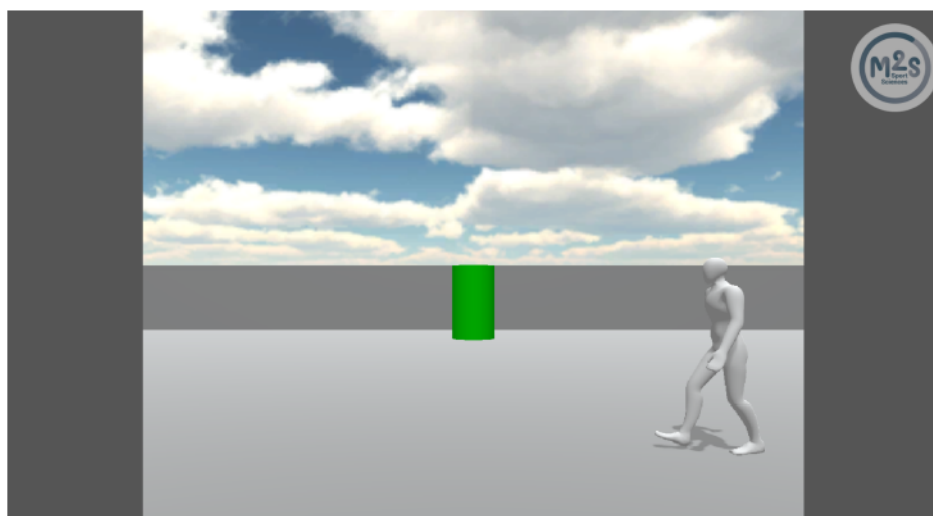


Figure 4.4 - Participant's perspective while exiting the occluding corridor

4.2.5 Questionnaire

We collected demographic information and measured simulator sickness with the Kennedy-Lane SSQ questionnaire [Kennedy1993] before and after the experiment. At the end of each block, participants filled out a subjective questionnaire. Participants answered the following questions using a 7-point Likert scale from 1 (strongly disagree) to 7 (strongly agree).

- ▶ I am satisfied with the ease of completing this task
- ▶ I am satisfied with the support information when completing this task
- ▶ The virtual obstacle motion was natural
- ▶ The interaction with the virtual obstacle was natural

4.2.6 Data analysis

Trajectories of the participant and virtual walker were recorded from the moment the participant could see the virtual walker ($MPD_{t_{see}}$). The post-processing of the interaction response of the participant was performed using customised MATLAB scripts (Mathworks 2016b). Using trajectory and velocity of both participant and virtual walker, we calculated minimal crossing distance, inversion of crossing order and collisions, if any. Where minimal crossing distance was defined as the shortest distance between participant and virtual walker centres, crossing order was classified as the participant passing the virtual walker as first or second, and an inversion would be when the initial order was altered by the participant as part of their collision avoidance strategy. A collision was defined when minimal crossing distance was less than 50 cm, which was the sum of both participant and virtual walkers radii. We also computed MPD evolution in time throughout each trial. Rectilinear R_{MPD} was calculated using the method of [Olivier2012], and curvilinear C_{MPD} was computed based on the following extrapolation of virtual walker position:

$$VW_x = C_x + r * \cos(t * \dot{\theta} + \theta_{start})$$

$$VW_y = C_y + r * \sin(t * \dot{\theta} + \theta_{start})$$

The future x and y positions of the virtual walker were derived from the fixed curvilinear centre (C), the radial distance r of the curve, and the trigonometric multiplication of the angular velocity from the initial starting angle with respect to time. Both R_{MPD} and C_{MPD} make a prediction of the future distance of approach between walkers, where the equation of C_{MPD} considers the constant acceleration in the prediction of future position. Thus, C_{MPD} makes an accurate prediction whereas R_{MPD} would be inaccurate by neglecting the acceleration, instead assuming the velocity is constant. The evolution of MPD was normalised to the period of interaction, that is, from the instant that the participant could see the virtual walker, MPD_{tsee} (0%), to the instant of crossing, MPD_{tcross} (100%).

Previously, it has been shown that the evolution of MPD has three distinct phases during the interaction [Olivier2012]: a stage where MPD is constant (observation), a stage where an adaptation is made to increase MPD (reaction), and a final stage where the MPD is constant or decreases slightly before crossing (regulation). To characterise the evolution of MPD and different events during the interaction phase, we computed the reaction time at the instant between MPD_{tsee} and the first instant when the absolute MPD difference was greater than 0.15m. Further, to minimise potential errors in reaction time detection, we used an absolute difference that persisted for 1.5s; removing possible incorrect spike detection. In trials where a reaction time was recorded at the instant MPD_{tsee} or sooner were excluded from further analysis as this suggests the participant attempted adaptation prior to MPD_{tsee} . Additionally, we computed the regulation stage with the same thresholds in reverse from MPD_{tcross} ; the first instant MPD was within the 0.15m threshold of MPD_{tcross} . Given the instant of reaction and regulation, we could then determine whether the onset of these specific stages vary as

a consequence of the path of the virtual walker. Finally, we re-sampled the time during the interaction between $MPD_{t_{see}}$ and $MPD_{t_{cross}}$.

Considering the variance of visual information from the virtual walker in relation to the nature of the curve we computed the orientation angle of the virtual walker relative to the participant. Specifically, we computed the angle of the participant's relative position to the virtual walker's tangential velocity vector (Figure 4.5). From these angles, we can then infer the amount of visual information the participant can perceive. For example, in a rectilinear setting, if the virtual walker passes directly in front of the participant, at the instant of intersection the orientation angle would be 90° .

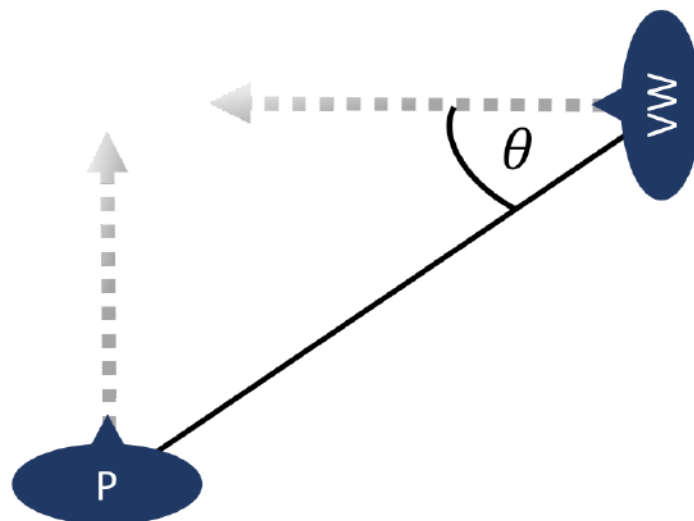


Figure 4.5 - Orientation angle of the virtual walker (VH) with respect to the participant (P)

4.2.7 Statistics

We set the level of significance to $\alpha = 0.05$. A Kolomogorov-Smirnov test was performed to evaluate whether the data was normally distributed. The dependent variables were: final crossing distance, number of collisions, number of inversions, reaction time, regulation time, and the virtual walker's orientation at time of reaction and time of regulation. We evaluated the effect of path type and initial $MPD_{t_{see}}$ on these dependent variables. A Friedman non-parametric test and post-hoc Wilcoxon signed ranked test with a Bonferroni correction was used for the number of collisions and inversions variables. Further, a repeated measures ANOVA with a Bonferroni post-hoc test was used for crossing distance, reaction time, regulation time and the respective orientation angles of the virtual walker. Reported significance values are the Bonferroni corrected p values. We compared the evolution of MPD of each of the curvilinear paths to the rectilinear control condition using statistical parametric mapping (SPM) [Friston2007]. With the SPM analysis, time-series data of different trials can be compared taking the variability at each time-step into account. Finally, the distribution of questionnaire responses were analysed using a Friedman non-parametric test with regards to the perception of immersion, interaction with the virtual obstacle and ability of task completion.

4.3 Results

4.3.1 Collisions

A collision occurred in 79 (out of 3501) trials (Table 4.1); of the 79 collision trials, there was a significant effect of virtual walker path on the percent of number of collision trials ($\chi^2(4)=20.737$, $p<0.001$). Post-hoc analysis showed there were more collisions in the P5 condition than INF ($Z = 3.117$, $p=0.02$) and N10 ($Z = 2.834$, $p=0.05$). Additionally, post-hoc analysis showed INF and P10 trended towards a difference, but was not significant ($Z = 2.674$, $p=0.07$). No further significant effects of virtual walker path on the percentage of the number of collisions were observed. Collisions occurred in all initial risk conditions except when crossing second at *MPD* -0.9m, there was no significant effect of the distribution of collisions per *MPD* ($p>0.05$).

Path	mean \pm SD (%)	lower (%)	median (%)	upper quartile (%)
INF	0.74 \pm 1.90	0	0	0
P10	3.15 \pm 4.69	0	0	4.56
N10	0.49 \pm 1.67	0	0	0
P5	5.17 \pm 6.16	0	3.64	7.14
N5	2.97 \pm 5.26	0	0	5.05

Table 4.1 - Percentages of the number of collisions as a function of virtual walker path.

4.3.2 Crossing order

340 inversions occurred out of 3501 trials, there was a significant overall effect of virtual walker path on the percentage of inversion of crossing order ($\chi^2(4)=17.634$, $p=0.001$). Post-hoc analysis showed that there were more inversions in condition N5 (17.86%) than INF (3.60%, $Z = 2.972$, $p=0.03$) and N10 (8.05%, $Z = 3.458$, $p=0.01$). Additionally, post-hoc analysis showed P5 (8.25%) and N5 trended towards a difference, but was not significant ($Z = 2.652$, $p=0.08$). No further effects were observed for virtual walker path (Figure 4.6). The distribution of inversions was not significantly different as a function of initial risk of collision ($p>0.05$).

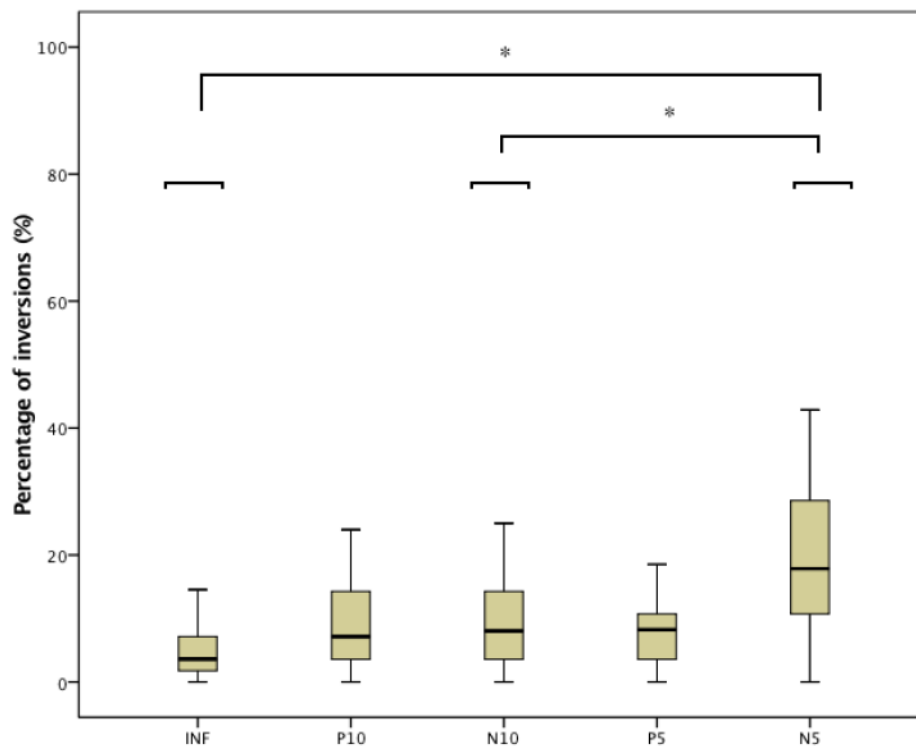


Figure 4.6 - Percentage of the number of inversions recorded while crossing paths with a virtual walker

4.3.3 MPD evolution

From the SPM comparisons (Figure 4.7), we can visually observe a qualitatively similar curve shape throughout the evolution of MPD . Each subplot is structured with the mean R_{MPD} as a blue dashed line and a blue standard deviation cloud. Thereafter, R_{MPD} is compared to C_{MPD} , the mean depicted as a red solid line and a red standard deviation cloud. Any significant differences during the evolution of normalised MPD between R_{MPD} and C_{MPD} are highlighted by the first instance of significance (green vertical line) and the terminus of significance (red vertical line). Quantitatively, only curvilinear conditions with a radius of 5m showed significant differences from rectilinear MPD ($p < 0.05$). The C_{MPD} for P5 and N5 in comparison to R_{MPD} showed significant differences starting from 39% and 46% of normalised time, respectively. These significant differences terminated at 65% and 100%, respectively. Additionally, the gradient of the slope for all C_{MPD} conditions was observably less than the control R_{MPD} .

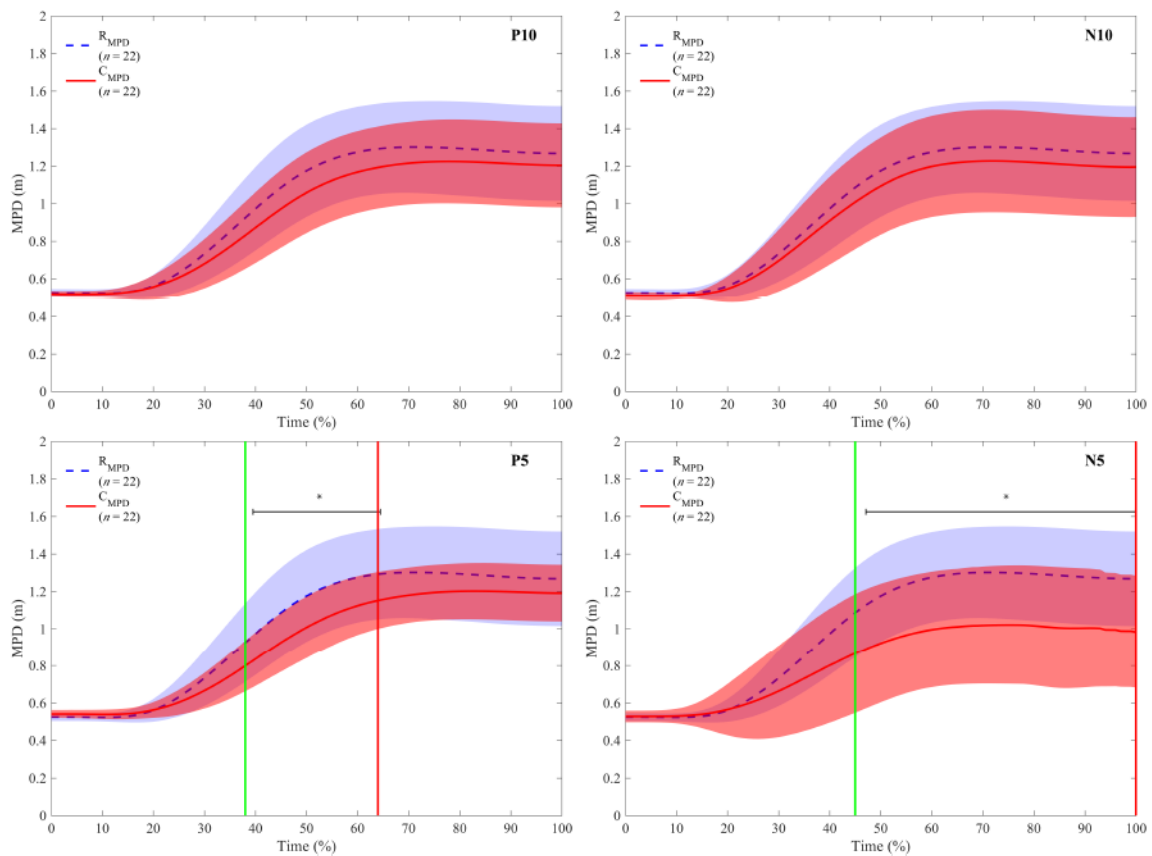


Figure 4.7 - SPM evolution analysis of normalised R_{MPD} and C_{MPD} , comparing the evolution of R_{MPD} with C_{MPD} of N10 (top left), N5 (top right), P10 (bottom left), and P5 (bottom right).

4.3.3.1 Timing

The overall duration of the interaction showed no significant effect of curve, conditions INF (3.15 ± 0.21 s), P10 (3.12 ± 0.20 s), N10 (3.13 ± 0.27 s), P5 (3.10 ± 0.19 s), and N5 (3.18 ± 0.33 s) were not significantly different from each other ($p > 0.05$). When considering specific timing of events during the interaction, we observed a significant main effect of the crossing order on reaction time after observation ($F(1,21) = 16.73$, $p = 0.001$, $\eta_p^2 = 0.443$); participants reacted later when crossing first (0.87 ± 0.33 s) than second (0.68 ± 0.18 s, $p < 0.001$). Additionally, we observed a main effect of the path curve on reaction time ($F(2.5,52.51) = 10.05$, $p < 0.001$, $\eta_p^2 = 0.324$). Post-hoc analysis showed that reaction time was longer in the P5 condition (0.87 ± 0.35 s) than INF (0.74 ± 0.24 s, $p = 0.001$), P10 (0.75 ± 0.31 s, $p = 0.001$) and N10 (0.73 ± 0.23 s, $p < 0.001$). Additionally, the reaction times in the N10 condition were significantly shorter than N5 (0.78 ± 0.24 s, $p = 0.020$). We observed a significant interaction between the reaction times of crossing order and path ($F(2.9,61.33) = 5.40$, $p = 0.003$, $\eta_p^2 = 0.204$); the interaction is presented in figure 4.8 with path main effects indicated. This interaction suggested that the effect of crossing order was more pronounced in P5 with a difference of 0.31s between means and less pronounced in N5 with a difference of 0.12s. Later in the interaction we did not observe a significant main effect of the crossing order at the instance of regulation ($p = 0.186$). There was a main effect of the path on regulation time ($F(1.92,40.28) = 9.75$, $p < 0.001$, $\eta_p^2 = 0.317$), where post-hoc analysis showed that in the N5 condition (2.49 ± 0.42 s) the regulation time was significantly longer than INF (2.28 ± 0.28 s, $p = 0.010$), P10 (2.29 ± 0.30 s, $p = 0.019$), N10 (2.36 ± 0.30 s, $p = 0.046$) and P5 (2.28 ± 0.28 s, $p = 0.025$). Further there were no differences (Figure 4.9). We did not observe an interaction between the regulation times of crossing order and path ($p = 0.348$).

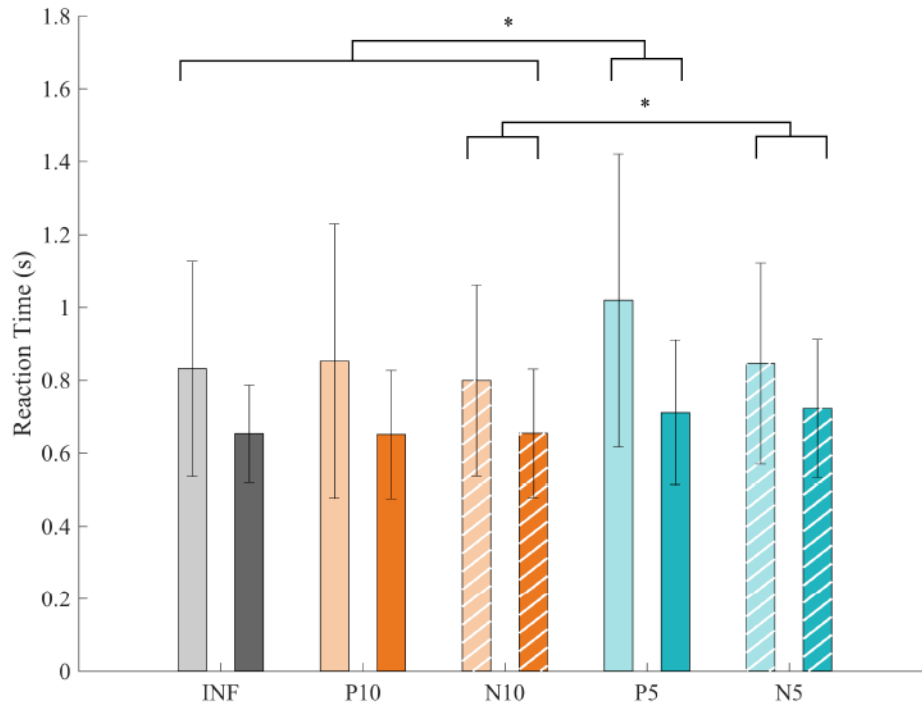


Figure 4.8 - Interaction effect between curve and crossing order on Reaction time. We plotted the reaction times per crossing order per curve for observational insight of the significant interaction between crossing order and curve. The control (INF) is grey, orange bars refer to curves with a 10 m radius, blue bars refer to curves with a 5m radius, filled bars are approaches from behind and striped bars are approaches from in front (c.f., figure 4.3). Lighter shaded bars are when the participant crossed first and darker bars are when the participant crossed second. Branched connections group and indicate main effects of curve types.

With respect to the *MPD*, we did not observe a main effect of the crossing order on *MPD* at the time of reaction ($p=0.080$). Additionally, we did not observe a main effect of the path on *MPD* at the time of reaction ($p=0.558$). We observed a significant interaction between the *MPD* at reaction time of crossing order and path ($F(2.48,52.11) = 181.10$, $p < 0.001$, $\eta_p^2 = 0.896$). This interaction suggested that the effect of crossing order was dependent of virtual walker direction of approach, a larger effect was observed when the participant either crossed first and the virtual walker approached from behind or the participant passed second when the virtual walker approached from in front (Figure 4.10). Further, with respect to *MPD* at regulation time, we did not observe a main effect of the crossing order ($p=0.369$). We observed a main effect of the path on *MPD* at the time of reaction ($F(2.40,50.31) = 6.11$, $p = 0.003$, $\eta_p^2 =$

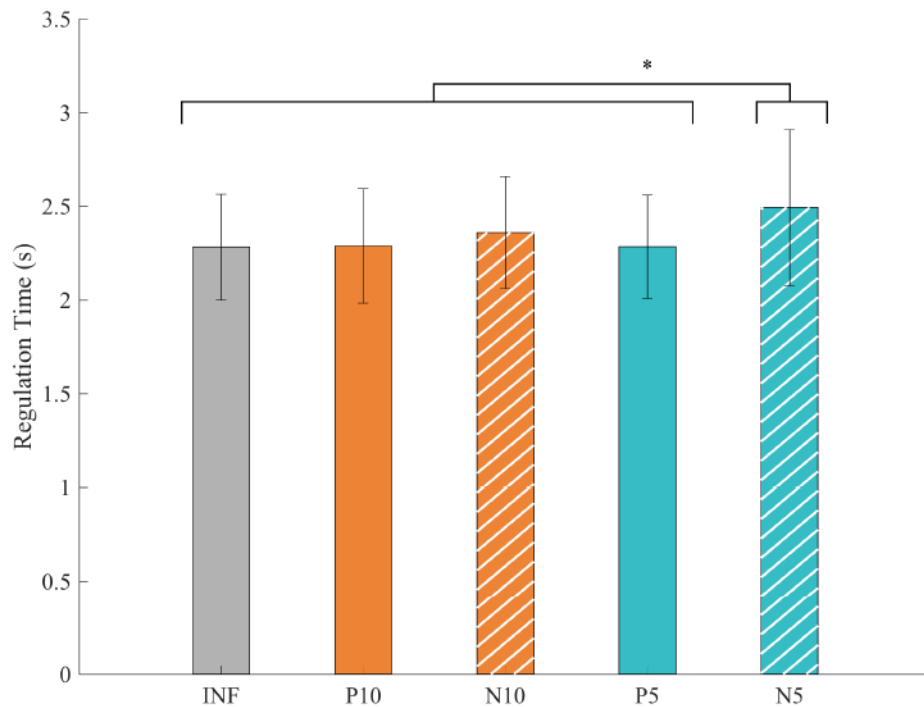


Figure 4.9 - Main effect of curve on mean (\pm SD) regulation time. Branched connections group and indicate main effects of curve types.

0.225). Post-hoc analysis showed that P5 ($1.29 \pm 0.32m$) was significantly lesser than INF ($1.38 \pm 0.27m$, $p=0.008$), P10 ($1.37 \pm 0.31m$, $p=0.004$) and N10 ($1.39 \pm 0.32m$, $p=0.049$). There were no further reported differences of the *MPD* at the first instance of regulation ($p>0.05$). Finally, we observed a significant interaction between the *MPD* at regulation time of crossing order and path ($F(2.48, 52.11) = 181.10$, $p < 0.001$, $\eta_p^2 = 0.896$); the interaction is presented in figure 4.10 with path main effects indicated. Similarly, this interaction suggested that the effect of crossing order was dependent of virtual walker direction of approach, a larger effect was observed when the participant either crossed first and the virtual walker approached from behind or the participant passed second when the virtual walker approached from in front.

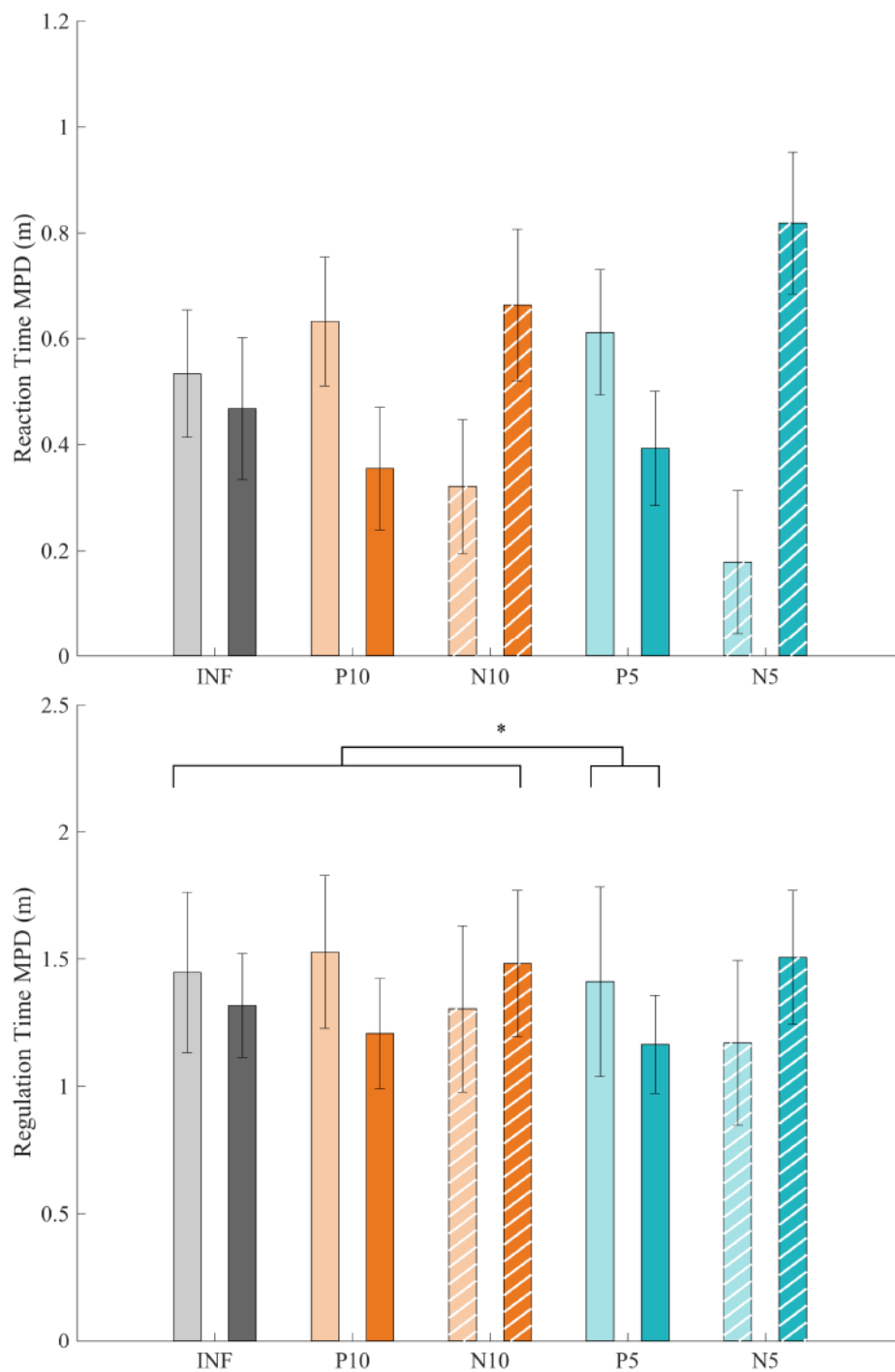


Figure 4.10 - Interaction effect between curve and crossing order on *MPD* at reaction time (top) and at regulation time (bottom). Interaction effects were plotted per crossing order per curve for observational insight of the significant interaction between crossing order and curve. The control (INF) is grey, orange bars refer to curves with a 10 m radius, blue bars refer to curves with a 5m radius, filled bars are approaches from behind and striped bars are approaches from in front (c.f., figure 4.3). Lighter shaded bars are when the participant crossed first and darker bars are when the participant crossed second. Branched connections group and indicate main effects of curve types

4.3.4 Crossing distance

From the total number of 3501 trials, 43 trials showed no adaptation that is MPD_{tcross} did not differ from MPD_{tsee} . For the remaining trials, there was an avoidance behaviour, the distance at crossing was greater than MPD_{tsee} . We did not observe a significant main effect of the crossing order on the final crossing distance ($p = 0.477$). However, we observed a main effect of the path curve on the final crossing distance ($F(1.94, 40.66) = 5.87$, $p = 0.006$, $\eta_p^2 = 0.218$). Post-hoc analysis showed that P5 ($1.27 \pm 0.33m$) was significantly smaller than INF ($1.37 \pm 0.27m$, $p=0.004$), P10 ($1.35 \pm 0.31m$, $p=0.002$) and N10 ($1.38 \pm 0.32m$, $p=0.032$). Further there was no significant differences of virtual walker path on final crossing distance ($p>0.05$). Further, we observed a significant interaction between the final crossing distance of crossing order and path ($F(2.08, 43.74) = 95.84$, $p < 0.001$, $\eta_p^2 = 0.204$); the interaction is presented in figure 4.11 with path main effects indicated. This interaction suggested that the effect of crossing order was dependent of virtual walker direction of approach, a larger effect was observed when the participant either crossed first and the virtual walker approached from behind or the participant passed second when the virtual walker approached from in front. We further examined the variability of virtual walker path on final crossing distance. The Friedman test reported there was no significant effect of virtual walker path on final crossing distance variability ($\chi^2(4)=6.309$, $p=0.177$): INF (0.38m), P10 (0.39m), N10 (0.32m), P5 (0.33m), and N5 (0.35m).

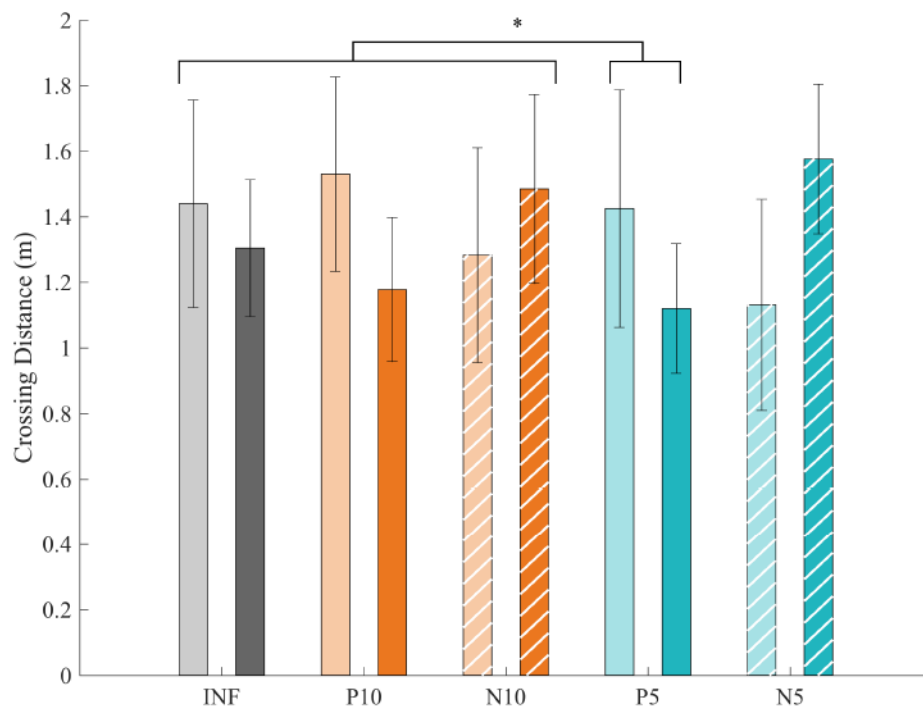


Figure 4.11 - Interaction effect between curve and crossing order on final crossing distance. Interaction effects were plotted per crossing order per curve for observational insight of the significant interaction between crossing order and curve. The control (INF) is grey, orange bars refer to curves with a 10 m radius, blue bars refer to curves with a 5m radius, filled bars are approaches from behind and striped bars are approaches from in front (c.f., figure 4.3). Lighter shaded bars are when the participant crossed first and darker bars are when the participant crossed second. Branched connections group and indicate main effects of curve types

4.3.5 Orientation angle

We considered the orientation of the virtual walker at both reaction and regulation timed events, we observed a main effect of crossing order on the angle at reaction time ($F(1,21) = 1204.11$, $p < 0.001$, $\eta_p^2 = 0.983$). The angle at reaction time was significantly smaller when crossing first ($39.18 \pm 19.78^\circ$) than crossing second ($52.35 \pm 16.81^\circ$, $p < 0.001$). Additionally, we observed a main effect of path on the angle at reaction time ($F(1.17,24.64) = 1242.55$, $p < 0.001$, $\eta_p^2 = 0.983$). Where post-hoc analysis revealed all conditions were significantly different from each other ($p < 0.001$). Furthermore, we observed an interaction between crossing order and path on the angle at reaction time ($F(1.53,32.18) = 25.51$, $p < 0.001$, $\eta_p^2 = 0.548$); the interaction is presented in figure 4.12 with path main effects indicated. This interaction suggested that the effect of crossing order was more pronounced in N10 and N5 with a difference of 14.65° and 18.37° , respectively.

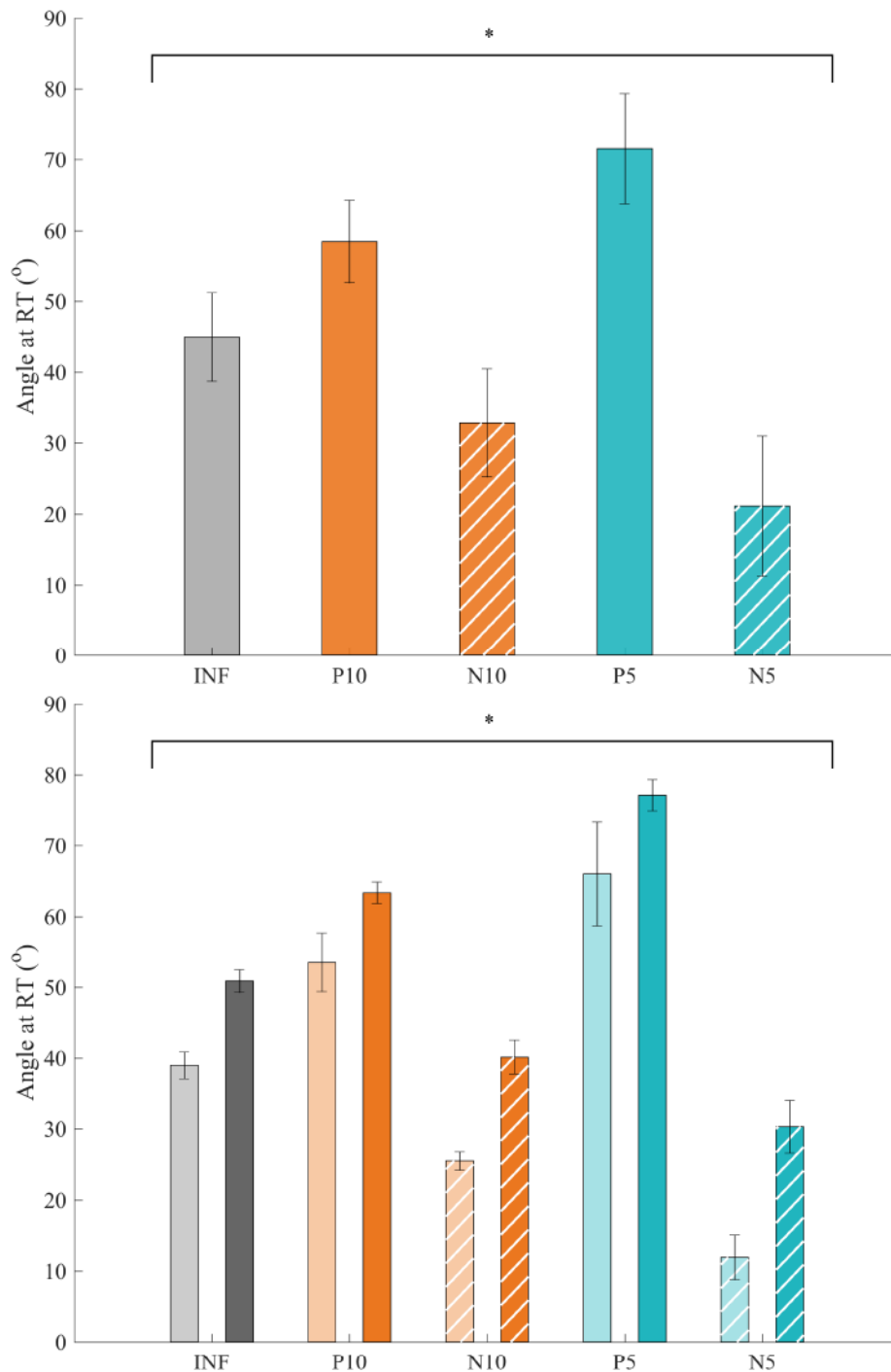


Figure 4.12 - Main effect of curve on angle at reaction time (top), and interaction effect between curve and crossing order on angle at reaction time (bottom). The control (INF) is grey, orange bars refer to curves with a 10 m radius, blue bars refer to curves with a 5m radius, filled bars are approaches from behind and striped bars are approaches from in front (c.f., figure 4.3). Lighter shaded bars are when the participant crossed first and darker bars are when the participant crossed second. Branched connections group and indicate main effects of curve types

We normalised the angles at reaction time with the mean angle of the control trial (INF, 45°) from the observed main effects of path. The main effect of crossing order was still observed ($F(1, 21) = 43.13$, $p < 0.001$, $\eta_p^2 = 0.673$), further the main effect of path was observed ($F(1.92, 40.31) = 263.17$, $p < 0.001$, $\eta_p^2 = 0.926$). Post-hoc analysis showed that the absolute normalised angle was greater when crossing first ($17.62 \pm 10.58^\circ$) than when crossing second ($15.19 \pm 10.22^\circ$). Additionally, the absolute normalised angles in the P10 ($13.43 \pm 5.83^\circ$) and N10 ($-12.20 \pm 7.63^\circ$) conditions were not significantly different ($p > 0.05$), while the INF ($5.94 \pm 1.74^\circ$), P5 ($26.56 \pm 7.78^\circ$) and N5 ($-23.90 \pm 9.89^\circ$) conditions were significantly different from each other and from the P10 and N10 conditions ($p < 0.001$); the difference between conditions P5 and N5 was close to the set alpha ($p = 0.049$). Finally, we observed an interaction between the crossing order and path on the normalised angle at reaction time ($F(1.96, 41.09) = 319.94$, $p < 0.001$, $\eta_p^2 = 0.938$); the interaction is presented in figure 4.13 with path main effects indicated. This interaction suggested that the effect of crossing order was dependent of virtual walker direction of approach, further, the size of the effect of crossing order was more pronounced for N10 (14.63° difference) and N5 (18.37° difference).

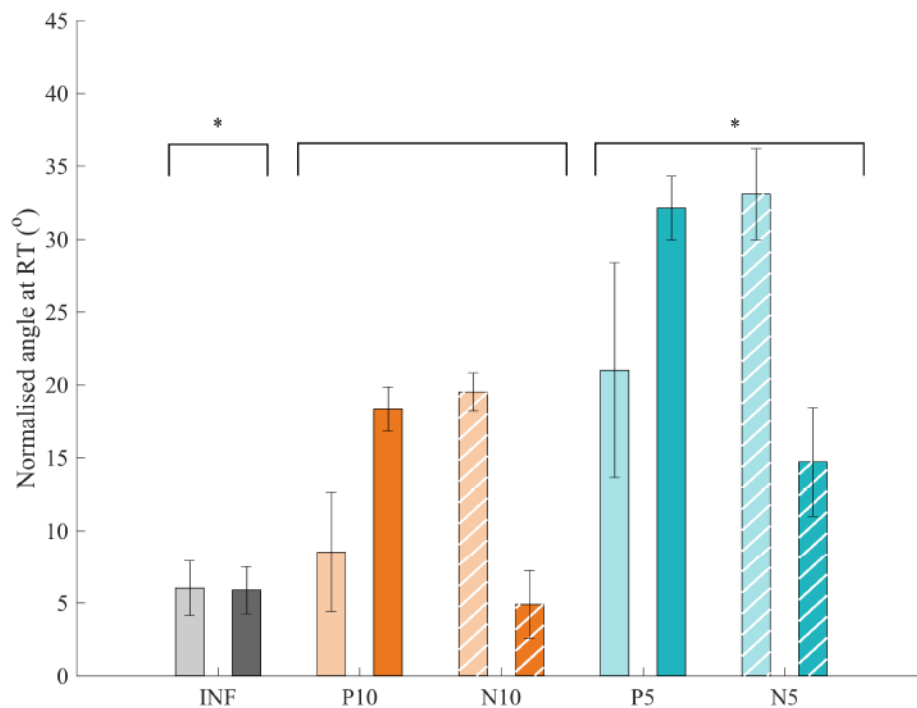


Figure 4.13 - Interaction effect between curve and crossing order on the normalised angle at reaction time. The control (INF) is grey, orange bars refer to curves with a 10 m radius, blue bars refer to curves with a 5m radius, filled bars are approaches from behind and striped bars are approaches from in front (c.f., figure 4.3). Lighter shaded bars are when the participant crossed first and darker bars are when the participant crossed second. Branched connections group and indicate main effects of curve types

When considering the angle at regulation time, we observed a main effect of crossing order on the angle at regulation time ($F(1,21) = 1100.25$, $p < 0.001$, $\eta_p^2 = 0.981$). The angle at regulation time was significantly smaller when crossing first ($22.30 \pm 7.54^\circ$) than crossing second ($80.98 \pm 12.35^\circ$, $p < 0.001$). Additionally, we observed a main effect of path on the angle at regulation time ($F(1.49,31.37) = 3.73$, $p = 0.047$, $\eta_p^2 = 0.151$). Post-hoc analysis showed that INF ($49.52 \pm 29.00^\circ$) was significantly smaller than P10 ($51.23 \pm 27.47^\circ$, $p = 0.006$) and P5 ($55.10 \pm 26.51^\circ$, $p < 0.001$), further, P5 was significantly larger than P10 ($p < 0.001$) and N10 ($50.22 \pm 32.81^\circ$, $p = 0.004$). There were no further significant differences. Finally, we observed an interaction between the crossing order and path on the angle at regulation time ($F(1.82,38.21) = 13.37$, $p < 0.001$, $\eta_p^2 = 0.389$); the interaction is presented in figure 4.14 with path main effects indicated. This interaction suggested that the effect of crossing order was more pronounced by the larger differences between crossing first and crossing second for P5 (62.52°) and N5 (72.22°).

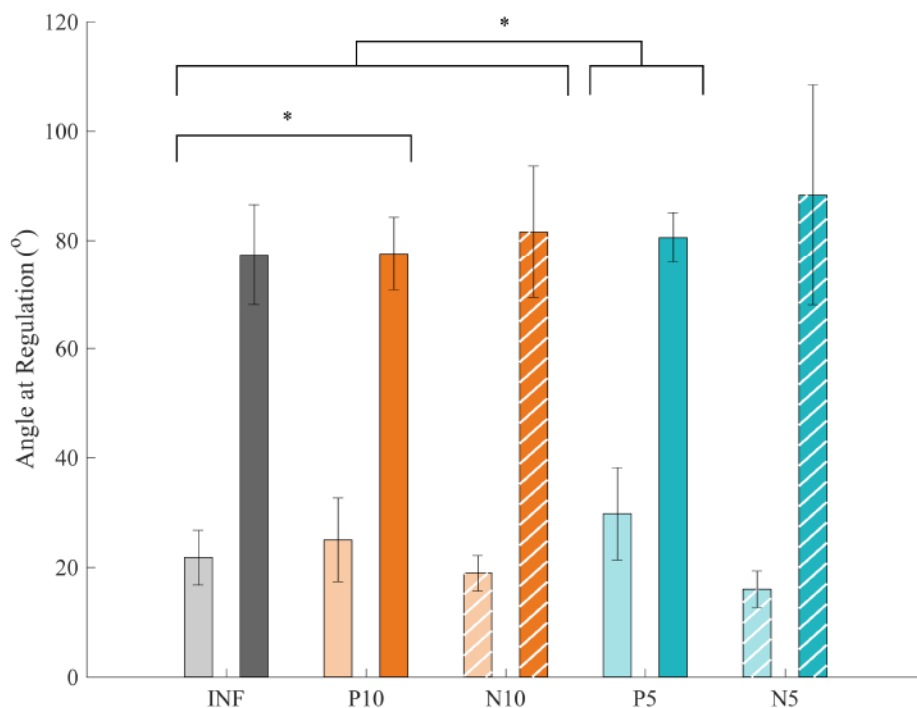


Figure 4.14 - Main effect of curve on angle reaction time. Branched connections group and indicate main effects of curve types

4.3.6 Questionnaires

There were no reported cases of motion sickness from the Kennedy-Lane questionnaire from pre- and post-immersion. Additionally, there was no significant effect of virtual walker path on the distribution of response with regard to the questions concerning motion, interaction, ease of the task and information availability ($p>0.05$). Open question responses about the interaction with the virtual walker and what may have been the variables or research questions involved in the study included comments of: the ability in the detection of collisions, the relation between the participant and the virtual walker trajectories, reaction timing, the duration of interaction, the acceleration of the virtual walker, participant adaptation behaviour, and the trajectory of the virtual walker.

4.4 Discussion

The present study aimed to examine collision avoidance behaviour while interacting with a virtual walker that had a constant acceleration and produced a curvilinear trajectory in comparison with a rectilinear trajectory with constant speed. We designed a collision avoidance task within virtual reality, using a rectilinear trajectory, similar to previous studies [Olivier2012, Olivier2013, Basili2013, Olivier2017], as a control situation. Further, we focused on curvilinear trajectories that intersected the path of the participant perpendicularly, as an initial study of curvilinear trajectories on collision avoidance behaviour we used trajectories with a fixed radius. To this end, we evaluated the influence of curvilinear trajectories on the adaptation behaviour and specific event timing, our analysis focused on the minimal predicted distance of closest approach between two walkers.

4.4.1 Qualitative motion adaptation

Interactions with all virtual walker paths, both rectilinear and curvilinear, led to qualitatively similar motion adaptations. Out of 3501 possible trials, an adaptation occurred in almost all trials. For each condition of virtual walker path, the collision avoidance behaviour of the participant presented three distinct phases of interaction: observation, reaction, and regulation. Observation infers that the participants were perceiving the virtual walker but not acting on the presented visual information. During the reaction stage, the participants modified their own trajectory, increasing their predicted future crossing distance of closest approach with the virtual walker to allow a safe crossing. Once the future crossing distance of closest approach had been obtained the participants began the regulation stage, maintaining the predicted distance

or decreasing it slightly until safe passage. These findings are similar to those observed between two walkers having linear trajectories in reality [Olivier2012, Olivier2013], between a walker and a wheeled robot [Vassallo2017, Vassallo2018], and in virtual reality [Olivier2017, Lynch2017, Lynch2018]. These findings suggest, while interacting with a virtual walker with a constant acceleration or with no acceleration, the collision avoidance strategy is globally similar. The perceived action-opportunities afforded by future predicted crossing distance are observed, an adaptation is necessarily made and the task is anticipated with the regulation of *MPD*.

4.4.2 Quantitative motion adaptation

Crossing distance. Our results showed a main effect of virtual walker path on the final crossing distance; the P5 condition (1.27 ± 0.33 m) had a significantly smaller final crossing distance than INF (1.37 ± 0.27 m), P10 (1.35 ± 0.31 m) and N10 (1.38 ± 0.32 m). We additionally considered the variability of the final crossing distance, if a condition was difficult to perceive the expected variability would have been larger. However, we observed no significant differences of virtual walker path on final crossing distance variability.

The final crossing distances reported here are larger than those previously reported in virtual reality [Olivier2017, Lynch2017, Lynch2018] and further larger than those observed in reality [Olivier2012, Vassallo2017, Vassallo2018]. When comparing our control trial experimental setup to those previously reported, we may hypothesise that the corridor, which was used for occlusion purposes in this study, may have influenced the avoidance behaviour. These findings further support that participants perceived the differences of virtual walker path and successfully adapted their trajectories to avoid collisions. Indeed, the final crossing distance of P5 was significantly smaller than INF, P10 and N10. However this distance did not result in a collision. Overall there were

few collisions reported, from the total number of collisions the P5 condition reported significantly more than INF. From these findings, we can summarise that when the virtual walker follows a curvilinear trajectory with a 5 m radius and approaches from behind the participant, the overall avoidance behaviour produces a smaller crossing distance and an increased probability of a collision. We may hypothesise that for the P5 condition participants may have required more time to perceive the task or conversely, perceived the task was solved sooner, and potentially incorrectly. Our analysis included the evolution of *MPD* and the timing of specific events during the interaction, thus we discuss the direction of this observed effect later.

Crossing order inversions. When considering inversions of the initial crossing order, our results showed an effect of path. Similar to investigations involving a wheeled robot [Vassallo2017] and within virtual reality [Lynch2017], we observed inversions ranging from 3% to 20%. From our results, INF had the least reported number of inversions and was similar to previous studies [Lynch2017], whereas N5 had the greatest number of inversions.

In a rectilinear setting between two walkers in real life, no inversion has been reported [Olivier2012, Olivier2013], the crossing order that was present at $MPD_{t_{see}}$ was maintained by both walkers. The role of an inversion was previously interpreted as an extreme behavioural response for the preservation of personal space from physical danger as it is inefficient in terms of energy [Vassallo2017], however ecological studies through virtual reality reduces the physical danger. Therefore, the inversion of crossing order was later attributed to the underpinning nonverbal social communication cues that may aide the maintenance of crossing order after $MPD_{t_{see}}$ [Lynch2017]. The number of inversions were later reduced when walkers interacted with a wheeled robot that collaborated in the collision avoidance task [Vassallo2018]. Although, these findings were not reproduced for virtual walkers that collaborated in the task with and without gazing behaviour [Lynch2018].

Our results had a similar range of inversions to those previously reported [Lynch2017], the presence of inversions in our study and their agreement to previous studies evidences the accuracy of perceiving the situation. Further, the reported number of inversions between conditions INF, P10, N10 and P5 suggests that crossing orders in these conditions were easily perceived and afforded similar avoidance behaviours. However, condition N5 had significantly more inversions. This result suggests that participants either more easily perceived the trajectory and adopted an avoidance behaviour as to pass behind the virtual walker, or they required a longer duration to perceive and adapt to the virtual walker's trajectory to ensure safe passage. We further detail and discuss the timing of events during the interaction in the following sections.

MPD evolution. We compared the evolution of R_{MPD} and C_{MPD} over normalised time, which was the interaction stage of the collision avoidance task between $MPD_{t_{see}}$ and $MPD_{t_{cross}}$. For this analysis, the limited number of trials that reported a collision or an inversion were excluded, where generally a trial with a collision or an inversion suggests that the characteristics of the interaction were not well perceived. Where this analysis was to specifically compare the pertinence and evolution of MPD for successful trials only. The evolution of C_{MPD} showed significant differences for paths with a radius of 5 m when compared to R_{MPD} . The C_{MPD} for P5 was significantly different from R_{MPD} after 39% of the interaction normalised time, participants adapted their trajectory that resulted in a less gradual increase of C_{MPD} . The observed difference was no longer present after 65% of the normalised time. Additionally, the C_{MPD} for N5 was significantly different from R_{MPD} after 46% of normalised time. Participants followed a trajectory that resulted in a less gradual increase of C_{MPD} than R_{MPD} , which later resulted in a smaller crossing distance when considering trials without changes in the crossing order. These results support our hypothesis, a trajectory with a constant acceleration that follows a path with a 5m radius perturbed collision avoidance behaviour when compared to a trajectory without acceleration. However, this was only true for a 5m radius; there was no significant difference for the constant acceleration of a

10m radius trajectory from the rectilinear trajectory. This suggests that a constant acceleration was more difficult to perceive for a 5m curved trajectory. However, from the observed similarities in the evolution of *MPD* curves, we have demonstrated that *MPD* is a pertinent affordance of constant speed and constant acceleration trajectories for collision avoidance tasks.

Timing. All paths presented the three distinct phases of collision avoidance behaviour during the evolution of *MPD*, observable in figure 4.7. Previous studies characterised the evolution of *MPD* by computing its time derivative, identifying a change of sign of the *MPD* time derivative and later comparing the corresponding *MPD* values [Olivier2012, Lynch2017]. To elucidate the three stages of the interaction, we set a threshold of absolute *MPD* difference greater than 0.15m, from $MPD_{t_{see}}$ for reaction time (i.e., terminus of observation stage) and from $MPD_{t_{cross}}$ for regulation time, that lasted for 1.5s. We selected a threshold of absolute *MPD* as 0.15m as this was within the previously reported standard deviation at the time of regulation [Olivier2012]. The set threshold was further validated by observing the difference between regulation time and total duration, the time of regulation was recorded approximately 0.8s before crossing, which was similar to previous findings [Olivier2012]. We observed that P5 had a longer period of observation than INF, P10 and N10. Additionally, N5 had a significantly longer period of observation than N10. Further, we interpret the instance of recorded regulation as the combination of the observation and adaptation stages; after the instant of recorded regulation, no further adaptation of *MPD* greater than the threshold of 0.15m was observed.

From our results, we observed a main effect of path; N5 had a later regulation time from all other conditions. When considering the differences between reaction time and regulation time we can summarise that P5 required longer periods of observation for visual information pickup and hence delayed their onset of adaptation, however, the avoidance behaviour during the reaction stage of P5 was solved sooner and the final crossing distance was shorter. Contrarily, N5 was not significantly longer than INF

during the observation period but had a later regulation time; N5 was initially perceived similarly to INF. However, N5 required more time to reach a comfortable regulation distance, although this did not influence the final crossing distance. These findings support our hypothesis, where the reaction time for the P5 condition suggests that the constant acceleration is initially poorly perceived. Further, the longer duration of adaptation and later regulation time of N5 suggests that the constant acceleration was incorrectly perceived.

From the observed differences of event timing; P5 had a longer period of observation than INF, and N5 required more time before a regulation distance was obtained. We considered the additional analysis of C_{MPD} from R_{MPD} and the orientation of the virtual walker at each respectively timed event. It allows for the inference of visual information presented to the participant. Overall, there was no main effect of path on MPD at reaction time, the longer duration of observation for P5 did not effect the predicted future crossing distance. However, the longer observation and the shorter adaptation duration that produced the similar regulation time of P5 from INF had influenced the predicted future crossing distance at the time of regulation. The shorter MPD at regulation is further observed by the shorter final crossing distance of P5. Contrarily, N5 had a similar duration for the observational stage of the interaction and took significantly longer during the period of adaptation that produced a significantly longer regulation time of N5 from INF. However, the longer adaptation did not significantly effect MPD at regulation time or the final crossing distance of N5 from INF.

Orientation angle. When considering the orientation of the virtual walker, our results showed that the normalised absolute angle for P10 and N10 were similar. Participants began their adaptations with the same kind of visual information from the virtual walker. The significant effect from a longer reaction time for P5 can also be observed in the absolute normalised orientation of the virtual walker at reaction time, P5 was significantly different from INF and N5. However, the difference between P5 and N5 trended towards not being significantly different ($p=0.049$). Considering this, we may suggest

that participants began their adaptations with a similar amount of visual information from the virtual walker following a trajectory fixed to a 5m radius independent of the direction of approach. Similarly, the orientation of the virtual walker at the time of regulation was similar between P5 and N5 and similar between P10 and N10. Further suggesting that independent of the direction of approach the same kind of visual information was used to determine a regulation time for each curve size. These findings are interesting in that the same kind of visual information may be used for decision making between adaptation stages. However, our findings still report differences of final crossing distance and the timing of adaptations.

We hypothesise that the reported differences may have been influenced by the direction of approach of the virtual walker. It has been reported that personal space is asymmetric between the anterior-posterior and mediolateral axis [Gérin-Lajoie2005], which has been discussed for its influence of risk being smaller when crossing first and larger when crossing second [Olivier2013]. From the interaction effects of final crossing distance and the normalised orientation angles, we can observe the amount of visual information, and the final crossing distance was influenced by the direction of approach of the virtual walker.

4.4.3 Rectilinear vs. curvilinear

The findings of this study evidence that participants successfully performed a collision avoidance task when interacting with a virtual human walking with a rectilinear trajectory of constant velocity and a curvilinear trajectory of constant acceleration. This is further confirmed by the end of experiment questionnaire that participants filled out concerning the virtual walker's motion, the interaction with the virtual walker, the ease of the task, and open question responses that often referred to the virtual walker's trajectory.

The ability to successfully detect curvilinear paths has previously been demonstrated during interception tasks [Bastin2006b, Bosco2012] and these capabilities have been presented in partial occlusion paradigms (see [Delle Monache2015] for a review). However, to our knowledge, this is the first study that has considered the interaction of curvilinear paths between two walkers during a collision avoidance task.

Bosco and colleagues [Bosco2012] studied the integration of different information processing in the control of an interception action of catching a ball that followed a parabolic flight path. Within their experimental design participants intercepted a fly-ball using a computer mouse and followed the trajectory on a computer monitor. The trajectory was either continually present or occluded shortly after maximum height was achieved. Additionally, the flight path was perturbed during the decent. The repeated measures mixed design allowed for the comparison between prospective visual control and predictive capabilities [Bosco2012]. Their findings showed that participants relied on a combination of prospective and predictive control when visual stimuli are constantly present, and relied more on predictive mechanisms when the stimuli were occluded. Participants had increased interception errors when initially interacting with perturbed and occluded flight trajectories. However, an implication of this study was the interaction through a computer monitor and mouse, the final position of the mouse cursor could have been specified prior to interception timing.

Our findings are in agreement, participants relied on a combination of both prospective and predictive control when completing the collision avoidance task. Indeed, our experimental setup was not designed to elucidate differences between prospective and predictive control. However, the evolution of *MPD* and the distinction of the three stages of the interaction support the hypothesis that the initial stages of the interaction are predicted. Moreover, the completion of adaptation before crossing and the presence of a regulation stage suggests that the completion of the task was anticipated. Future work would be to consider a temporal occlusion paradigm during a collision avoidance task to investigate the predictive aspect of the control.

Similar to our experimental design, Bastin and colleagues [Bastin2006b] conducted an interception task of a ball that followed a rectilinear or curvilinear trajectories based on 5 and 10m radius curves. Further, the distance at which the ball intercepted the path of the participant was offset, so participants were required to accelerate (1m), maintain a constant speed (0m) or decelerate (-1m) to successfully intercept the ball. In their design, all ball trajectories originated from in front of the participant and approached from the right. Participants were attached to the frame of the treadmill in order to confine motion adaptation to walking velocity [Bastin2006b]. The findings of their study showed an ability to perceive and intercept a ball that followed a rectilinear or curvilinear path with only adaptations to walking velocity. Moreover, their results showed that a constant bearing angle strategy could explain displacement adaptations during an interception task; participants prospectively controlled their actions by maintaining an invariant bearing angle [Bastin2006b]. Bastin and colleagues later confirmed, using the same paradigm, the constant bearing strategy accounted for the effect of curvature. Moreover, the walking speed of participants was also effected by curve. [Bastin2008].

We have demonstrated, for a collision avoidance task, that indeed curvilinear trajectories are well perceived. We have further shown that the task can be predicted in advance and is anticipated before crossing. Within our study, we did not consider the bearing angle of the participant during the interaction or the constant bearing angle theory. Considering the consistency of the orientation angles reported here, it would suggest that a consistent threshold of bearing angle may have been a visual cue for effective decision making. Further work could consider the role of bearing angle in the detection and decision making process of collision avoidance behaviour in curved paths. As the rate of change of bearing angle has previously been evidenced as a potential vision based model with time-to-contact information for collision avoidance in a walking task [Ondřej2010]. Moreover, similar to [Bastin2008] we could investigate the effect of optical expansion during a collision avoidance task.

Finally, Olivier and colleagues [Olivier2012] proposed *MPD* to describe combined interpersonal interactions during collision avoidance. The linear extrapolation of instantaneous speed and orientation to a future crossing point between two walkers represents the future distance of closest approach if no adaptation is performed. *MPD* quantifies the notion of *risk of collision*, adaptations of *MPD* indeed occur when there is a risk of future collision [Olivier2012]. Where the adaptation strategy is performed by anticipation [Olivier2012] and further depends on the characteristics of the interaction; previous works have considered different angles of intersection with rectilinear paths [Huber2014]. Within our experimental design, we considered an adaptation of *MPD* for curvilinear trajectories of a fixed radius to express the interaction between two walkers. Our results showed qualitatively and quantitatively that participants predicted future crossing distances and successfully performed avoidance behaviours, further, our results showed that the interaction with curvilinear trajectories is performed by anticipation.

4.5 Limitations

A Limitation of our experimental design can be observed in the reported crossing distances. We used a passive virtual walker as this allowed for more control and standardisation of the conditions that participants were exposed to. Previous studies have reported an increase of final crossing distances, and the observed differences were attributed to the passive behaviour of the virtual walker or robot [Olivier2017, Lynch2017, Vassallo2017]. In reality, a collaborative avoidance behaviour from a wheeled robot significantly reduced the final crossing distance [Vassallo2018]. However, these observations were not consistent for collaborative virtual walkers [Lynch2018]. Therefore, while participants were informed of the virtual walker's passivity and should not expect cooperation during the collision avoidance task, this still may have led to an over adaptation in the avoidance behaviours of the participants.

While the increased crossing distance can indeed be attributed to the passive nature of the motion of the virtual human as well as the change in depth perception within virtual reality, our reported crossing distances were larger than those previously reported for passive virtual walkers [Lynch2017, Olivier2017, Lynch2018]. These observed differences may be attributed to the use of an occlusion corridor as opposed to an open floor plan with occluding walls [Olivier2012, Olivier2013, Olivier2017, Lynch2017]. The occlusion corridor allowed for more control and standardisation of the instant when both walkers were visible ($MPD_{t_{see}}$). Indeed, we could have maintained a similar paradigm to previous studies. However, it would be necessary to shift the orientation, size and position of the occluding walls for each condition, which could provide cues to the identification of conditions. Alternatively, we could have designed the experiment so that the virtual walker appeared at a specified location; however, this would limit the ecological validity of the interaction.

Finally, we initially studied the effects of fixed radii curvilinear paths on collision avoidance behaviour similar to previous studies that investigated the ability to intercept objects [Bastin2006b]. However, when considering observed trajectories in reality and virtual reality for goal-oriented tasks [Hicheur2007, Cirio2013] and ball flight trajectories [Bosco2012, Craig2006], the observed trajectories are not necessarily uniform with a fixed radial curve. When considering the fixed curve trajectory in combination with the passive behaviour of the virtual walker, these two limitations may have resulted in poorer ecological validity and reduced the sense of presence. Future work should include the measure of the sense of presence to determine whether or not trajectories with a constant acceleration reduce or possibly increase the sense of presence.

4.5.1 Conclusion

This study investigated the influence of a passive virtual walker's rectilinear and curvilinear trajectory on collision avoidance behaviour. We showed that the nature of information from the virtual walker's path indeed affected the final crossing distance and the stages of *MPD* evolution. However, these influences were only observed when the virtual walker followed a trajectory with a 5 m radius curve.

When the virtual walker approached from behind the participant had a longer period of observation, but the duration of adaptation was shorter, which resulted in a shorter final crossing distance. Conversely, when the virtual walker approached from in front of the participant the duration of observation was similar to a rectilinear path; however the duration of adaptation was longer. The longer duration of observation and adaptation did not influence the final crossing distance.

Qualitatively, all experimental conditions reproduced similar motion adaptations; participants anticipated the interaction through observation, reaction and regulation. From the small number of trials that had a reported collision or inversion, P5 had the greatest number of collisions, and N5 had the greatest number of inversion. There were no significant effects of a 10 m curvilinear path on the number of collisions or inversions from the control condition.

From these findings, we can conclude that a constant acceleration from a 5m radius curved path perturbed collision avoidance behaviour. However, this was not true for the 10m radius curve. However, when *MPD* accounts for the constant acceleration of a fixed radial curve, the evolution of the task is solved with qualitatively similar adaptations. This suggests that the future risk of collision was predicted early in interaction and was later prospectively controlled and anticipated during a final stage of regulation before crossing. This study offers a first attempt to investigate how an observer interprets the trajectory of another walker. Here we have discussed a prospective control

that takes into account acceleration, which appears to be a good candidate to model the situation. Future work is needed to consider alternatively accelerated trajectories, for example, additional constant accelerations from differently sized radius curves, and the presence of acceleration in rectilinear conditions.

Chapter 5

Effect of Virtual Human Gaze Behaviour During an Orthogonal Collision Avoidance Walking Task

Associated publications:

- ▶ Lynch, S. D., Pettré, J., Bruneau, J., Kulpa, R., Cretual, A. and Olivier, A.-H. *Effects of virtual human gaze behaviour during an orthogonal collision avoidance walking task*. 2018 IEEE Virtual Reality, Reutlingen, Germany, 18 - 22 March, 2018.
- ▶ Lynch, S. D., Pettré, J., Bruneau, J., Kulpa, R., Cretual, A. and Olivier, A.-H. *Effect of mutual gaze on collision avoidance behavior during human walking*. AFRV 2017 - L'Association française de Réalité Virtuelle, Augmentée, Mixte et d'Interaction 3D, Rennes, France, 11 - 13 October, 2017.

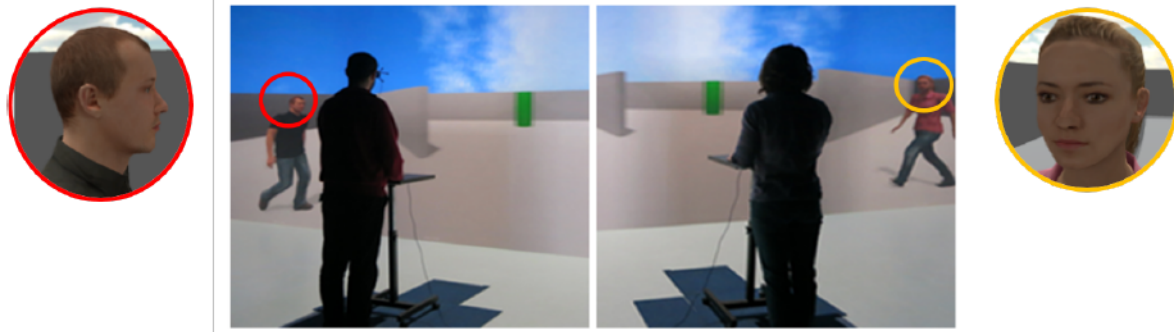


Figure 5.1 - Third person perspective of participants navigating through a virtual environment; male participant interacting without gaze (left, red circle) and female participant interacting with gaze (right, orange circle).

5.1 Objectives and contributions

This study investigated the influence of gaze behaviour on a collision avoidance task between a real human and a virtual human character. In contrast with previous works, we focused on the effect of gaze on the kinematics of interactions with two questions in mind. Would the presence or absence of gaze interception change the kinematics of collision avoidance between two walkers? And by extension, as Virtual Reality is today used to study locomotion and interactions [Bruneau2015, Lynch2017], is it important to correctly control virtual characters' gaze behaviours so as to not bias the experimental data acquired this way?

To answer these questions, we asked participants to perform a trajectory in a virtual environment and controlled a virtual character to cross their path. Among trials, the character would present a varying risk of collision with the subject, the character would gaze or not at subjects, and the character would perform or not avoidance manoeuvres.

We assumed that the presence or the absence of gaze interception during the negotiation of collision avoidance will have an effect on the trajectories performed by a participant to avoid a virtual character. The first hypothesis (**H1**) is that the absence of gaze

interception (i.e., due to the character not gazing at the subject) may result into larger avoidance manoeuvres by the participant, who does not expect collaboration to solve the task. However, the absence of gaze can be compensated by the presence of avoidance manoeuvres perceived in the motion of the character. Which of these two visual cues plays the greatest role? The second hypothesis (**H2**) is that if the gaze-related visual cue plays no important role in the interaction, the distance of crossing will not be impacted by the gaze factor (the subject controls their trajectory according to the relative motion of the character, whatever the gaze behaviour). A final hypothesis (**H3**) is that, when some incongruent stimulus is displayed, i.e., when the character looks at the participant but does not avoid them, we may observe a lack of avoidance by the participant who should expect collaboration (and thus, potential collision or abnormally low crossing distances).

The contribution of this work is to demonstrate that, in the simple kind of situation we considered, the locomotion of virtual characters provided sufficient information for participants to control their own motion. The presence or absence of gaze interception did not affect their motion. This result is detailed in the next sections.

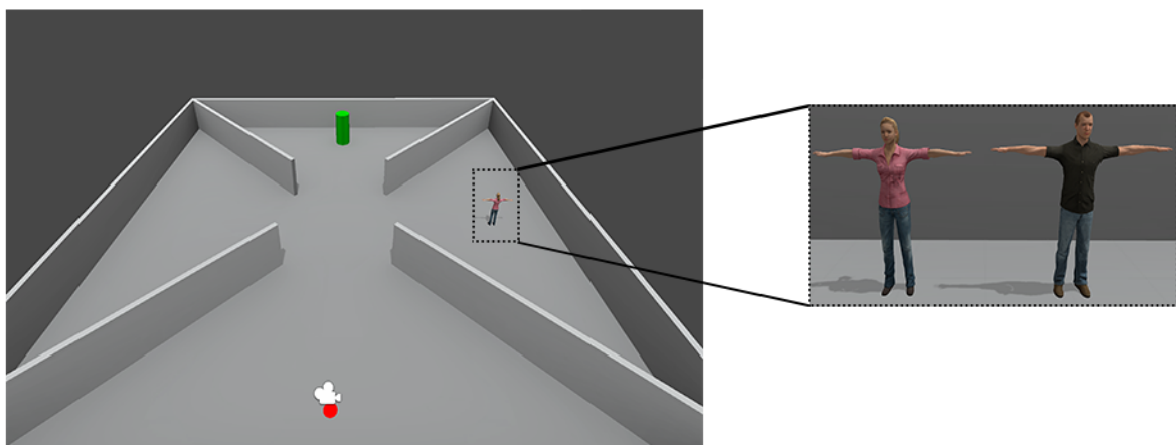


Figure 5.2 - Participants navigated from the red circle to the green cylinder using a joystick, avoiding gender matched virtual characters.

5.2 Method

5.2.1 Participants

Seventeen healthy participants (12 males, 5 females), aged 24.6 ± 2.9 years (mean \pm SD) volunteered for this study. Written informed consent forms were obtained prior to the experimentation and the study standards were in accordance to the Declaration of Helsinki.

5.2.2 Task

Participants were immersed in a virtual environment (Figures 5.1 and 5.2) and asked to navigate from their initial position (red circle) to a goal position (green cylinder) using a joystick. The apparatus was the same as the one used in [Olivier2017, Lynch2017]; participants were immersed in a 20m² virtual room, using a 9m wide, 3m high and 3m deep Computer Assisted Virtual Environment (CAVE) equipped with 13 projectors with 15MPixels resolution in total. Character animation and the 3D environment was designed using Unity game engine, multi-surface rendering was performed by MiddleVR, and active stereoscopy was achieved using Volfony ActiveEyes Pro Radiofrequency wearable glasses that were tracked by a 16 camera ART tracking system. User starting position was located 9.5m from the centre of the room (Figure 5.2, red circle). Participants were instructed to avoid potential collisions with a virtual character that would appear in their path whilst advancing towards their goal, located 19m opposite their starting position. To limit any gender effect in the interaction, female and male participants were interacting respectively with female and male virtual characters. The character moved along a trajectory perpendicular to participants' own trajectory. We set occlu-

sion walls in the environment to control the moment at which participants can perceive the character (t_{see}). This allowed participants to reach a baseline steady state speed ($1.4\text{m}\cdot\text{s}^{-1}$), which resembles a typical normative human walking speed [Bohannon1997], before the interaction and before being able to adapt their speed and trajectory using the joystick. The longitudinal axis of the joystick controlled speed linearly from $0.8\text{m}\cdot\text{s}^{-1}$ to $2.0\text{m}\cdot\text{s}^{-1}$, and the lateral axis controlled angular rotation speed linearly from $-25\text{deg}\cdot\text{s}^{-1}$ to $+25\text{deg}\cdot\text{s}^{-1}$ [Olivier2017, Lynch2017, Bruneau2015].

5.2.3 Experimental Design

Following our hypotheses, two main factors, namely gaze with head rotation behaviour and the reciprocal avoidance behaviour of the virtual character, were manipulated in our study. Each factor has two levels described below:

1) Gaze Behaviour: For the first level **No Gaze (NG)**, the virtual character does not look at the participant but straight ahead, as a stereotypical interferer that does not formulate social interactions with the agent. For the second level, **Gaze (G)**, the virtual character looks at the participant. More precisely, the character first looks ahead, then, 0.2s after $MPD_{t_{see}}$, it directs its gaze to the head of participants. During 1.5s , the character fixates on the participant before returning gaze to walking direction. Gaze behaviour is performed by animating eye, head and neck components (through head and shoulder rotation) of the virtual character, based on previous work of [Grillon2009].

2) Avoidance Behaviour: For the first level **No Avoidance (NA)**, the virtual character maintained a straight path towards its goal at a constant speed. For the second level **Avoidance (A)**, the virtual character adapted its path to ensure a safe passage at the future predicted crossing point using the RVO algorithm [Van Den Berg2011].

We combined these two factors so that we had the following conditions: No Gaze +

No Avoidance (*NGNA*), No Gaze + Avoidance (*NGA*), Gaze + No Avoidance (*GNA*), Gaze + Avoidance (*GA*).

In this study, the virtual character would advance from the agent's occluded right or left. We controlled the potential danger of the interaction to assess whether the gaze behaviour had an effect on the perception of the situation. The future risk of collision was computed using the Minimum Predicted Distance variable (*MPD*) as previously defined by [Olivier2012]. It was set at the beginning of the interaction by controlling participant's baseline speed and heading until t_{see} , and further controlling the starting position of the character, which had the same baseline speed as the participant and a constant heading [Olivier2012]. Both participant and virtual character were located 9.5m from the intersection point, at constant heading and velocity both arrive at the same instant. For our experimental conditions, we offset the starting position of the character, in place of offsetting the starting time. A total of 5 future crossing distances computed at t_{see} ($MPD_{t_{see}}$) were chosen, varying the initial risk of collision in the interaction; 2 high risk distances, where a collision would occur if no adaptation is implemented (0.1 and 0.3m), an intermediary distance (0.6m) that would require no adaptation, what is actually observed between two pedestrians, but an inversion is reported while interacting with robots and virtual characters [Vassallo2017, Lynch2017], and finally 2 low risk distances, where no collision would occur if no adaptation is implemented (0.9 and 1.2m). Furthermore, we controlled the initial crossing order at t_{see} where the virtual character would pass the participant either in front ($MPD_{t_{see}} < 0$) or behind ($MPD_{t_{see}} > 0$) at these randomised risk of collision distances.

Each participant performed 80 randomised trials (4 behaviour responses \times 2 crossing sides (left-right) \times 5 *MPD* \times 2 crossing orders). At the end of the experiment, we asked participants to report which parameters they thought we evaluated during this study. We also collected self-reported feedback. The duration of the experiment per participant was one hour.

5.2.4 Data analysis

Post-processing of trajectories and the interaction response of the participant was performed using customised MATLAB scripts (Mathworks 2015b). The dependant variables were: final crossing distance, number of collisions, and number of inversions of initial crossing order. Where crossing distance was the shortest distance between the participant's and the character's centres, collision occurred when crossing distance was less than the sum of both participant's and character's radii, and crossing order was classified as the participant passing the character first or second and an inversion was a change from initial order (initial order is estimated by a linear extrapolation of trajectories based on the initial positions and velocities). MPD evolution over time was also computed and was normalised to the period of interaction, that is, from $MPD_{t_{see}}$ to $MPD_{t_{cross}}$ (i.e. the instant when the crossing distance is minimal).

A Kolomogorov-Smirnov test determined whether data followed a normal distribution. In congruence with the aim of this study, *NA* and *A* behaviours were considered separately, focusing on an effect of gaze behaviours. Since data were not normally distributed, we evaluated this effect using Wilcoxon's signed-rank non-parametric test. We performed this comparison considering all the trials for each condition of gaze/avoidance but also separately with respect to $MPD_{t_{see}}$ values, defining the initial risk of collision in the interaction. We set the level of significance to $\alpha = 0.05$ and we reported median values. Finally, we compared the evolution of MPD using statistical parametric mapping (SPM, [Friston2007]).

5.3 Results and Discussion

5.3.1 Collisions

Table 5.1 - Total percentage of collisions observed for each $MPD_{t_{see}}$ values (in meters) with respect to the conditions of gaze and avoidance: Gaze + No Avoidance (*GNA*), No Gaze + No Avoidance (*NGNA*), Gaze + Avoidance (*GA*), No Gaze + Avoidance (*NGA*)

<i>mpd tsee</i>	% of Collisions			
	<i>GNA</i>	<i>NGNA</i>	<i>GA</i>	<i>NGA</i>
-1.2	0	0	0	0
-0.9	0	0	0	0
-0.6	0	2.94	0	0
-0.3	2.94	0	0	0
-0.1	5.88	2.94	0	0
0.1	2.94	11.76	0	0
0.3	5.88	5.88	0	0
0.6	0	0	0	0
0.9	0	0	0	0
1.2	0	0	0	0

First, we inspected the presence of collisions between the participants and the virtual character. Among all of the 1360 trials performed by all participants, the collision avoidance task was successfully performed: there was a total of 14 collisions between the character and the participant, meaning that only 1% of the trials performed presented a collision. Figure 5.1 illustrates the percentage of collisions observed depending on the $MPD_{t_{see}}$ values as well as the conditions of gaze and avoidance. Obviously, no collision was observed in the avoidance condition since the RVO navigation algorithm prevented the character from colliding with the user. Collisions were observed only in the No Avoidance trials where $MPD_{t_{see}}$ ranged from -0.6m to 0.3m.

There was no significant effect of the virtual character gaze behaviour ($p > 0.05$) neither in *NA* nor in *A* conditions when considering the number of collisions per participant for all trials (median value: $GNA=0\%$ and $NGNA=0\%$, $GA=0\%$ and $NGA=0\%$) or separately for each $MPD_{t_{see}}$ conditions (i.e., defining the initial risk of collision).

These results are not in accordance with hypothesis **(H3)**. Indeed, in the *GNA* condition, we hypothesised that the virtual character gaze would let participants expect collaboration in the avoidance task while there is not. Assuming collaboration, the participant would not adapt the trajectory enough to avoid the character, resulting into more collisions. Comparisons between gaze and no gaze conditions (resp. *GNA* and *NGNA*) show no significant difference in the number of collisions. Therefore, there was almost no ambiguity in the interpretation of the virtual character trajectory whatever the gaze conditions, allowing safe crossings even in most situations without avoidance strategy being implemented by the virtual character where the initial risk of collision was high ($-0.3\text{m} < MPD_{t_{see}} < 0.3\text{m}$).

5.3.2 Inversions of Crossing Order

Second, we explored inversions of the crossing order between the participant and the virtual character. Among all of the 1360 trials, 165 trials presented an inversion of the crossing order (i.e., 12% in total). The percentage of inversions depending on $MPD_{t_{see}}$ values with respect to the conditions of gaze and avoidance is illustrated on figure 5.2. Inversions were observed for $MPD_{t_{see}}$ values ranging from -0.6m to 0.6m . Especially, we found a high percentage of inversions in the -0.1m condition with half of those trials recording an inversion of the crossing order.

Table 5.2 - Total percentage of inversions of crossing order observed for each MPD_{tsee} (in meters) values with respect to the conditions of gaze and avoidance.

mpd_{tsee}	% of Inversions			
	<i>GNA</i>	<i>NGNA</i>	<i>GA</i>	<i>NGA</i>
-1.2	0	0	0	0
-0.9	0	0	0	0
-0.6	20.59	17.65	8.82	11.76
-0.3	32.35	17.65	38.24	29.41
-0.1	47.06	55.88	50	50
0.1	8.82	20.59	17.65	20.59
0.3	8.82	11.76	2.94	8.82
0.6	0	0	2.94	2.94
0.9	0	0	0	0
1.2	0	0	0	0

Considering the influence of our experimental parameters, mutual gaze had no significant effect ($p > 0.05$) on these percentages neither in *NA* nor in *A* conditions either considering all the trials together ($GNA = 10\%$ and $NGNA = 10\%$, $GA = 10\%$ and $NGA = 15\%$) or when performing the statistics separately for each MPD_{tsee} values. These results are in contradiction with our expectations, i.e., in the No Gaze conditions, the participant would not expect collaboration and would more readily give way, even when likely to pass first. While [Olivier2013] reported no inversion within unconstrained collision avoidance between two real walkers, Vassallo et al. [Vassallo2017] reported inversions between a walker and a robot when MPD_{tsee} values ranged between 0 and 0.8m. Olivier et al. [Olivier2013] attributed the task resolution as a nonverbal communication between two walkers, where [Vassallo2017, Lynch2017] presented subjects with non-communicative partners, a passive robot and passive virtual obstacles respectively. While, Vassallo et al. [Vassallo2017] suggested a level of perceived danger, a lack of experience of interacting with robots as well as the passive nature of the robot as causes of inversion, Lynch et al. [Lynch2017] attributed inversions to a lack of nonverbal communication and behaviour uncertainty. Here we studied the effect of gaze behaviour and reciprocal avoidance be-

haviour during a collision avoidance task with a virtual character. Similarly to collisions, the gaze behaviour had no effect. Few inversions were reported when considering all the trials but a large number were reported for the -0.1m condition. This result can be linked to the one previously observed in [Olivier2017] involving the interaction between a participant and a non reactive and neutral virtual character. In their perceptual study, authors showed that participants were not accurate to predict the future crossing order when $MPD_{t_{see}}$ was equal to -0.1m. They interpreted this inaccuracy as a forward shift in space of the perceived body envelope in virtual reality. We can then hypothesize that in our set-up, the perception of the relative motion of the virtual character with respect to the participant perceived position was more important than the gaze to define the interaction.

5.3.3 Crossing Distance

Crossing distances for all trials considered together are illustrated in Figure 5.3 (the large variability is explained by the fact that we plot the values for all the $MPD_{t_{see}}$ conditions).

Gaze behaviour of the virtual character had no significant effect ($p > 0.05$) on the final crossing distance, neither in *NA* nor in *A* conditions ($GNA = 1.22m$ and $NGNA = 1.20m$, $GA = 1.20m$ and $NGA = 1.20m$) when considering all the trials performed by participants. This is also true when considering the trials with respect to the initial risk of collision ($MPD_{t_{see}}$). These results validate our hypothesis **(H2)**. The final crossing distances reported here are similar to those of [Olivier2017, Lynch2017], which are larger than those observed in reality [Olivier2012, Vassallo2017]. The increased crossing distance in VR may have been caused through immersive depth perception that was mainly reported in previous studies. Gerin-Lajoie et al. [Gérin-Lajoie2008] compared behavioural

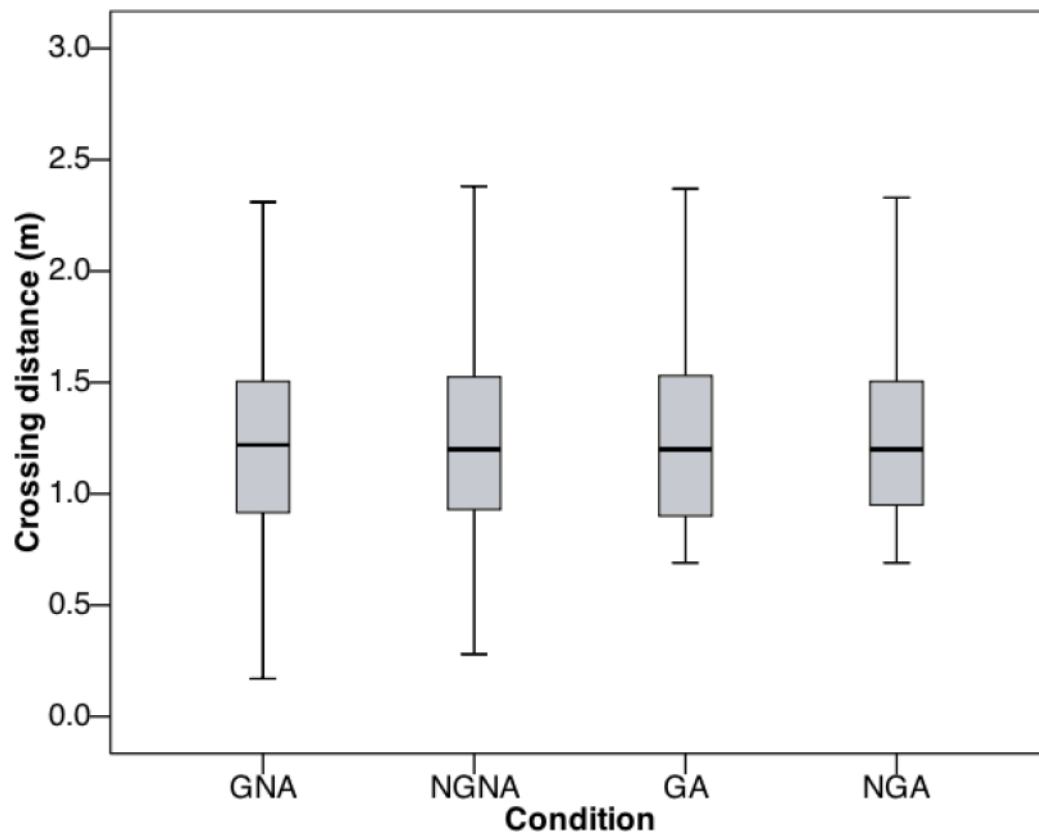


Figure 5.3 - Boxplot of crossing distance (median, 1st-3rd quartiles, min-max values) depending on gaze and avoidance behaviour.

differences and personal space preservation between reality and VR during an obstacle circumvention task, it was reported that the personal space elliptical shape was similar to reality although the size increased within VR. Furthermore, the fidelity of the environment or the perceived agency of the the virtual characters may have affected the behavioural responses. Where, considering the effect of gaze with virtual characters, behaviour is significantly altered if an individual is in belief of interacting with a virtual avatar or a virtual agent [Bailenson2003]. Which was in agreement to the sense of being gazed upon, with decelerated heart rate, skin conductive responses, and positive frontal P3 cortex response [Myllyneva2015]. Considering these previous findings, participants may have adapted their behaviour to the belief of interacting with an avatar as opposed to a reciprocal agent. Therefore, participants may have directed their attention to perceptual variables, such as bearing angle and optic expansion of full body motion, which are sufficient for collision avoidance from full body motion cues [Lynch2017].

5.3.4 MPD Evolution over Time

Finally, we investigated the collision avoidance behaviour during the interaction by considering *MPD* evolution over time. For each condition of gaze and avoidance, the behaviour conformed to those previously reported in real and virtual conditions [Olivier2012, Olivier2017, Lynch2017]. Indeed, as illustrated in Figure 5.4 for all the trials, we can describe for each condition of the present study the three distinct phases of interaction: observation (*MPD* value is constant), reaction (*MPD* is increased), and regulation (*MPD* is maintained constant at a comfortable distance). The anticipation previously reported during interactions between real walkers is preserved since we observed the regulation phase that showed that the task is solved before the end of the interaction.

Quantitatively, the SPM analysis showed that there was no significant effect of gaze behaviour on $MPD(t)$ values or duration of each phase, neither in *NA* nor in *A* conditions ($p > 0.05$) when considering all the trials together (considering the absolute value of *MPD*) as illustrated in Figure 5.4 or separately with respect to initial $MPD_{t_{see}}$ values. These findings are not in accordance with Hypothesis **(H1)** and thus further corroborates Hypothesis **(H2)**. There were no reported differences throughout the evolution of *MPD*, independent of our experimental parameters. Interestingly, the evolution of *MPD* in both *NA* and in *A* conditions were similar. This similarity was observed for all initial $MPD_{t_{see}}$ with no reported significant differences ($p > 0.05$), suggesting that participants may have directed their attention to perceptual variables related to the trajectory [Lynch2017] rather than to the gaze behaviour of the character to avoid.

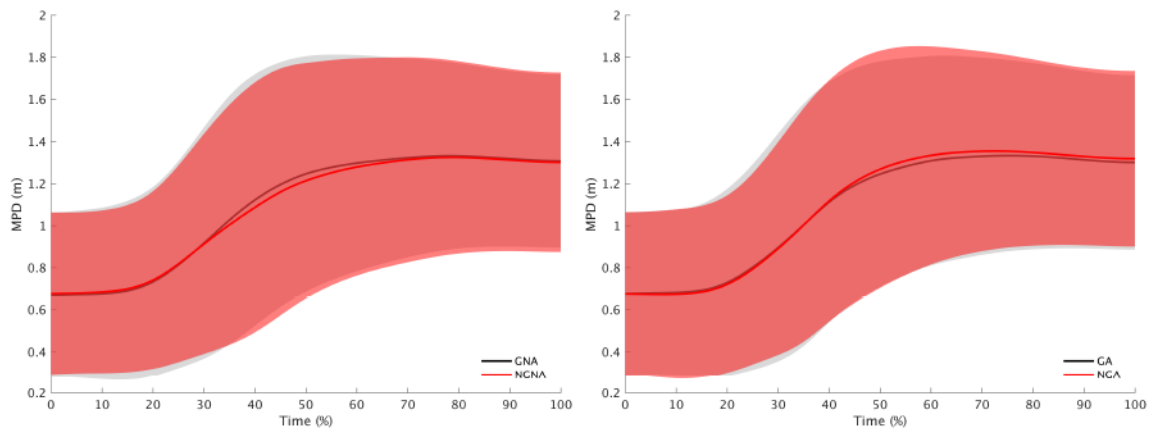


Figure 5.4 - SPM analysis of *MPD* evolution, comparing effect of gaze within trials of No Avoidance (NA, left) and Avoidance (A, right) conditions. Each plot shows mean *MPD* evolution with gaze (black line) and without gaze (red line), with respective standard deviation clouds.

5.3.5 Gaze Behaviour and Collision Avoidance

From these results, our first **(H1)** and third **(H3)** hypotheses were not validated and our second hypothesis **(H2)** was, since the presence of virtual character gaze activity towards the participants did not modify collision avoidance behaviour neither whilst interacting with a passive nor a reactive virtual character. Indeed, as suggested by [Marschner2015, Jung2016], we would have expected that interaction is influenced by both mutual gaze and body motion cues.

Considering our results, we can conclude that within this current experimental set up, body motion cues conveyed by the virtual character were enough for the collision avoidance task. We reiterate that our set up considered a pairwise interaction within a simple environment, without challenging conditions requiring adaptation in a small amount of time, or within a restricted space. Therefore, when designing a simple situation of interaction where a user has to avoid a collision with a virtual character, it is important to focus on the generation of a relevant walking trajectory rather than focusing on the gaze behaviour of the character.

However, we can hypothesise that stronger spatial and temporal constraints of the virtual environment would have increased the importance of mutual gaze in the decision-making process of avoiding a collision. In particular, the effect of gaze during a collision avoidance task within a crowd should be considered as future work. The increased immersion that subjects experience from a crowded environment and the increased complexity as opposed to a single virtual character could increase the role of mutual gaze between walkers, which may produce significant differences of avoidance behaviour.

5.4 Limitations

One can wonder whether these results can be explained by the fact that users did not perceive the gaze behaviour of the virtual character. However, we validated that the gaze behaviour was perceived by the participants and thus forming a mutual gaze between walkers, through their subjective questionnaire post immersion. Each participant responded to the question "In your opinion, what were the parameters being investigated today", to which several example responses were: "The movement of the head", "The orientation of the head and eyes", "Orientation of the eyes and head during collision avoidance", and "The trajectory and function of position, speed and gaze of the virtual character". These subjective reports confirm that participants noticed the gaze and body motion cues of the character, however, there were no differences on avoidance behaviour. In our study a social presence questionnaire was not included due to the randomised experimental design. However, it would have been interesting to evaluate this potential effect of the mutual gaze since it was previously shown that mutual gaze can increase the sense of immersion [Narang2016]. Additionally, being an interaction through virtual reality and joystick, one can wonder whether the ecological validity of the interaction is preserved and therefore whether the gaze behaviour is the same as in real conditions. Nevertheless, the apparatus we used was previously valid-

ated for goal directed locomotion trajectories [Cirio2013] as well as interaction involving collision avoidance between walkers [Olivier2017]. Especially, during collision avoidance tasks, it was shown that the trajectory performed by the user qualitatively matched the ones performed in real conditions even if quantitatively some differences exist (e.g., over-adaptation to avoid the collision). Therefore, the quantitative differences that exist between virtual and real conditions in such a situation may have hidden the influence of gaze if this influence is subtle. It should of course be interesting to design new experiments which include other locomotion metaphors to be more accurate in the quantification of the avoidance behaviour and its link with gaze behaviour. Finally, we can question the gaze behaviour model we used in this study [Grillon2009]. While, the model is efficient and easily introduced to our experimental set up, it is based on joint rotational timing laws and a fixed point of interest, in this case the participants position. It is generally accepted that participants gaze at their confederates and reported to influence avoidance behaviour depending on number of fixations and duration [Croft2017]. However, to our knowledge, there have been no report specifying limits for fixation location, duration and, head and eye rotational limits for a similar paradigm of occluded walkers intersecting paths. Therefore, future work should consider the capture and analysis of the gaze behaviour between two unconstrained participants to experimentally assess that there is indeed a gazing behaviour and furthermore a mutual gaze during the interaction.

5.5 Conclusion

The results of this study showed that mutual gaze had no effect on pairwise avoidance behaviour, neither whilst interacting with a passive nor a reactive virtual character. We still believe that gaze plays an important role in collision avoidance, but our experiment was not able to reveal an effect on avoidance behaviour. The influence of gaze may be dependent of the characteristics of this task, such as the duration of interaction and its complexity. Alternatively, body motion cues conveyed enough information to solve this task. Future work should then consider more complex situations and the use of eye tracking, which allows specification of cues derived for future collision prediction. For example, we can immerse a user within a crowd with some virtual walkers gazing and others not gazing at the user. This situation would allow to investigate whether the selection of the interactions within the users' neighbourhood as well as their trajectory is influenced by the gaze of the virtual walkers. Finally, even though we do not report a significant effect of gaze on avoidance behaviour within our experimental set up we would still conclude that a gaze behaviour should be included in the animation of virtual characters. Where the inclusion of gaze has been previously reported to increase immersion [Narang2016] and within our experiment, even though no presence questionnaire was included, participants acknowledged the change in the virtual characters behaviour.

Conclusion

The review of the literature in chapter 1 has demonstrated the dynamic coupling humans have with their environment, and the continuous interaction with the environment. Humans do not aimlessly displace within a given environment instead they perceive the dense information of the environment and act on what is afforded. A few examples could include the navigation and climbing of stairwells, the safe passage through doorway apertures, and the safe navigation around fixed obstacles or other pedestrians. This thesis has focused on the latter, the coordination of one's movement with another person and more specifically a collision avoidance task between two walkers. To further develop an understanding of this interaction we have focused on the underlying perceptual mechanisms, that is the perceptual cues that may or may not be used, in the perception and action coupling for collision avoidance.

Therefore, the aim of the thesis was to determine what visual cues are perceived from the movement of another walker. Further, the thesis considered the mechanisms of interpretation and possible models used for the prediction of future crossing distances and their inferred notion of risk. The overall objective of the thesis was to provide new knowledge and understanding on the interaction between two walkers while developing guidelines of consideration for future applications of human behavioural responses and

interactions within virtual reality. That is, to identify the important visual cues during interpersonal interactions that may additionally provide virtual humans with a realistic behaviour.

The first study focused on the nature of visual information provided from another walker. More specifically, this study focused on the visual cues that convey relevant information for accurate estimation of others' global motion, specifically, whether these visual cues are extracted from local body parts or from global perception of the body motion. The application of virtual reality allowed for the manipulation of a virtual obstacles visual appearance while strictly preserving the kinematics of interactions (i.e., the relative motion of the obstacle with respect to participants). The findings of this study showed that the nature of visual information had indeed affected the avoidance behaviour of participants. We suggested that the associated variances observed could be linked to the perceived action-opportunities of the observer. Overall, global motion provided sufficient information for successful collision avoidance however local motion variants reproduce more accurate and repeatable responses.

The second study focused on the nature of information from the path of another walker and the pertinence of a minimally predicted distance to describe the interaction between two walkers. More specifically, we investigated whether collision avoidance behaviour is perturbed when a virtual walker has a constant acceleration that constantly changes the direction of the future position. To evaluate the pertinence of *MPD*, we adapted the previous computation to take into account the constant acceleration of a curvilinear trajectory. Our analysis of this study was then to focus on the differences in the evolution of *MPD* and the adaptations behaviours of curvilinear trajectories with reference to known rectilinear trajectories of a constant speed without acceleration.

The findings of the second study demonstrated that the nature of a virtual walker's path did indeed perturb the avoidance behaviour of the participants. However, this was only true while interacting with a virtual walker that followed a curvilinear trajectory

with a constant velocity of a 5m radius. Collision avoidance behaviour was not perturbed when the trajectory was of a 10m radius. Moreover, the findings demonstrated that *MPD* was pertinent for the description of a collision avoidance between two walkers for both rectilinear trajectories of a constant speed and curvilinear trajectories of a constant acceleration. This was evidenced by the qualitatively similar adaptations between rectilinear and curvilinear conditions; during the interaction, there was a stage of observation, the risk was predicted, and an adaptation occurred before crossing, and finally, the task was anticipated as the *MPD* was regulated before crossing. To our knowledge, this was the first study to consider how an observer interprets a trajectory of a constant acceleration for a constant direction change of another walker during a collision avoidance task. Future work should consider the constant acceleration from differently sized radii, and the presence of acceleration in rectilinear trajectories.

The third study focused on the social aspects of the interaction between the two walkers, namely the gazing behaviour of a virtual walker. Previous studies evidenced that in reality, two unconstrained walkers assigned roles for who would cross first and whom would cross second without verbal communication [Olivier2013]. Whereas, while interacting with passive walkers, robots or obstacles, participants adopted an over adaptation of their avoidance behaviour and changed their predicted order of crossing. This phenomenon was observed while interacting with passive wheeled robots [Vassallo2017] however the over adaptation response was significantly reduced when the robot collaboratively solved the collision avoidance task [Vassallo2018]. This study was then a continuation of these previous findings and the reported observations within the other studies of the thesis. We introduced gaze as a potential non-verbal cue between two walkers, focusing on two questions: would the presence or absence of gaze interception change the kinematics of collision avoidance between two walkers? And by extension, as virtual reality is today used to study locomotion and interactions [Bruneau2015, Olivier2017], is it important to correctly control virtual walker's gaze behaviours so as to not bias the experimental data acquired this way? In addition to a gazing behaviour, we included

collaborative avoidance behaviour by the virtual walker. The results of this study showed that gaze had no effect on avoidance behaviour, neither while interacting with a passive nor a collaborative virtual walker. Considering that we did not find any significant effects of gaze behaviour on collision avoidance behaviour within our experimental setup, we still suggest that gaze plays a vital role in the non-verbal communication between two walkers during a collision avoidance task. We attributed the lack of significant effect to the spatial and temporal constraints of the interaction and suggested that within this specific paradigm body motion cues conveyed enough information to solve this task.

Overall, the scope of the results within this thesis can appeal to a much broader framework than applied psychology and biomechanics. As mentioned in the introduction, the study of human locomotion spans the interest of neuroscience, sports sciences, medicine and computer sciences. As evidenced by some of the literature cited within this thesis, the further understanding of the underlying perceptual mechanisms are sought after for improved virtual human animation and interaction [Narang2016], improved human-robot interactions [Vassallo2017, Vassallo2018] and rehabilitative training for stroke patients [Darekar2015], for example. Note that the desired understanding of the underlying perceptual mechanisms does not present the same applications. Virtual human animation can be related to the realism of the interaction and an increased sense of immersion, whereas, stroke rehabilitation can be used to evaluate and train environment navigation by manipulating moving virtual obstacles in safe and controlled virtual environments.

In conclusion, these three studies have demonstrated two key points. The first would be the possible mechanism of humans using the minimally predicted distance to regulate their interpersonal distances during a collision avoidance task. We have evidenced the pertinence of *MPD* while interacting with virtual humans, and obstacles. Our findings suggest the sensitivity to the action-opportunities of the observer are bound directly to the perceived visual appearance within the optic array. Moreover, the pertinence of *MPD* was demonstrated for complex trajectories that included a constant acceleration.

The second key point demonstrated from this thesis was the perceptual cues that can be perceived from another walker. From the first study, we showed that global motion provided sufficient information for the detection of future collisions. The second study evidenced that the future risk of collision can be predicted in the presence of a constant acceleration and a constant velocity. The final study supported the findings of the first study, which was global motion cues provided sufficient information for successful collision avoidance.

The current works within this thesis have studied the underlying perceptual mechanisms of a simple pairwise interaction between two walkers. However, crowd interactions are more complex than this simple pairwise interaction, as observers must consider their interaction with multiple walkers. One possible future direction of the thesis would be to consider these complex interactions; whether collision avoidance behaviour is sequentially solved for each individual pairwise interaction or that collision avoidance is solved for simultaneous interactions. Furthermore, from the third study of the thesis, as the complexity of the interaction increases, the potential role and influence of a walker gazing behaviour can be an additional social cue that in turn will aid such complex interactions. Therefore, a second prospective extension of the thesis would firstly be to consider the immersion of a crowd interaction and the use of eye-tracking technologies to determine the focus of attention and the detection of future collision events from multiple walkers. Thereafter, future work may consider the influence of a virtual walker's gaze behaviour in such larger and immersive crowd interactions. Finally, age-related differences have previously been reported in the anticipatory behavioural responses and body segment timing coordination when circumventing obstacles [Vallis2005]. It has further been observed that adults are better attuned to temporal information than spatial information [Siegler2013], whereas children are more attuned to spatial information and adapt to temporal information with ageing [Benguigui2008, Bazile2016]. Therefore, an additional prospective direction of future work from the thesis should consider collision avoidance interactions with younger and older populations.

Moreover, to demonstrate one of the possible fields of interest and the possible future directions of this work, we completed an additional experiment in parallel with the work of this thesis (Annexe A). We applied the same methodology as the first study in the detection of deceptive motion during a rugby attacker-defender dyad. Previous works have shown the importance of centre of mass in experts performance and the detection of deceptive motion. It remains unclear whether, the visual cues necessary for a defender to detect the deception of an attacker are based on global, such as the centre of mass, or on local information, such as lower limbs motion. This study showed that the superimposition of the centre of mass with local information had no additional effect on the performance to correctly detect deceptive motion, neither did it affect the reaction times. This work allowed us to determine if these specific visual information cues can be beneficial in directing attention for training purposes.

Bibliography

- [Abernethy1985] Abernethy, B. *Cue usage in 'open' motor skills: A review of the available procedures*. In Russell, D. G. and Abernethy, B., Eds., *Motor Memory and Control: Otago Symposium*, volume ed. Dunedin, New Zealand: Human Performance Associates, Dunedin, New Zealand: Human Performance Associates, 1985.
- [Andersen1999] Andersen, G. J., Cisneros, J., Atchley, P. and Saidpour, A. *Speed, size, and edge-rate information for the detection of collision events*. *Journal of Experimental Psychology: Human Perception and Performance*, vol. 25, n° 1, page 256, 1999.
- [Andersen2001] Andersen, G. J. and Kim, R. D. *Perceptual information and attentional constraints in visual search of collision events*. *Journal of Experimental Psychology: Human Perception and Performance*, vol. 27, n° 5, page 1039, 2001.
- [Andersen2007] Andersen, G. J. and Sauer, C. W. *Optical information for car following: The driving by visual angle (DVA) model*. *Human factors*, vol. 49, n° 5, pages 878–896, 2007.
- [Argelaguet-Sanz2015] Argelaguet-Sanz, F., Olivier, A.-H., Bruder, G., Pettré, J. and Lécuyer, A. *Virtual proxemics: Locomotion in the presence of*

obstacles in large immersive projection environments. In Virtual Reality (VR), 2015 IEEE, pages 75–80. IEEE, 2015.

[Arnaldi2003] Arnaldi, B., Fuchs, P. and Tisseau, J. *Chapitre 1 du volume 1 du traité de la réalité virtuelle.* Les Presses de l'Ecole des Mines de Paris, vol. 1, 2003.

[Austin2011] Austin, D. J., Gabbett, T. J. and Jenkins, D. J. *Repeated High-Intensity Exercise in a Professional Rugby League.* The Journal of Strength & Conditioning Research, vol. 25, n° 7, pages 1898–1904, 2011.

[Bailenson2003] Bailenson, J. N., Blascovich, J., Beall, A. C. and Loomis, J. M. *Interpersonal Distance in Immersive Virtual Environments.* Personality and Social Psychology Bulletin, vol. 29, n° 7, pages 819–833, 2003.

[Bailenson2005] Bailenson, J. N., Beall, A. C., Loomis, J., Blascovich, J. and Turk, M. *Transformed social interaction, augmented gaze, and social influence in immersive virtual environments.* Human communication research, vol. 31, n° 4, pages 511–537, 2005.

[Baker2017] Baker, C. S. and Cinelli, M. E. *The effects of obstacle proximity on aperture crossing behaviours.* Experimental brain research, vol. 235, n° 2, pages 497–506, 2017.

[Banton2005] Banton, T., Stefanucci, J., Durgin, F., Fass, A. and Proffitt, D. *The perception of walking speed in a virtual environment.* Presence: Teleoperators and Virtual Environments, vol. 14, n° 4, pages 394–406, 2005.

- [Barfield1995] Barfield, W., Zeltzer, D., Sheridan, T. and Slater, M. *Presence and performance within virtual environments*. Virtual environments and advanced interface design, pages 473–513, 1995.
- [Barwise1981] Barwise, J. and Perry, J. *Situations and attitudes*. The Journal of Philosophy, vol. 78, n° 11, pages 668–691, 1981.
- [Basili2013] Basili, P., Sağlam, M., Kruse, T., Huber, M., Kirsch, A. and Glasauer, S. *Strategies of locomotor collision avoidance*. Gait and Posture, vol. 37, n° 3, pages 385–390, 2013.
- [Bastin2006a] Bastin, J., Calvin, S. and Montagne, G. *Muscular proprioception contributes to the control of interceptive actions*. Journal of experimental psychology: human perception and performance, vol. 32, n° 4, page 964, 2006.
- [Bastin2006b] Bastin, J., Craig, C. and Montagne, G. *Prospective strategies underlie the control of interceptive actions*. Human movement science, vol. 25, n° 6, pages 718–732, 2006.
- [Bastin2008] Bastin, J., Jacobs, D. M., Morice, A. H., Craig, C. and Montagne, G. *Testing the role of expansion in the prospective control of locomotion*. Experimental Brain Research, vol. 191, n° 3, pages 301–312, 2008.
- [Bazile2016] Bazile, C., Benguigui, N. and Siegler, I. *Development of information–movement couplings in a rhythmical ball-bouncing task: from space-to time-related information*. Experimental brain research, vol. 234, n° 1, pages 173–183, 2016.
- [Benguigui2003] Benguigui, N., Ripoll, H. and Broderick, M. P. *Time-to-contact estimation of accelerated stimuli is based on first-order inform-*

- ation*. Journal of Experimental Psychology: Human Perception and Performance, vol. 29, n° 6, page 1083, 2003.
- [Benguigui2008] Benguigui, N., Broderick, M. P., Baurès, R. and Amorim, M.-A. *Motion prediction and the velocity effect in children*. British Journal of Developmental Psychology, vol. 26, n° 3, pages 389–407, 2008.
- [Bennett2013] Bennett, S. J. and Benguigui, N. *Is acceleration used for ocular pursuit and spatial estimation during prediction motion?* PLoS One, vol. 8, n° 5, page e63382, 2013.
- [Bennett2016] Bennett, S. J. and Benguigui, N. *Spatial Estimation of Accelerated Stimuli Is Based on a Linear Extrapolation of First-Order Information*. Experimental psychology, 2016.
- [Bernstein1967] Bernstein, N. *The coordination and regulation of movement*. Oxford: Pergamon Press, 1967.
- [Berthelon1993] Berthelon, C. and Mestre, D. *Curvilinear approach to an intersection and visual detection of a collision*. Human Factors, vol. 35, n° 3, pages 521–534, 1993.
- [Berthoz1997] Berthoz, A. *Sens du mouvement (le)*. Odile Jacob, 1997.
- [Bohannon1997] Bohannon, R. W. *Comfortable and maximum walking speed of adults aged 20—79 years: reference values and determinants*. Age and ageing, vol. 26, n° 1, pages 15–19, 1997.
- [Bootsma1994] Bootsma, R. J. *Le couplage perception-action dans des activités d'interception*. Thèse, Aix-Marseille Université, 1994.
- [Bosco2012] Bosco, G., Delle Monache, S. and Lacquaniti, F. *Catching what we can't see: manual interception of occluded fly-ball trajectories*. PLoS One, vol. 7, n° 11, page e49381, 2012.

- [Brain1941] Brain, W. R. *Visual disorientation with special reference to lesions of the right cerebral hemisphere*. Brain, vol. 64, n° 4, pages 244–272, 1941.
- [Brault2010] Brault, S., Bideau, B., Craig, C. and Kulpa, R. *Balancing deceit and disguise: How to successfully fool the defender in a 1 vs. 1 situation in rugby*. Human Movement Science, vol. 29, n° 3, pages 412 – 425, 2010.
- [Brault2012] Brault, S., Bideau, B., Kulpa, R. and Craig, C. M. *Detecting deception in movement: The case of the side-step in rugby*. PLoS ONE, vol. 7, n° 6, pages 1–13, 2012.
- [Brenton2016] Brenton, J., Müller, S. and Mansingh, A. *Discrimination of Visual Anticipation in Skilled Cricket Batsmen*. Journal of Applied Sport Psychology, vol. 28, n° 4, pages 483–488, 2016.
- [Brooks1991] Brooks, R. A. *Intelligence without representation*. Artificial intelligence, vol. 47, n° 1-3, pages 139–159, 1991.
- [Brooks1999] Brooks, R. A. *Cambrian intelligence: The early history of the new ai*, volume 97. MIT press Cambridge, MA, 1999.
- [Brouwer2002] Brouwer, A.-M., Brenner, E. and Smeets, J. B. *Perception of acceleration with short presentation times: Can acceleration be used in interception?* Perception & Psychophysics, vol. 64, n° 7, pages 1160–1168, 2002.
- [Bruce2003] Bruce, V., Green, P. R. and Georgeson, M. A. *Visual perception: Physiology, psychology, & ecology*. Psychology Press, 2003.
- [Bruneau2015] Bruneau, J. and Pettré, J. *Going through, going around: A study on individual avoidance of groups*. IEEE Transactions on

Visualization and Computer Graphics, vol. 1, pages 520–528, jan 2015.

[Cañal-Bruland2010] Cañal-Bruland, R., van der Kamp, J. and van Kesteren, J. *An examination of motor and perceptual contributions to the recognition of deception from others' actions*. Human Movement Science, vol. 29, n° 1, pages 94 – 102, 2010.

[Cañal-Bruland2011] Cañal-Bruland, R., van Ginneken, W. F., van der Meer, B. R. and Williams, A. M. *The effect of local kinematic changes on anticipation judgments*. Human Movement Science, vol. 30, n° 3, pages 495–503, 2011.

[Caruana2017] Caruana, N., Spirou, D. and Brock, J. *Human agency beliefs influence behaviour during virtual social interactions*. PeerJ, vol. 5, page e3819, Septembre 2017.

[Casanova2015] Casanova, R., Borg, O. and Bootsma, R. J. *Perception of spin and the interception of curved football trajectories*. Journal of Sports Sciences, vol. 33, n° 17, pages 1822–1830, 2015. PMID: 25686376.

[Chapman1968] Chapman, S. *Catching a baseball*. American Journal of Physics, vol. 36, n° 10, pages 868–870, 1968.

[Chardenon2004] Chardenon, A., Montagne, G., Laurent, M. and Bootsma, R. *The perceptual control of goal-directed locomotion: a common control architecture for interception and navigation?* Experimental Brain Research, vol. 158, n° 1, pages 100–108, 2004.

[Chardenon2005] Chardenon, A., Montagne, G., Laurent, M. and Bootsma, R. *A robust solution for dealing with environmental changes in*

- intercepting moving balls*. Journal of Motor Behavior, vol. 37, n° 1, pages 52–62, 2005.
- [Chemero2011] Chemero, A. Radical embodied cognitive science. MIT press, 2011.
- [Cinelli2007] Cinelli, M. E. and Patla, A. E. *Travel path conditions dictate the manner in which individuals avoid collisions*. Gait & Posture, vol. 26, n° 2, pages 186–193, jul 2007.
- [Cinelli2008a] Cinelli, M. E. and Patla, A. E. *Locomotor avoidance behaviours during a visually guided task involving an approaching object*. Gait & posture, vol. 28, n° 4, pages 596–601, 2008.
- [Cinelli2008b] Cinelli, M. E., Patla, A. E. and Allard, F. *Strategies used to walk through a moving aperture*. Gait & posture, vol. 27, n° 4, pages 595–602, 2008.
- [Cirio2013] Cirio, G., Olivier, A. H., Marchal, M. and Pettré, J. *Kinematic evaluation of virtual walking trajectories*. IEEE Transactions on Visualization and Computer Graphics, vol. 19, n° 4, pages 671–680, 2013.
- [Clark1997] Clark, A. Being there. MIT Press Cambridge, MA, 1997.
- [Clark2015] Clark, A. Surfing uncertainty: Prediction, action, and the embodied mind. Oxford University Press, 2015.
- [Craig2006] Craig, C. M., Berton, E., Rao, G., Fernandez, L. and Bootsma, R. J. *Judging where a ball will go: the case of curved free kicks in football*. Naturwissenschaften, vol. 93, n° 2, pages 97–101, 2006.

- [Craig2011] Craig, C. M., Bastin, J. and Montagne, G. *How information guides movement: Intercepting curved free kicks in soccer*. Human Movement Science, vol. 30, n° 5, pages 931–941, 2011.
- [Creem-Regehr2005] Creem-Regehr, S. H., Willemsen, P., Gooch, A. A. and Thompson, W. B. *The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual indoor environments*. Perception, vol. 34, n° 2, pages 191–204, 2005.
- [Croft2017] Croft, J. L. and Panchuk, D. *Watch Where You're Going? Interferer Velocity and Visual Behavior Predicts Avoidance Strategy During Pedestrian Encounters*. Journal of Motor Behavior, vol. 0, n° 0, pages 1–11, 2017. PMID: 28925812.
- [Crowell1990] Crowell, J., Royden, C., Banks, M., Swenson, K. and Sekuler, A. *Optic flow and heading judgements*. Investigative Ophthalmology & Visual Science, vol. 31, n° Suppl., page 522, 1990.
- [Cruz-Neira1992] Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V. and Hart, J. C. *The CAVE: audio visual experience automatic virtual environment*. Communications of the ACM, vol. 35, n° 6, pages 64–72, 1992.
- [Cruz-Neira1993] Cruz-Neira, C., Sandin, D. J. and DeFanti, T. A. *Surround-screen projection-based virtual reality: the design and implementation of the CAVE*. In Proceedings of the 20th annual conference on Computer graphics and interactive techniques, pages 135–142. ACM, 1993.
- [Cutting1977] Cutting, J. E. and Kozlowski, L. T. *Recognizing friends by their walk: Gait perception without familiarity cues*. Bulletin of the psychonomic society, vol. 9, n° 5, pages 353–356, 1977.

- [Cutting1992] Cutting, J. E., Springer, K., Braren, P. A. and Johnson, S. H. *Wayfinding on foot from information in retinal, not optical, flow*. Journal of Experimental Psychology: General, vol. 121, n° 1, page 41, 1992.
- [Cutting1995] Cutting, J. E., Vishton, P. M. and Barren, P. A. *How do we avoid collision with stationary and moving obstacles*. Psychological Review, vol. 102, n° 4, pages 627–651, 1995.
- [Darekar2015] Darekar, A., Lamontagne, A. and Fung, J. *Dynamic clearance measure to evaluate locomotor and perceptuo-motor strategies used for obstacle circumvention in a virtual environment*. Human Movement Science, vol. 40, pages 359–371, apr 2015.
- [de la Rosa2018] de la Rosa, S. and Breidt, M. *Virtual reality: A new track in psychological research*. British Journal of Psychology, 2018.
- [Delle Monache2015] Delle Monache, S., Lacquaniti, F. and Bosco, G. *Eye movements and manual interception of ballistic trajectories: effects of law of motion perturbations and occlusions*. Experimental brain research, vol. 233, n° 2, pages 359–374, 2015.
- [Dennett1969] Dennett, D. Content and consciousness: An analysis of mental phenomena. Humanities Press, 1969.
- [Dessing2010] Dessing, J. C. and Craig, C. M. *Bending it like Beckham: how to visually fool the goalkeeper*. PLoS One, vol. 5, n° 10, page e13161, 2010.
- [Dewey1896] Dewey, J. *The reflex arc concept in psychology*. Psychological review, vol. 3, n° 4, page 357, 1896.
- [di Pellegrino2015] di Pellegrino, G. and Làdavas, E. *Peripersonal space in the brain*. Neuropsychologia, vol. 66, pages 126–133, 2015.

- [Diaz2012] Diaz, G. J., Fajen, B. R. and Phillips, F. *Anticipation from biological motion: the goalkeeper problem*. Journal of Experimental Psychology: Human Perception and Performance, vol. 38, n° 4, page 848, 2012.
- [Dicks2010a] Dicks, M., Button, C. and Davids, K. *Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in information pickup for perception and action*. Attention, Perception, & Psychophysics, vol. 72, n° 3, pages 706–720, Apr 2010.
- [Dicks2010b] Dicks, M., Davids, K. and Button, C. *Individual differences in the visual control of intercepting a penalty kick in association football*. Human movement science, vol. 29, n° 3, pages 401–411, 2010.
- [Dubrowski2002] Dubrowski, A. and Carnahan, H. *Action–perception dissociation in response to target acceleration*. Vision Research, vol. 42, n° 11, pages 1465–1473, 2002.
- [Evans2007] Evans, G. W. and Wener, R. E. *Crowding and personal space invasion on the train: Please don't make me sit in the middle*. Journal of Environmental Psychology, vol. 27, n° 1, pages 90–94, 2007.
- [Fajen2003] Fajen, B. R. and Warren, W. H. *Behavioral dynamics of steering, obstacle avoidance, and route selection*. Journal of experimental psychology. Human perception and performance, vol. 29, n° 2, pages 343–362, 2003.
- [Fajen2004] Fajen, B. R. and Warren, W. H. *Visual Guidance of Intercepting a Moving Target on Foot*. Perception, vol. 33, n° 6, pages 689–715, 2004.

- [Fajen2007] Fajen, B. R. and Warren, W. H. *Behavioral dynamics of intercepting a moving target*. Experimental Brain Research, vol. 180, n° 2, pages 303–319, 2007.
- [Fajen2009] Fajen, B. R., Riley, M. A., Turvey, M. T. *et al.* *Information, affordances, and the control of action in sport*. international Journal of sport psychology, vol. 40, n° 1, page 79, 2009.
- [Feyerabend1963] Feyerabend, P. K. *How to be a good empiricist*. In Philosophy of science: The Delaware seminar, volume 2. Interscience Publishers New York, 1963.
- [Feyerabend1965] Feyerabend, P. K. *Problems of empiricism*. In Colodny, R., Ed., *Beyond the Edge of Certainty*, volume ed. Englewood Cliffs, NJ: Prentice Hall, Englewood Cliffs, NJ: Prentice Hall, 1965.
- [Fink2007] Fink, P. W., Foo, P. S. and Warren, W. H. *Obstacle avoidance during walking in real and virtual environments*. ACM Transactions on Applied Perception, vol. 4, n° 1, 2007.
- [Fisher1987] Fisher, S. S., McGreevy, M., Humphries, J. and Robinett, W. *Virtual environment display system*. In Proceedings of the 1986 workshop on Interactive 3D graphics, pages 77–87. ACM, 1987.
- [Fodor1981] Fodor, J. A. *Representations: Philosophical essays on the foundations of cognitive science*. MIT Press, 1981.
- [Fodor1988] Fodor, J. A. *A Reply to Churchland's "Perceptual Plasticity and Theoretical Neutrality"*. Philosophy of Science, vol. 55, n° 2, pages 188–198, 1988.
- [Fodor1990] Fodor, J. A. *A theory of content and other essays*. MIT press, 1990.

- [Franchak2014] Franchak, J. and Adolph, K. *Affordances as probabilistic functions: Implications for development, perception, and decisions for action*. Ecological Psychology, vol. 26, n° 1-2, pages 109–124, 2014.
- [Friston2007] Friston, K., Ashburner, J., Kiebel, S., Nichols, T. and Penny, W. *Statistical Parametric Mapping*. Academic Press, 2007.
- [Gabbett2012] Gabbett, T. J., Jenkins, D. G. and Abernethy, B. *Physical demands of professional rugby league training and competition using microtechnology*. Journal of science and medicine in sport, vol. 15 1, pages 80–6, 2012.
- [Gabbett2016] Gabbett, T. J. *Influence of Fatigue on Tackling Ability in Rugby League Players: Role of Muscular Strength, Endurance, and Aerobic Qualities*. PLOS ONE, vol. 11, n° 10, pages 1–11, 10 2016.
- [Gérin-Lajoie2005] Gérin-Lajoie, M., Richards, C. L. and McFadyen, B. J. *The negotiation of stationary and moving obstructions during walking: anticipatory locomotor adaptations and preservation of personal space*. Motor control, vol. 9, n° 3, pages 242–269, 2005.
- [Gérin-Lajoie2006] Gérin-Lajoie, M., Richards, C. L. and McFadyen, B. J. *The circumvention of obstacles during walking in different environmental contexts: a comparison between older and younger adults*. Gait & posture, vol. 24, n° 3, pages 364–369, 2006.
- [Gérin-Lajoie2008] Gérin-Lajoie, M., Richards, C. L., Fung, J. and McFadyen, B. J. *Characteristics of personal space during obstacle circumvention in physical and virtual environments*. Gait and Posture, vol. 27, n° 2, pages 239–247, 2008.

- [Gibson1950] Gibson, J. J. *The perception of the visual world*. Houghton Mifflin, 1950.
- [Gibson1961] Gibson, J. J. *Ecological optics*. *Vision research*, vol. 1, n° 3-4, pages 253–262, 1961.
- [Gibson1966] Gibson, J. J. *The senses considered as perceptual systems*. Houghton Mifflin, 1966.
- [Gibson1979] Gibson, J. *The ecological approach to visual perception*. Houghton Mifflin, 1979.
- [Gibson2001] Gibson, E. J. *et al.* *Perceiving the affordances: A portrait of two psychologists*. Psychology Press, 2001.
- [Gottsdanker1956] Gottsdanker, R. M. *The ability of human operators to detect acceleration of target motion*. *Psychological bulletin*, vol. 53, n° 6, page 477, 1956.
- [Grillon2009] Grillon, H. and Thalmann, D. *Simulating gaze attention behaviors for crowds*. *Computer Animation and Virtual Worlds*, vol. 20, n° 2-3, pages 111–119, 2009.
- [Güldenpenning2017] Güldenpenning, I., Kunde, W. and Weigelt, M. *How to trick your opponent: a review article on deceptive actions in interactive sports*. *Frontiers in psychology*, vol. 8, page 917, 2017.
- [Hackney2011] Hackney, A. L. and Cinelli, M. E. *Action strategies of older adults walking through apertures*. *Gait & posture*, vol. 33, n° 4, pages 733–736, 2011.
- [Hackney2013] Hackney, A. L. and Cinelli, M. E. *Young and older adults use body-scaled information during a non-confined aperture crossing task*. *Experimental brain research*, vol. 225, n° 3, pages 419–429, 2013.

- [Hackney2014a] Hackney, A. L., Cinelli, M. E. and Frank, J. S. *Is the critical point for aperture crossing adapted to the person-plus-object system?* Journal of motor behavior, vol. 46, n° 5, pages 319–327, 2014.
- [Hackney2014b] Hackney, A. L., Van Ruymbeke, N., Bryden, P. J. and Cinelli, M. E. *Direction of single obstacle circumvention in middle-aged children.* Gait and Posture, vol. 40, n° 1, pages 113–117, 2014.
- [Hackney2015a] Hackney, A. L., Cinelli, M. E., Denomme, L. T. and Frank, J. S. *The effects of narrow and elevated path walking on aperture crossing.* Human movement science, vol. 41, pages 295–306, 2015.
- [Hackney2015b] Hackney, A. L., Cinelli, M. E. and Frank, J. S. *Does the passability of apertures change when walking through human versus pole obstacles?* Acta Psychologica, vol. 162, pages 62–68, 2015.
- [Hackney2018] Hackney, A. L., Cinelli, M. E. and Frank, J. S. *Action strategies for walking through multiple, misaligned apertures.* Acta psychologica, vol. 182, pages 100–106, 2018.
- [Hall1966] Hall, E. T. *The hidden dimension*, volume 609. Garden City, NY: Doubleday, 1966.
- [Harris2008] Harris, J. M., Nefs, H. T. and Grafton, C. E. *Binocular vision and motion-in-depth.* Spatial vision, vol. 21, n° 6, pages 531–547, 2008.
- [Haugeland1985] Haugeland, J. *Artificial intelligence: The very idea.* MIT Press Cambridge, MA, 1985.

- [Hediger1955] Hediger, H. Studies of the psychology and behavior of captive animals in zoos and circuses. Criterion Books, Inc., 1955.
- [Heft2001] Heft, H. Ecological psychology in context: James gibson, roger barker, and the legacy of william james's radical empiricism. Psychology Press, 2001.
- [Helmholtz1925] Helmholtz, H. v. and Southall, J. Treatise on physiological optics. iii. the perceptions of vision. New York, 1925.
- [Hicheur2007] Hicheur, H., Pham, Q.-C., Arechavaleta, G., Laumond, J.-P. and Berthoz, A. *The formation of trajectories during goal-oriented locomotion in humans. I. A stereotyped behaviour.* European Journal of Neuroscience, vol. 26, n° 8, pages 2376–2390, 2007.
- [Hommel2001] Hommel, B., Müsseler, J., Aschersleben, G. and Prinz, W. *Codes and their vicissitudes.* Behavioral and brain sciences, vol. 24, n° 5, pages 910–926, 2001.
- [Honma2015] Honma, M., Koyama, S. and Kawamura, M. *Hesitant avoidance while walking: an error of social behavior generated by mutual interaction.* Frontiers in Psychology, vol. 6, page 1013, 2015.
- [Hooge1999] Hooge, I. T. C., Beintema, J. A. and Van den Berg, A. *Visual search of heading direction.* Experimental brain research, vol. 129, n° 4, pages 615–628, 1999.
- [Hu2016] Hu, R., Adeagbo, M., Interrante, V. and Guy, S. J. *Virtual human head turning during collision avoidance in crowd simulation.* In IEEE Virtual Humans and Crowds for Immersive Environments (VHCIE), 2016.

- [Huber2014] Huber, M., Su, Y.-H., Krüger, M., Faschian, K., Glasauer, S. and Hermsdörfer, J. *Adjustments of Speed and Path when Avoiding Collisions with Another Pedestrian*. PLoS ONE, vol. 9, n° 2, page e89589, feb 2014.
- [Hulin2015a] Hulin, B. T. and Gabbett, T. J. *Activity Profiles of Successful and Less-successful Semi-elite Rugby League Teams*. International Journal of Sports Medicine, vol. 36, pages 485–489, 2015.
- [Hulin2015b] Hulin, B. T., Gabbett, T. J., Kearney, S. and Corvo, A. *Physical Demands of Match Play in Successful and Less-Successful Elite Rugby League Teams*. International Journal of Sports Physiology and Performance, vol. 10, n° 6, pages 703–710, 2015.
- [Huys2009] Huys, R., Cañal-Bruland, R., Hagemann, N., Beek, P. J., Smeeton, N. J. and Williams, A. M. *Global information pickup underpins anticipation of tennis shot direction*. Journal of Motor Behavior, vol. 41, n° 2, pages 158–171, 2009.
- [Iachini2014] Iachini, T., Coello, Y., Frassinetti, F. and Ruggiero, G. *Body space in social interactions: a comparison of reaching and comfort distance in immersive virtual reality*. PloS one, vol. 9, n° 11, page e111511, 2014.
- [Iachini2015] Iachini, T., Ruggiero, G., Ruotolo, F., di Cola, A. S. and Senese, V. P. *The influence of anxiety and personality factors on comfort and reachability space: A correlational study*. Cognitive processing, vol. 16, n° 1, pages 255–258, 2015.

- [Ingle1977] Ingle, D. and Cook, J. *The effect of viewing distance upon size preference of frogs for prey*. Vision research, vol. 17, n° 9, pages 1009–1013, 1977.
- [Interrante2008] Interrante, V., Ries, B., Lindquist, J., Kaeding, M. and Anderson, L. *Elucidating factors that can facilitate veridical spatial perception in immersive virtual environments*. Presence: Teleoperators and Virtual Environments, vol. 17, n° 2, pages 176–198, 2008.
- [Jackson2006] Jackson, R. C., Warren, S. and Abernethy, B. *Anticipation skill and susceptibility to deceptive movement*. Acta Psychologica, vol. 123, n° 3, pages 355 – 371, 2006.
- [Jacob2003] Jacob, R. J. and Karn, K. S. *Eye tracking in human-computer interaction and usability research: Ready to deliver the promises*. In The mind's eye, pages 573–605. Elsevier, 2003.
- [Jiang1994] Jiang, Y. and Mark, L. S. *The effect of gap depth on the perception of whether a gap is crossable*. Perception & Psychophysics, vol. 56, n° 6, pages 691–700, 1994.
- [Johansson1973] Johansson, G. *Visual perception of biological motion and a model for its analysis*. Perception & psychophysics, vol. 14, n° 2, pages 201–211, 1973.
- [Jung2016] Jung, E., Takahashi, K., Watanabe, K., de la Rosa, S., Butz, M. V., Bühlhoff, H. H. and Meilinger, T. *The influence of human body orientation on distance judgments*. Frontiers in psychology, vol. 7, page 217, 2016.

- [Katsumata2012] Katsumata, H. and Russell, D. M. *Prospective versus predictive control in timing of hitting a falling ball*. Experimental brain research, vol. 216, n° 4, pages 499–514, 2012.
- [Kaufer2015] Kaufer, S. and Chemero, A. Phenomenology: an introduction. John Wiley & Sons, 2015.
- [Kennedy1993] Kennedy, R. S., Lane, N. E., Berbaum, K. S. and Lilienthal, M. G. *Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness*. The international journal of aviation psychology, vol. 3, n° 3, pages 203–220, 1993.
- [Kleinke1986] Kleinke, C. L. *Gaze and eye contact: a research review*. Psychological bulletin, vol. 100, n° 1, page 78, 1986.
- [Knorr2016] Knorr, A. G., Willacker, L., Hermsdörfer, J., Glasauer, S. and Krüger, M. *Influence of Person- and Situation-Specific Characteristics on Collision Avoidance Behavior in Human Locomotion*. Journal of Experimental Psychology: Human Perception and Performance, vol. 42, n° 9, pages 1332–1343, sep 2016.
- [Kober2012] Kober, S. E., Kurzmann, J. and Neuper, C. *Cortical correlate of spatial presence in 2D and 3D interactive virtual reality: an EEG study*. International Journal of Psychophysiology, vol. 83, n° 3, pages 365–374, 2012.
- [Koffka2013] Koffka, K. Principles of gestalt psychology, volume 44. Routledge, 2013.
- [Kozlowski1977] Kozlowski, L. T. and Cutting, J. E. *Recognizing the sex of a walker from a dynamic point-light display*. Perception & psychophysics, vol. 21, n° 6, pages 575–580, 1977.

- [Kugler2015] Kugler, P. N. and Turvey, M. T. *Information, natural law, and the self-assembly of rhythmic movement*. Routledge, 2015.
- [Kulik2018] Kulik, A. *Virtually the ultimate research lab*. British Journal of Psychology, 2018.
- [Kunde2007] Kunde, W., Elsner, K. and Kiesel, A. *No anticipation–no action: the role of anticipation in action and perception*. Cognitive Processing, vol. 8, n° 2, pages 71–78, Jun 2007.
- [Kuzmanovic2009] Kuzmanovic, B., Georgescu, A. L., Eickhoff, S. B., Shah, N. J., Bente, G., Fink, G. R. and Vogeley, K. *Duration matters: Dissociating neural correlates of detection and evaluation of social gaze*. NeuroImage, vol. 46, n° 4, pages 1154 – 1163, 2009.
- [La Scaleia2014] La Scaleia, B., Zago, M., Moscatelli, A., Lacquaniti, F. and Viviani, P. *Implied dynamics biases the visual perception of velocity*. PloS one, vol. 9, n° 3, page e93020, 2014.
- [Lampton1995] Lampton, D. R., McDonald, D. P., Singer, M. and Bliss, J. P. *Distance Estimation in Virtual Environments*. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 39, n° 20, pages 1268–1272, 1995.
- [Lappi2015] Lappi, O. *Eye tracking in the wild: the good, the bad and the ugly*. Journal of Eye Movement Research, vol. 8, n° 5, 2015.
- [Lee1975] Lee, D. N. and Lishman, J. *Visual proprioceptive control of stance*. Journal of human movement studies, 1975.
- [Lee1976] Lee, D. N. *A theory of visual control of braking based on information about time-to-collision*. Perception, vol. 5, n° 4, pages 437–459, 1976.

- [Lee1981] Lee, D. N. and Reddish, P. E. *Plummeting gannets: a paradigm of ecological optics*. *Nature*, vol. 293, n° 5830, page 293, 1981.
- [Lee1985] Lee, D. N. and Young, D. S. *Visual timing of interceptive action*. In *Brain mechanisms and spatial vision*, pages 1–30. Springer, 1985.
- [Lee1998] Lee, D. N. *Guiding movement by coupling taus*. *Ecological psychology*, vol. 10, n° 3-4, pages 221–250, 1998.
- [Lee2011] Lee, D. N. *How movement is guided*. <http://www.perception-in-action.ed.ac.uk/news/index.html>, 2011. accessed online, 18 June 2018.
- [Lettich2016] Lettich, F., Alvares, L. O., Bogorny, V., Orlando, S., Raffaetà, A. and Silvestri, C. *Detecting avoidance behaviors between moving object trajectories*. *Data & Knowledge Engineering*, vol. 102, pages 22–41, 2016.
- [Loomis1999] Loomis, J. M., Blascovich, J. J. and Beall, A. C. *Immersive virtual environment technology as a basic research tool in psychology*. *Behav. Res. Methods Instr. Comput.*, vol. 31, n° 4, pages 557–564, 1999.
- [Loomis2003] Loomis, J. M., Knapp, J. M. et al. *Visual perception of ego-centric distance in real and virtual environments*. *Virtual and adaptive environments*, vol. 11, pages 21–46, 2003.
- [Lopes2014] Lopes, J. E., Jacobs, D. M., Travieso, D. and Araújo, D. *Predicting the lateral direction of deceptive and non-deceptive penalty kicks in football from the kinematics of the kicker*. *Human Movement Science*, vol. 36, pages 199–216, 2014.

- [Lynch2017] Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Crétual, A. and Olivier, A.-H. *Collision avoidance behavior between walkers: global and local motion cues*. IEEE Transactions on Visualization and Computer Graphics, vol. PP, n° 99, pages 1–1, 2017.
- [Lynch2018] Lynch, S. D., Pettré, J., Bruneau, J., Kulpa, R., Crétual, A. and Olivier, A.-H. *Effects of virtual human gaze behaviour during an orthogonal collision avoidance walking task*. In 2018 IEEE Virtual Reality (VR), page pp, March 2018.
- [Manning2018] Manning, C., Thomas, R. T. and Braddick, O. *Can speed be judged independent of direction?* Journal of Vision, vol. 18, n° 6, pages 15–15, 2018.
- [Marigold2007] Marigold, D. S. and Patla, A. E. *Gaze fixation patterns for negotiating complex ground terrain*. Neuroscience, vol. 144, n° 1, pages 302–313, 2007.
- [Mark1990] Mark, L. S., Balliett, J. A., Craver, K. D., Douglas, S. D. and Fox, T. *What an actor must do in order to perceive the affordance for sitting*. Ecological Psychology, vol. 2, n° 4, pages 325–366, 1990.
- [Marr1982] Marr, D. Vision. WH Freeman, 1982.
- [Marschner2015] Marschner, L., Pannasch, S., Schulz, J. and Graupner, S.-t. *Social communication with virtual agents: The effects of body and gaze direction on attention and emotional responding in human observers*. International Journal of Psychophysiology, vol. 97, n° 2, pages 85–92, 2015.

- [Marshall2001] Marshall, J. C. and Fink, G. R. *Spatial cognition: where we were and where we are*. Neuroimage, vol. 14, n° 1, pages S2–S7, 2001.
- [Masselink2015] Masselink, J. and Lappe, M. *Translation and articulation in biological motion perception*. Journal of vision, vol. 15, n° 11, pages 10–10, 2015.
- [McFadyen2001] McFadyen, B. J., Malouin, F. and Dumas, F. *Anticipatory locomotor control for obstacle avoidance in mid-childhood aged children*. Gait & posture, vol. 13, n° 1, pages 7–16, 2001.
- [McGuckian2018] McGuckian, T. B., Cole, M. H. and Pepping, G.-J. *A systematic review of the technology-based assessment of visual perception and exploration behaviour in association football*. Journal of sports sciences, vol. 36, n° 8, pages 861–880, 2018.
- [Meerhoff2014] Meerhoff, L. A., De Poel, H. J. and Button, C. *How visual information influences coordination dynamics when following the leader*. Neuroscience Letters, vol. 582, pages 12–15, oct 2014.
- [Meerhoff2018a] Meerhoff, L. A., Bruneau, J., Vu, A., Olivier, A.-H., Julien and Pettré. *Guided by gaze: Prioritization strategy when navigating through a virtual crowd can be assessed through gaze activity*. Acta Psychologica, Accepted 2018.
- [Meerhoff2018b] Meerhoff, L. A., Pettré, J., Lynch, S. D., Crétual, A. and Olivier, A.-H. *Collision avoidance with multiple walkers: Sequential or simultaneous interactions?* In review, 2018.
- [Miles2012] Miles, H. C., Pop, S. R., Watt, S. J., Lawrence, G. P. and John, N. W. *A review of virtual environments for training in*

- ball sports*. Computers & Graphics, vol. 36, n° 6, pages 714–726, 2012.
- [Mishkin1982] Mishkin, M. and Ungerleider, L. G. *Contribution of striate inputs to the visuospatial functions of parieto-preoccipital cortex in monkeys*. Behavioural brain research, vol. 6, n° 1, pages 57–77, 1982.
- [Montagne2000] Montagne, G., Fraise, F., Ripoll, H. and Laurent, M. *Perception–action coupling in an interceptive task: First-order time-to-contact as an input variable*. Human Movement Science, vol. 19, n° 1, pages 59–72, 2000.
- [Montepare1987] Montepare, J. M., Goldstein, S. B. and Clausen, A. *The identification of emotions from gait information*. Journal of Non-verbal Behavior, vol. 11, n° 1, pages 33–42, Mar 1987.
- [Mori2013] Mori, S. and Shimada, T. *Expert anticipation from deceptive action*. Attention, Perception, & Psychophysics, vol. 75, n° 4, pages 751–770, May 2013.
- [Myllyneva2015] Myllyneva, A. and Hietanen, J. K. *There is more to eye contact than meets the eye*. Cognition, vol. 134, n° Supplement C, pages 100 – 109, 2015.
- [Narang2016] Narang, S., Best, A., Randhavane, T., Shapiro, A. and Manocha, D. *PedVR: Simulating Gaze-based Interactions Between a Real User and Virtual Crowds*. In VRST '16, pages 91–100, Munich, Germany, 2016. ACM.
- [Navia2018] Navia, J.-A., Avilés, C., López, S. and Ruiz, L.-M. *A current approach to anticipation in sport/Un enfoque actual de la an-*

ticipación en el deporte. Estudios de Psicología, vol. 39, n° 1, pages 1–19, 2018.

[Neisser2014] Neisser, U. Cognitive psychology: Classic edition. Psychology Press, 2014.

[Newell1994] Newell, K. M. and McDonald, P. V. *Learning to coordinate redundant biomechanical degrees of freedom*. In *Interlimb Coordination*, pages 515–536. Elsevier, 1994.

[Nummenmaa2009] Nummenmaa, L., Hyönä, J. and Hietanen, J. K. *I'll Walk This Way: Eyes Reveal the Direction of Locomotion and Make Passersby Look and Go the Other Way*. Psychological Science, vol. 20, n° 12, pages 1454–1458, 2009. PMID: 19883491.

[Olivier2012] Olivier, A. H., Marin, A., Crétual, A. and Pettré, J. *Minimal predicted distance: A common metric for collision avoidance during pairwise interactions between walkers*. Gait and Posture, vol. 36, n° 3, pages 399–404, 2012.

[Olivier2013] Olivier, A.-H., Marin, A., Crétual, A., Berthoz, A. and Pettré, J. *Collision avoidance between two walkers: Role-dependent strategies*. Gait & Posture, vol. 38, n° 4, pages 751–756, sep 2013.

[Olivier2017] Olivier, A. H., Bruneau, J., Kulpa, R. and Pettré, J. *Walking with virtual people: Evaluation of locomotion interfaces in dynamic environments*. IEEE Transactions on Visualization and Computer Graphics, vol. PP, n° 99, pages 1–1, 2017.

[Ondřej2010] Ondřej, J., Pettré, J., Olivier, A.-H. and Donikian, S. *A synthetic-vision based steering approach for crowd simulation*. ACM Transactions on Graphics, vol. 29, n° 4, page 1, 2010.

- [Oudejans1996] Oudejans, R. R., Michaels, C. F., Bakker, F. C. and Dolné, M. A. *The relevance of action in perceiving affordances: Perception of catchableness of fly balls.* Journal of Experimental Psychology: Human Perception and Performance, vol. 22, n° 4, page 879, 1996.
- [Pan2018] Pan, X. and Hamilton, A. F. d. C. *Why and how to use virtual reality to study human social interaction: The challenges of exploring a new research landscape.* British Journal of Psychology, 2018.
- [Patla1991] Patla, A. E., Prentice, S. D., Robinson, C. and Neufeld, J. *Visual control of locomotion: strategies for changing direction and for going over obstacles.* Journal of Experimental Psychology: Human Perception and Performance, vol. 17, n° 3, page 603, 1991.
- [Patla1996] Patla, A. and Vickers, J. *Visual search patterns as we approach and slip over obstacles in the travel path.* In Soc Neurosci Abstr, page 1848, 1996.
- [Patla1997] Patla, A. E. *Understanding the roles of vision in the control of human locomotion.* Gait & Posture, vol. 5, n° 1, pages 54–69, 1997.
- [Patla2004] Patla, A. E. *Gaze behaviors during adaptive human locomotion: Insights into how vision is used to regulate locomotion.* In Optic flow and beyond, pages 383–399. Springer, 2004.
- [Pelphrey2004] Pelphrey, K. A., Viola, R. J. and McCarthy, G. *When Strangers Pass.* Psychological Science, vol. 15, n° 9, pages 598–603, 2004.

- [Perry1983] Perry, J. and Barwise, J. *Situations and attitudes*. MIT Press, 1983.
- [Pfeiffer2013] Pfeiffer, U. J., Vogeley, K. and Schilbach, L. *From gaze cueing to dual eye-tracking: Novel approaches to investigate the neural correlates of gaze in social interaction*. *Neuroscience & Biobehavioral Reviews*, vol. 37, n° 10, Part 2, pages 2516 – 2528, 2013.
- [Phillips2010] Phillips, L., Ries, B., Kaeding, M. and Interrante, V. *Avatar self-embodiment enhances distance perception accuracy in non-photorealistic immersive virtual environments*. In *Virtual Reality Conference (VR)*, 2010 IEEE, pages 115–1148. IEEE, 2010.
- [Pierce2013] Pierce, R., Bian, Z., Braunstein, M. and Andersen, G. *Detection of 3D curved trajectories: the role of binocular disparity*. *Frontiers in Behavioral Neuroscience*, vol. 7, page 12, 2013.
- [Pimentel1993] Pimentel, K. and Teixeira, K. *Virtual reality through the new looking glass*, 1993.
- [Plumert2005] Plumert, J. M., Kearney, J. K., Cremer, J. F. and Recker, K. *Distance perception in real and virtual environments*. *ACM Transactions on Applied Perception (TAP)*, vol. 2, n° 3, pages 216–233, 2005.
- [Previc1990] Previc, F. H. *Functional specialization in the lower and upper visual fields in humans: Its ecological origins and neurophysiological implications*. *Behavioral and Brain Sciences*, vol. 13, n° 3, pages 519–542, 1990.

- [Prevost2002] Prevost, P. Stratégies d'anticipation et rôle du contexte dans les tâches visuo-motrices. Mémoire de doctorat en Sciences, Université Paris XI, UFR Scientifique d'Orsay, 2002.
- [Proffitt2013] Proffitt, D. R. and Linkenauger, S. A. *Perception viewed as a phenotypic expression*. Action science: Foundations of an emerging discipline, vol. 171, 2013.
- [Regan2000] Regan, D. and Gray, R. *Visually guided collision avoidance and collision achievement*. Trends in cognitive sciences, vol. 4, n° 3, pages 99–107, 2000.
- [Renshaw2000] Renshaw, I. and Fairweather, M. M. *Cricket bowling deliveries and the discrimination ability of professional and amateur batters*. Journal of Sports Sciences, vol. 18, n° 12, pages 951–957, 2000.
- [Rhea2007] Rhea, C. K. and Rietdyk, S. *Visual exteroceptive information provided during obstacle crossing did not modify the lower limb trajectory*. Neuroscience letters, vol. 418, n° 1, pages 60–65, 2007.
- [Rio2014] Rio, K. W., Rhea, C. K. and Warren, W. H. *Follow the leader: Visual control of speed in pedestrian following*. Journal of vision, vol. 14, n° 2, pages 4–4, 2014.
- [Rizzolatti2001] Rizzolatti, G., Fogassi, L. and Gallese, V. *Neurophysiological mechanisms underlying the understanding and imitation of action*. Nature reviews neuroscience, vol. 2, n° 9, page 661, 2001.

- [Rockwell2005] Rockwell, W. T. Neither brain nor ghost: A nondualist alternative to the mind-brain identity theory. MIT Press Cambridge, MA, 2005.
- [Ruffaldi2011] Ruffaldi, E., Filippeschi, A., Avizzano, C. A., Bardy, B., Gopher, D. and Bergamasco, M. *Feedback, Affordances, and Accelerators for Training Sports in Virtual Environments*. Presence: Teleoperators and Virtual Environments, vol. 20, n° 1, pages 33–46, 2011.
- [Runeson1983a] Runeson, S. and Frykholm, G. *Kinematic specification of dynamics as an informational basis for person-and-action perception: Expectation, gender recognition, and deceptive intention*. Journal of Experimental Psychology: General, pages 585–615, 1983.
- [Runeson1983b] Runeson, S. and Frykholm, G. *Kinematic specification of dynamics as an informational basis for person-and-action perception: expectation, gender recognition, and deceptive intention*. Journal of experimental psychology: general, vol. 112, n° 4, page 585, 1983.
- [Rushton2001] Rushton, S. K. and Salvucci, D. D. *An egocentric account of the visual guidance of locomotion*. Trends in Cognitive Sciences, vol. 5, n° 1, pages 6–7, 2001.
- [Rymill2005] Rymill, S. J. and Dodgson, N. A. *A Psychologically-Based Simulation of Human Behaviour*. In TPCG, pages 35–42. Citeseer, 2005.
- [Savelsbergh1991] Savelsbergh, G., Whiting, H. and Bootsma, R. J. *Grasping tau*. Journal of Experimental Psychology: Human Perception and Performance, vol. 17, n° 2, page 315, 1991.

- [Schneider1969] Schneider, G. E. *Two visual systems*. Science, 1969.
- [Schütz-Bosbach2007] Schütz-Bosbach, S. and Prinz, W. *Perceptual resonance: action-induced modulation of perception*. Trends in cognitive sciences, vol. 11, n° 8, pages 349–355, 2007.
- [Schwarzkopf2013] Schwarzkopf, S., von Stülpnagel, R., Büchner, S. J., Konieczny, L., Kallert, G. and Hölscher, C. *What lab eye tracking tells us about wayfinding: A comparison of stationary and mobile eye tracking in a large building scenario*. In Eye Tracking for Spatial Research, Proceedings of the 1st International Workshop (in conjunction with COSIT 2013), pages 31–36, 2013.
- [Senju2009] Senju, A. and Johnson, M. H. *The eye contact effect: mechanisms and development*. Trends in Cognitive Sciences, vol. 13, n° 3, pages 127 – 134, 2009.
- [Sharples2008] Sharples, S., Cobb, S., Moody, A. and Wilson, J. R. *Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems*. Displays, vol. 29, n° 2, pages 58 – 69, 2008. Health and Safety Aspects of Visual Displays.
- [Siegler2013] Siegler, I., Bazile, C. and Warren, W. *Mixed control for perception and action: timing and error correction in rhythmic ball-bouncing*. Experimental brain research, vol. 226, n° 4, pages 603–615, 2013.
- [Silva2018] Silva, W. S., Aravind, G., Sangani, S. and Lamontagne, A. *Healthy young adults implement distinctive avoidance strategies while walking and circumventing virtual human vs. non-human obstacles in a virtual environment*. Gait & posture, vol. 61, pages 294–300, 2018.

- [Sinnett2010] Sinnett, S. and Kingstone, A. *A preliminary investigation regarding the effect of tennis grunting: does white noise during a tennis shot have a negative impact on shot perception?* PLoS one, vol. 5, n° 10, page e13148, 2010.
- [Slater1997] Slater, M. and Wilbur, S. *A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments.* Presence: Teleoperators & Virtual Environments, vol. 6, n° 6, pages 603–616, 1997.
- [Slater2014] Slater, M. and Sanchez-Vives, M. V. *Transcending the self in immersive virtual reality.* Computer, vol. 47, n° 7, pages 24–30, 2014.
- [Slater2016] Slater, M. and Sanchez-Vives, M. V. *Enhancing Our Lives with Immersive Virtual Reality.* Frontiers in Robotics and AI, vol. 3, page 74, 2016.
- [Spaulding1991] Spaulding, S. and Patla, A. *Obstacle avoidance during locomotion: effect of obstacle shape on gait modifications.* In IBRO World Congress of Neuroscience, volume 3, 1991.
- [Stapel2016] Stapel, J. C., Hunnius, S., Meyer, M. and Bekkering, H. *Motor system contribution to action prediction: Temporal accuracy depends on motor experience.* Cognition, vol. 148, pages 71–78, 2016.
- [Stich1983] Stich, S. P. *From folk psychology to cognitive science: The case against belief.* the MIT press, 1983.
- [Stulp2015] Stulp, G., Buunk, A. P., Verhulst, S. and Pollet, T. V. *Human height is positively related to interpersonal dominance in dyadic interactions.* PLoS One, vol. 10, n° 2, page e0117860, 2015.

- [Sutherland1965] Sutherland, I. E. *The ultimate display*. Multimedia: From Wagner to virtual reality, pages 506–508, 1965.
- [Sutherland1968] Sutherland, I. E. *A head-mounted three dimensional display*. In Proceedings of the December 9-11, 1968, fall joint computer conference, part I, pages 757–764. ACM, 1968.
- [Tarr2002] Tarr, M. J. and Warren, W. H. *Virtual reality in behavioral neuroscience and beyond*. nature neuroscience, vol. 5, page 1089, 2002.
- [Templer1995] Templer, J. *The staircase: studies of hazards, falls, and safer design*. MIT press, 1995.
- [Temprado2001] Temprado, J. and Montagne, G. *Les coordinations perceptivo-motrices*. Paris: Armand Colin, vol. 24, 2001.
- [Tharanathan2006] Tharanathan, A. and DeLucia, P. R. *Time-to-collision judgments of constant and non-constant velocities: Implications for rear-end collisions*. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, pages 2463–2467. Sage Publications Sage CA: Los Angeles, CA, 2006.
- [Tharanathan2009] Tharanathan, A. *Effects of constant and non-constant velocity motion on judgments of collision-avoidance action gap*. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, pages 1762–1765. Sage Publications Sage CA: Los Angeles, CA, 2009.
- [Thornton1998] Thornton, I. M., Pinto, J. and Shiffrar, M. *The visual perception of human locomotion*. Cognitive Neuropsychology, vol. 15, n° 6-8, pages 535–552, 1998.

- [Titchener1895] Titchener, E. B. *Simple reactions*. Mind, vol. 4, n° 13, pages 74–81, 1895.
- [Travassos2013] Travassos, B., Araujo, D., Davids, K., O'hara, K., Leitão, J. and Cortinhas, A. *Expertise effects on decision-making in sport are constrained by requisite response behaviours—A meta-analysis*. Psychology of Sport and Exercise, vol. 14, n° 2, pages 211–219, 2013.
- [Tresilian1999a] Tresilian, J. R. *Analysis of recent empirical challenges to an account of interceptive timing*. Perception & psychophysics, vol. 61, n° 3, pages 515–528, 1999.
- [Tresilian1999b] Tresilian, J. R. *Visually timed action: time-out for 'tau'?* Trends in cognitive sciences, vol. 3, n° 8, pages 301–310, 1999.
- [Tresilian2012] Tresilian, J. *Sensorimotor control and learning: An introduction to the behavioral neuroscience of action*. Palgrave Macmillan London, UK, 2012.
- [Trevvarthen1968] Trevarthen, C. B. *Two mechanisms of vision in primates*. Psychologische Forschung, vol. 31, n° 4, pages 299–337, 1968.
- [Troje2002] Troje, N. F. *Decomposing biological motion: A framework for analysis and synthesis of human gait patterns*. Journal of Vision, vol. 2, n° 5, page 2, 2002.
- [Turvey1981] Turvey, M. T., Shaw, R. E., Reed, E. S. and Mace, W. M. *Ecological laws of perceiving and acting: In reply to Fodor and Pylyshyn (1981)*. Cognition, vol. 9, n° 3, pages 237–304, 1981.
- [Turvey1986] Turvey, M. *Intentionally: A problem of multiple reference frames, specificational information, and extraordinary bound-*

ary conditions on natural law. Behavioral and Brain Sciences, vol. 9, n° 1, pages 153–155, 1986.

[Vagnoni2017] Vagnoni, E., Andreanidou, V., Lourenco, S. F. and Longo, M. R. *Action ability modulates time-to-collision judgments.* Experimental brain research, vol. 235, n° 9, pages 2729–2739, 2017.

[Vallis2005] Vallis, L. A. and McFadyen, B. J. *Children use different anticipatory control strategies than adults to circumvent an obstacle in the travel path.* Experimental Brain Research, vol. 167, n° 1, pages 119–127, 2005.

[Van Den Berg2011] Van Den Berg, J., Guy, S. J., Lin, M. and Manocha, D. *Reciprocal n-body collision avoidance.* In Robotics research, pages 3–19. Springer, 2011.

[Van der Kamp2008] Van der Kamp, J., Rivas, F., Van Doorn, H. and Savelsbergh, G. *Ventral and dorsal system contributions to visual anticipation in fast ball sports.* International Journal of Sport Psychology, vol. 39, n° 2, page 100, 2008.

[Varma2017] Varma, K., Guy, S. J. and Interrante, V. *Assessing the Relevance of Eye Gaze Patterns During Collision Avoidance in Virtual Reality.* In Lindeman, R. W., Bruder, G. and Iwai, D., Eds., ICAT-EGVE 2017 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments. The Eurographics Association, 2017.

[Vassallo2017] Vassallo, C., Olivier, A.-H., Souères, P., Crétual, A., Stasse, O. and Pettré, J. *How do walkers avoid a mobile robot crossing their way?* Gait & Posture, vol. 51, pages 97–103, 2017.

- [Vassallo2018] Vassallo, C., Olivier, A.-H., Souères, P., Crétual, A., Stasse, O. and Pettré, J. *How do walkers behave when crossing the way of a mobile robot that replicates human interaction rules?* *Gait & posture*, vol. 60, pages 188–193, 2018.
- [Vázquez2017] Vázquez, M., Carter, E. J., McDorman, B., Forlizzi, J., Steinfield, A. and Hudson, S. E. *Towards Robot Autonomy in Group Conversations: Understanding the Effects of Body Orientation and Gaze*. In *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, HRI '17*, pages 42–52, Vienna, Austria, 2017. ACM.
- [Warren1984] Warren, W. H. *Perceiving affordances: visual guidance of stair climbing*. *Journal of experimental psychology. Human perception and performance*, vol. 10, n° 5, pages 683–703, 1984.
- [Warren1987] Warren, W. H. and Whang, S. *Visual guidance of walking through apertures: body-scaled information for affordances*. *Journal of experimental psychology: human perception and performance*, vol. 13, n° 3, page 371, 1987.
- [Warren1988a] Warren, W. H. *Action modes and laws of control for the visual guidance of action*. In *Advances in psychology*, volume 50, pages 339–379. Elsevier, 1988.
- [Warren1988b] Warren, W. H., Hannon, D. J. et al. *Direction of self-motion is perceived from optical flow*. *Nature*, vol. 336, n° 6195, pages 162–163, 1988.
- [Warren1990] Warren, W. H. *The perception-action coupling*. In *Sensory-motor organizations and development in infancy and early childhood*, pages 23–37. Springer, 1990.

- [Warren1991] Warren, W. H., Mestre, D. R., Blackwell, A. W. and Morris, M. W. *Perception of circular heading from optical flow*. Journal of Experimental Psychology: Human Perception and Performance, vol. 17, n° 1, page 28, 1991.
- [Warren1998] Warren, W. H. *Visually controlled locomotion: 40 years later*. Ecological Psychology, vol. 10, n° 3-4, pages 177–219, 1998.
- [Warren2001] Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P. and Sahuc, S. *Optic flow is used to control human walking*. Nature neuroscience, vol. 4, n° 2, page 213, 2001.
- [Warren2006] Warren, W. H. *The dynamics of perception and action*. Psychological review, vol. 113, n° 2, pages 358–389, 2006.
- [Watamaniuk2003] Watamaniuk, S. N. and Heinen, S. J. *Perceptual and oculomotor evidence of limitations on processing accelerating motion*. Journal of vision, vol. 3, n° 11, pages 5–5, 2003.
- [Werkhoven1992] Werkhoven, P., Snippe, H. P. and Alexander, T. *Visual processing of optic acceleration*. Vision research, vol. 32, n° 12, pages 2313–2329, 1992.
- [Williams1999] Williams, A. M., Davids, K. and Williams, J. G. P. *Visual perception and action in sport*. Taylor & Francis, 1999.
- [Wilmot2010] Wilmot, K. and Barnett, A. L. *Locomotor adjustments when navigating through apertures*. Human Movement Science, vol. 29, n° 2, pages 289–298, 2010.
- [Winter1991] Winter, D. A. *Biomechanics and motor control of human gait: normal, elderly and pathological*. University of Waterloo Press, 1991.

- [Withagen2012] Withagen, R., De Poel, H. J., Araújo, D. and Pepping, G.-J. *Affordances can invite behavior: Reconsidering the relationship between affordances and agency*. *New Ideas in Psychology*, vol. 30, n° 2, pages 250–258, 2012.
- [Withagen2017] Withagen, R., Araújo, D. and de Poel, H. J. *Inviting affordances and agency*. *New Ideas in Psychology*, vol. 45, pages 11–18, 2017.
- [Woods2003] Woods, R., Shieh, J., Bobrow, L., Vora, A., Barabas, J., Goldstein, R. and Peli, E. *Perceived collision with an obstacle in a virtual environment*. *Investigative Ophthalmology & Visual Science*, vol. 44, n° 13, pages 4321–4321, 2003.
- [Wright2014] Wright, M. J. and Jackson, R. C. *Deceptive Body Movements Reverse Spatial Cueing in Soccer*. *PLOS ONE*, vol. 9, n° 8, pages 1–9, 08 2014.
- [Zaal2012] Zaal, F. T., Bongers, R. M., Pepping, G.-J. and Bootsma, R. J. *Base on balls for the Chapman strategy: Reassessing Brouwer, Brenner, and Smeets (2002)*. *Attention, Perception, & Psychophysics*, vol. 74, n° 7, pages 1488–1498, 2012.
- [Zeki1993] Zeki, S. *A vision of the brain*. Blackwell Scientific Publ., 1993.

List of Figures

1	City life, a crowd of people walking in multiple directions and completing several forms of interaction.	1
2	Two example environments of perception-action opportunities	3
1.1	Cross-sectional view displaying the anatomy of the eye.	7
1.2	Taxonomy of the theories of the mind, adapted from [Chemero2011].	9
1.3	Model of perception and action for neuro-musculoskeletal organisation after considering situated constraints. Adapted from [Temprado2001, Newell1994].	11
1.4	A visual conception of indirect and direct theories of perception and action, adapted from [Williams1999].	13
1.5	The perception and action loop with the consideration of behavioural dynamics. Adapted from [Warren2006]	15
1.6	Ambient optic array of a room from two points of observation.	16
1.7	Examples of textured gradation and an impression of distance. From [Bruce2003]	17

1.8	Representations of the optic array and optic flow	18
1.9	Simplified visualisation of Lee's tau, the optical expansion of a surface (R) as it approaches the eye of the observer. From [Chemero2011]. . .	20
1.10	Derivative of bearing angle	22
1.11	Modelled solutions of interception using a constant bearing strategy . .	23
1.12	An adaptation of Gibson's conception of affordances	27
1.13	Affordances expressed as actionable categories and as probabilistic functions	28
1.14	Two examples of occlusion techniques	30
1.15	An example point light display of a walker	31
1.16	Two examples of immersive technologies	32
1.17	An adaptation of the perception action loop that considers immersive technologies a part of the loop	35
1.18	Examples of modified glasses for the study of visual perception.	36
1.19	An illustration of <i>MPD</i> being calculated at four different times between two walkers on perpendicular paths	42
1.20	<i>MPD</i> evolution of ten grouped initial <i>MPD</i> conditions over normalised time.	43
1.21	A representation of the experimental setup of Bastin <i>et al.</i> , [Bastin2006b].	46
1.22	The experimental setup of Casanova <i>et al.</i> , [Casanova2015].	47
1.23	Representation of global and local motion cues	50
1.24	Three example images of differences in personal space	52

1.25	Personal space during locomotion	54
1.26	Personal space in reality and virtual reality	56
1.27	Types of collision	59
1.28	Collision avoidance behaviours	60
1.29	Experimental setup from Gérin-Lajoie <i>et al.</i> , 2005	63
1.30	Experimental setup from Cinelli, M. and Patla, A., 2007	64
1.31	Picture of experimental setup from Olivier and colleagues 2012	66
1.32	Three stages of interaction during collision avoidance	66
1.33	Experimental setup from Huber <i>et al.</i> , 2014	68
1.34	Experimental setup from Croft <i>et al.</i> , 2017	72
1.35	Joint attention task	75
1.36	Influence of avatars with and without gaze behaviour	76
1.37	Preliminary collision avoidance task with virtual gaze behaviour	77
1.38	Examples of variation in the visual appearance	79
2.1	An overview image of two paths intersecting and the possible visual cues available	81
3.1	Overview and third person perspective of the virtual environment	91
3.2	Visual appearances used as visual cues of local and global appearances	93
3.3	Mean <i>MPD</i> curves for each visual appearance condition and their three distinct stages of the interaction.	100

3.4	SPM evolution analysis of normalised <i>MPD</i>	101
3.5	Overall effect of each visual appearance on the crossing distance. . . .	104
3.6	Crossing distance differences between conditions where the participant crossed first or second.	105
3.7	Crossing distance for each condition of obstacle appearance, each con- ditional appearance plotted according to crossing order	105
4.1	An example of constant velocity <i>MPD</i> predicting future risk for curved trajectories	119
4.2	Layout of the virtual environment	120
4.3	Experimental rectilinear and curvilinear conditions	123
4.4	Participant's perspective while exiting the occluding corridor	124
4.5	Orientation angle of the virtual walker (VH) with respect to the parti- cipant (P)	127
4.6	Percentage of the number of inversions recorded while crossing paths with a virtual walker	130
4.7	SPM plots comparing rectilinear <i>MPD</i> with curvilinear <i>MPD</i>	132
4.8	Interaction effect between curve and crossing order on Reaction time .	134
4.9	Main effect of curve on Regulation time	135
4.10	<i>MPD</i> at reaction and regulation time	136
4.11	Interaction effect between curve and crossing order on final crossing distance.	138
4.12	Virtual walker orientation angles at reaction time	140

4.13	Virtual walker normalised orientation angles at reaction time	142
4.14	Virtual walker orientation angles at regulation time	143
5.1	Third person perspective of participants navigating through a virtual environment	160
5.2	Participants navigated from the red circle to the green cylinder using a joystick, avoiding gender matched virtual characters.	161
5.3	Boxplot of crossing distance (median, 1st-3rd quartiles, min-max values) depending on gaze and avoidance behaviour.	170
5.4	SPM analysis of <i>MPD</i> evolution, comparing effect of gaze within trials of No Avoidance and Avoidance conditions.	172
A.1	Third person perspective of a participant immersed within the virtual environment	238
A.2	Visual appearances of stimuli: full body (left), centre of gravity (centre), full body and centre of gravity combined (right)	241
A.3	Mean \pm SD percentage of success for four-way interaction between expertise, appearance, cut off times and motion during the perception task	246
A.4	Mean \pm SD percentage of success when considering effect of expertise during the perception task, for interactions between level and appearance, motion, cut off time, and the interaction between level, appearance and motion.	247
A.5	Mean \pm SD percentage of success for the interaction between appearance, motion and cut off times during the perception task.	249

A.6	Mean \pm SD percentage of success during the perception-action tasks, showing the overall three-way interaction for novices, and experts, during DM and NDM while interacting with CG, VH, or HC	251
A.7	Mean \pm SD percentage of success when considering effects observed for interactions during the perception-action task between level and appearance, level and motion, and appearance and motion.	253
A.8	Mean \pm SD reaction times during the perception-action tasks, showing the overall three-way interaction for novices, and experts, during DM and NDM while interacting with CG, VH, or HC	255
A.9	Average medio-lateral displacement during normalised time of expert and novice defenders in successfully and unsuccessfully detecting final crossing direction of the attackers deceptive motion	256
A.10	Average medio-lateral displacement during normalised time of expert and novice defenders in successfully and unsuccessfully detecting final crossing direction of the attackers non-deceptive motion	257
A.11	Mean \pm SD reaction times from interactions between level and appearance, level and motion, and motion and appearance	258
B.1	La vie urbaine, une foule de personnes marchant dans de multiples directions et réalisant différentes formes d'interaction.	267
B.2	Deux exemples d'environnements de couplage perception-action.	269
B.3	Vue d'ensemble de deux chemins qui se croisent et les indices visuels sur le marcheur observé considérés dans cette thèse	272
B.4	En haut). Vue d'ensemble de l'environnement virtuel utilisé pour l'expérience. En bas). Perspective à la troisième personne du participant	278

B.5	Apparences visuelles utilisées comme indices visuels des apparences locales et globales	282
B.6	Exemples de courbes présentées à partir de la configuration.	285
B.7	Perspective à la troisième personne des participants se déplaçant dans un environnement virtuel	287
B.8	Exemple de vitesse constante <i>MPD</i> prédisant le risque futur pour les trajectoires courbes.	300
B.9	Boxplot de distance de croisement (médiane, 1er-3ème quartiles, valeurs min-max) en fonction du regard et du comportement d'évitement. . . .	321
B.10	Analyse SPM de l'évolution du <i>MPD</i> , comparant l'effet du regard dans les conditions de No Avoidance et Avoidance	322

List of Tables

1.1	Collision detection decision tree	40
3.1	Median values of MPD_{tcross} depending on the obstacle visual appearance and MPD_{tsee}	103
4.1	Percentages of the number of collisions as a function of virtual walker path.	129
5.1	Total percentage of collisions observed for each MPD_{tsee} values (in meters) with respect to the conditions of gaze and avoidance	166
5.2	Total percentage of inversions of crossing order observed for each MPD_{tsee} (in meters) values with respect to the conditions of gaze and avoidance.	168
B.1	Pourcentage total des collisions observées pour chaque valeur de MPD_{tsee} (en mètres) par rapport aux conditions de regard et d'évitement.	316
B.2	Pourcentage total des inversions d'ordre de croisement observées pour chaque MPD_{tsee} (en mètres) par rapport aux conditions de regard et d'évitement.	318

Annexes

Annexe A

Global motion visualisation for detection of deceptive motion in rugby

Abstract

Rugby is a multifactorial sport that involves high-intensity bursts throughout longer low-intensity periods of a game. Frequently, players incorporate deceptive motions (e.g., a side-step) in order to pass their opponent. Previous works showed that expert defenders are more efficient in detecting deceptive motions. Their performance was shown to be correlated with the evolution of the centre of gravity of the attacker, suggesting that experts may rely on global motion cues. This study aims at investigating whether a representation of centre of gravity can be useful for training purposes, by using this representation alone or by combining it with the local motion cues given by body parts. We designed an experiment in virtual reality to control the motion cues available to the defenders. Sixteen healthy participants (seven experts and nine novices) acted as defenders while a virtual attacker approached. The virtual attacker would appear as a full human, a human with its centre of gravity visible or only the centre of gravity present. Participants completed two separate tasks. The first was a time occlusion perception task, where the attacker disappeared after 100ms, 200ms or 300ms after the initial change in direction, where participants would indicate the direction they believed the attacker would pass. The second was a perception-action task where participants were instructed to intercept the oncoming attacker by displacing medio-laterally. The attacker would perform a non-deceptive motion, running directly toward the final passing direction or a deceptive motion, performing a side-step initially toward a false direction before quickly reorienting in their true direction. There was a main effect of expertise, appearance, cut off times and motion on correct responses during both tasks. There was an interaction between visual appearance and expertise, and between motion type and expertise during the perception task, however, this interaction was not present during the perception-action task. We observed that experts maintained superiority in the perception of deceptive motion; however when the visual appearance is reduced to global motion alone the difference in superiority between novices and experts is reduced. We further explore the interactions and discuss the effects observed for the visual appearance and expertise.

Keywords: Deception, Sport, Rugby, Perception, Perception-action, Anticipation, centre of gravity

A.1 Introduction

Rugby, as per field-based team sports, is characterised by brief high-intensity efforts of running and acceleration over longer low-intensity periods [Austin2011]. The game consists of two teams competing over two 40-minute halves for the highest accumulation of points scored, with the greatest number of points being awarded for carrying the ball over the opponents try-line. Therefore, a primary objective of the game is to gain territory by advancing the ball towards the opponents try-line. In order to prevent the advancement of the attacking team (the ball carrying team) and possibly gain possession, the defending team will tackle the player that is carrying the ball. A tackle as defined by the international governing body of rugby is when the ball-carrier is held by one or more opponents and brought to the ground. Due to this nature, a proportion of the game consists of tackling [Gabbett2012, Gabbett2016], where an increased number of tackles has been associated to game success rate [Hulin2015a, Hulin2015b]. To gain an attacking advantage, attackers can use their bodily movements to generate deceptive motion (e.g., a side-step in rugby), misleading the defender with the intention to run in one direction while actually intending to run in the other direction [Jackson2006, Brault2010, Brault2012, Wright2014]. While generally, motor control and orientation of the body is coordinated according to a top-down strategy of head and gaze alignment before body reorientation [Patla1991], in a sport-specific context of deceptive motion Brault *et al.* [Brault2010] reported a bottom-up strategy, where a displacement of support is prior to upper trunk and head reorientation. Further, Brault *et al.* [Brault2010] reported that the centre of mass displacement on the medio-lateral plane was minimised, it was the upper limbs, head, and trunk that were organised for deception. Although trunk yaw was similar between deceptive and non-deceptive motion, the upper trunk angular movement changes (i.e., shoulders) would be exaggerated in deception.

Within the attacker-defender dyad, while the attacker intends to deceive the defender with specific body motion, the defender utilises the relevant visual cue information available to intercept the attacker [Kunde2007]. Previous studies demonstrated the ability of observers to distinguish between a deceptive and non-deceptive motion of another person [Runeson1983b]. Using point-light displays, participants were required to observe actors lifting boxes of various weights. It was reported that the participants could perceive the action of a box being picked up, even from a limited point-light display, further, also the relative weight and if the actor was attempting to deceive the observer about the true weight. In a sports specific context, authors showed that the ability to perceive and to correctly anticipate an opponent motion is related to the level of expertise (see [Jackson2006], [Cañal-Bruland2010] and [Mori2013]). Jackson *et al.* [Jackson2006] were the first to study deceptive movement and anticipation in sport, using temporally occluded videos of an attacker approaching a camera, the perspective of a defender. Participants were given the role of the defender and required to predict the side which the attacker would pass, left or right. The attacker would undertake a non-deceptive movement or a deceptive movement. From these findings, it was concluded that expertise may affect anticipation ability, where experts more accurately detect final passing direction when compared to novices [Jackson2006]. Since, the study of perception, anticipation and deceptive motion within sporting contexts has been further studied, confirming the superiority of expertise [Renshaw2000, Sinnett2010, Mori2013, Wright2014, Brenton2016]. However, few studies have considered the underlying mechanisms to explain these findings [Huys2009, Brault2012, Lopes2014]. Huys *et al.* [Huys2009] studied the manipulation of corresponding dynamics of a tennis serve through point-light displays. They reported that spatial occlusion impacted the dominant dynamics, additionally, suggesting cue information pick up was more global (i.e., whole body movement) than local (i.e., limb motion). Furthermore, Lopes *et al.* [Lopes2014] performed a biomechanical analysis of penalty kicks in soccer and reported that limbs providing local information were modified during the early stages of approach for deceptive motion. Finally, Brault *et al.*

[Brault2012] reported that the performance of experts correlated with the evolution of the perceptual variable tau (cf., [Lee1976]), that is, experts fixated on honest signals from global motion (e.g., Centre of Gravity (CG)) than local ones (e.g., limbs). While these findings were correlated, they have yet been investigated directly.

While Brault *et al.* [Brault2012] showed how tau of parameters such as CG explained performance superiority in experts, no competitive study has directly studied the effects of intercepting CG or representations of tau in place of an attacker. In non-competitive settings, Savelsbergh *et al.* [Savelsbergh1991] showed that subjects could regulate their hand aperture through optical size expansion alone (i.e., tau [Lee1976]). Additionally, Lynch *et al.* [Lynch2017] studied interactions of a crossing task with varying global and local obstacle appearances, a cylinder, CG, a virtual human, the trunk alone and the legs alone, within virtual reality. They reported differences of crossing distance between the global and local visual cue appearances but reported no difference in the ability to complete the task. Finally, Meerhoff *et al.* [Meerhoff2014] also studied the role of global and local motion information during a distance regulatory locomotor task. Their findings suggested that ability to complete the task, while interacting with a large sphere or a virtual human, was not impeded; however, there was a temporal advantage when both local and global motion cues were available. We can then wonder how to train novices to perceive these relevant motion cues. In this context, virtual reality is a powerful tool that has become increasingly readily available for ecological and psychological studies [Meerhoff2014, Lynch2017] and as a training tool in sport (see [Miles2012] for a review). Training through virtual reality allows for additional enrichment of the environment (augmentation), an ability to reduce the task to several smaller steps (simplification) and change the speed or distort the environment (variability) [Ruffaldi2011]. Additionally, virtual reality allows for the uncoupling of perception-action, although this may lead to biased results [Dicks2010a], better anticipation skills remains widely debated within the literature, through visual expertise or motor action capability expertise [Güldenpenning2017].

A.1.1 Objectives and Contribution

From the work of [Brault2012], there was a reported correlation with the expansion rate of tau of the CG and rate of success in expertise. This observed correlation is interesting as it can be interpreted that global displacement of CG may be perceptually important, a focal point of attention during interaction, which in turn can be treated as a trainable variable to attune defender attention. This work focuses on the visual cues that can be conveyed by an attacker and perceived by the defender. Our objectives are two-fold: firstly, where previous studies have shown a correlation of CG rate of expansion and performance to intercept an attacker, we aim to investigate whether this global motion cue depicts sufficient information in detecting deceptive attacker motion. Secondly, contrary to experts, the performance of novices is correlated with the tau of upper trunk. Therefore we aim to investigate whether an emphasis of CG could act as an aid if combined with limbs local cues, where we would expect a more significant increase of correct response performance for novices.

To answer these questions, we proposed to manipulate the visual appearance of the attacker. To preserve and repeat kinematic motion while manipulating visual appearance, we conducted our experiment in virtual reality. The application of virtual reality in ecological perception and action has been proven a powerful tool [Loomis1999] although it is not without limitations, as there exist variances in depth perception [Loomis2003] and forward gaze-driven speed is underestimated compared to actual speed [Banton2005]. Considering these notable variances, virtual reality has been validated to conform with reality; a sense of personal space [Gérin-Lajoie2008], interactions with virtual humans [Olivier2017, Lynch2017, Caruana2017] and within competitive settings [Brault2012].

We completed two experiments, both in virtual reality, where participants were presented a dynamic virtual attacker on an approach to a defender (the participant). Between trials, the visual appearance of the virtual attacker would vary the amount of global

and local visual cues available. In the first experiment, we focused on perception, where participants recorded their responses through a peripheral device, this first task aimed to identify variances from the manipulation of available perceptual information. We used this paradigm since our experiment involved both inexperienced novices and highly competitive experts, as specific responses observed in the perception-action condition could be attributed to the physical (action) capabilities [Güldenpenning2017]. For the second experiment, we focused on perception-action, the position of the participant was tracked during the interaction, investigating perceptual expertise with reaction time responses. This experiment was designed to complement the results of the first experiment and to consider the results of previous works that showed the importance of preserving the representativeness of experimental task designs when exploring the performance of the athletes, particularly in time-constrained actions [Van der Kamp2008, Travassos2013].

In that context, we formulated two hypotheses:

- H1: considering the previous findings of a correlation between CG motion and performance in expert rugby players [Brault2012], we hypothesised that performance will not be impeded for experts whilst interacting with only a visual representation of CG.
- H2: we hypothesise that the presence of CG will act as an aid and the performance of novices will be greater whilst interacting with a combination of a virtual attacker and CG than whilst interacting with a virtual attacker alone.

Our first contribution is to design an experimental platform in virtual reality to study the influence of global and local motion cues within a rugby attacker-defender dyad task. Our second contribution is that while global motion can be visualised and acted upon, there is insufficient information to maintain success rate. Local cues such as limbs motion and trunk orientation are necessary for effective perception and perception-action tasks. To demonstrate this, we have formulated the paper in the following way: the method section describes both perception and perception-action tasks separately, high-

lighting their differences. Results from the perception and perception-action task are presented as separate sections, and we discuss the findings collectively in the discussion.

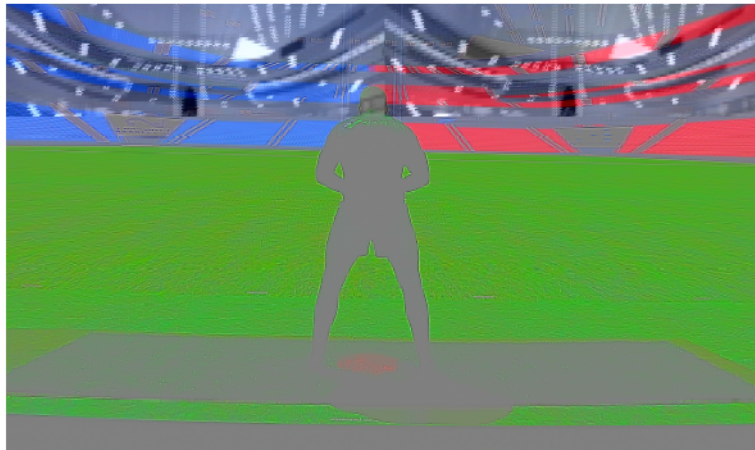


Figure A.1 - Third person perspective of a participant immersed within the virtual environment

A.2 Method

A.2.1 Participants

Seven expert rugby players aged 24.71 ± 2.43 (mean \pm SD) and nine inexperienced subjects aged 27.56 ± 10.69 years participated in this study. All participants had normal or corrected-to-normal vision and no history of disease or impairment which could have affected their ability of participation. The expert rugby players competed regularly in the French second national league (ProD12) with 16.29 ± 4.23 years of experience in playing rugby. Novices were university staff and students with no prior experience of competitive rugby. This study was carried out in accordance with the recommendations of the research institute. All participants gave their written informed consent in accordance with the declaration of Helsinki.

A.2.2 Apparatus

Experiments took place in a 4-screen Computer Assisted Virtual Environment (CAVE), which was 9m wide, 3m high and 3m deep. The CAVE was fitted with a synthetic all weather turf surface for increased immersion during experimentation. It was equipped with 13 projectors with 15MPixels resolution in total. The 3D environment display and character animation (Figure A.1) was designed in the Unity game engine. Multi-surface rendering was performed by the MiddleVR plugin. Active stereoscopy was achieved with Volfony ActiveEyes Pro Radiofrequency wearable glasses. Glasses were tracked by a 16 camera ART tracking system.

A.2.3 Stimulus

For all trials, an attacker was positioned in front of the participant and advanced towards the participant after a visual countdown of three seconds. Attacker motion was realised through previously captured motion of eight French national league rugby players [Brault2012] using the optoelectronic motion capture ViconMX system (Oxford Metrics, Oxford, UK). A total of 16 motions were presented as stimuli; attackers either performed one of 8 deceptive motions (DM), otherwise known as a side-step, or one of 8 non-deceptive motions (NDM), no change of direction after initial reorientation. Several attacker motions were used, opposed to the repetition of one attacking motion, to reduce possible identification of repeated motions.

A.2.4 Appearances

To investigate the role of the centre of gravity in deceptive motion detection, we have manipulated the visual appearance of a virtual attacker using the following conditions, as illustrated in figure A.2:

1. Full body: A mobile mannequin with a shoulder width of 37cm and hip width of 27cm, was rendered without a face to avoid any influence of gaze direction. Furthermore, the motion was animated as carrying an invisible ball to maximise character perception and reduce occlusion of character motion by the presence of a rugby ball.
2. Sphere: With recent findings of Brault and colleagues [Brault2012] suggesting a strong correlation between CG and interception during a deceptive sporting task in terms of success, we chose to remove all body encasing information and use a small sphere (8cm diameter) as an appearance of CG. Such a reduction would

remove all information including, orientation and ground contact.

3. Combination: Both a full body attacker with their CG are presented to the participant, a combination of orientation and ground contact with the less deceptive motion of CG being present.

Note that condition 1) served as a control condition, using a virtual human (VH), condition 2) completely removed any local motion cues leaving only global information of motion (CG), finally, condition 3) combined both VH local and CG global motion cues to maximise stimuli (HC).

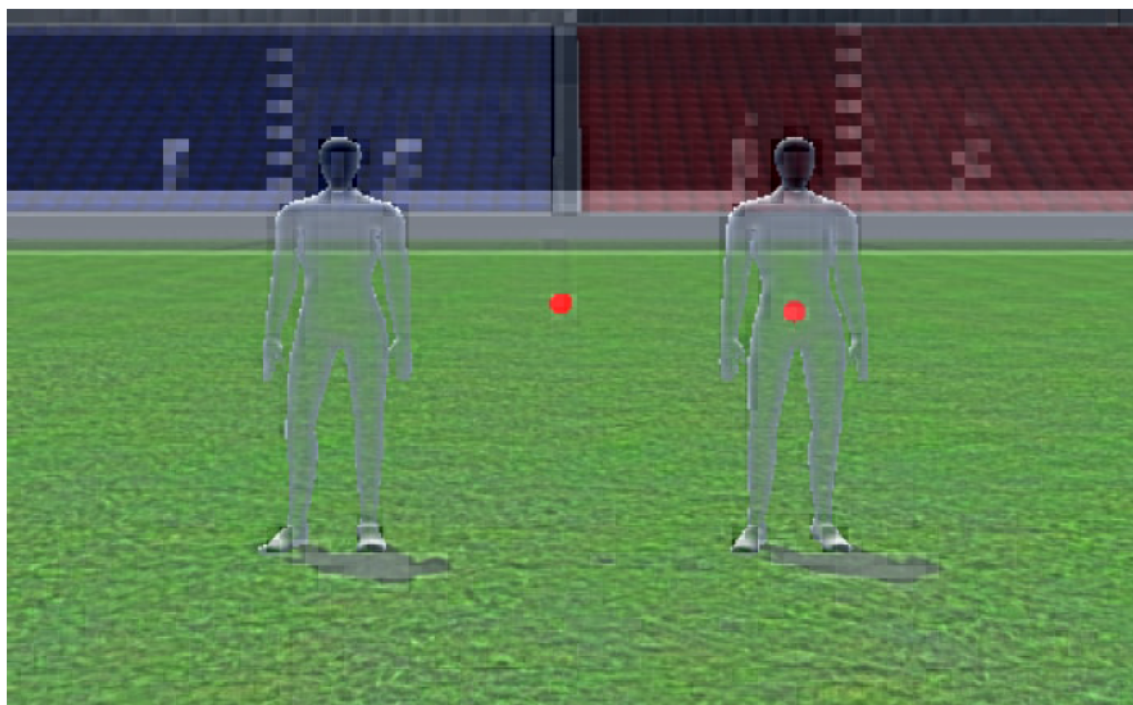


Figure A.2 - Visual appearances of stimuli: full body (left), centre of gravity (centre), full body and centre of gravity combined (right)

A.2.5 Perception task

Participants were immersed in a virtual environment (Figure A.1), where they were instructed to stand in a designated location, as indicated by a red circle on the floor of the immersive environment that remained visible throughout. Using a Latin square design, experimentation divided into three randomised blocks of attacker appearance (Figure A.2). Within the perception only task for each visual appearance, we also set conditions based on an occlusion time paradigm, allowing to test for the quantity of visual information on decision processing for future actions. The moment of toe off, as the attacker's foot leaves the ground, before reorientation occurred was used as a reference point for all attacker motions (T0). Thereafter, our three experimental conditions consisted of the duration of visual appearance before occlusion, cut off times were 100ms (T1), 200ms (T2), and 300ms (T3). Participants were informed that they would be acting as a defender and would be required to detect the direction which the attacker would go after occlusion for a successful interception. There was no feedback of success or failure throughout the experiment. For each visual appearance, a total of 16 attacking motions (8 DM and 8 NDM) were repeated with three different occlusion cut off times (100ms, 200ms, and 300ms). After occlusion participants were required to indicate, using the hand-held wand, which direction the attacker was going to pass. Participants were given a period of familiarisation prior to data capture.

For each block of visual appearance, these conditions were presented randomly within and between subjects. In total, each participant performed 144 trials (3 appearances x 3 cut off times x 16 motions). The duration of the experiment per participant, including training and resting periods, was 30 minutes.

A.2.6 Perception-action task

Participants were immersed in the same virtual environment, and the appearances were presented in the same order as the perception task, the conditions per block were randomised independently. For the perception-action task, there was no occlusion paradigm, and the attacker would approach and pass the defender. Participants were informed that they maintained the role of defender, however, in this instance the defender would not disappear but continue running. They were then instructed to move medio-laterally in an attempt to intercept the attacker. Participants wore a belt fitted with reflective markers, and their medio-lateral displacement was tracked using the 16 camera ART tracking system. We used the same threshold of displacement velocity as [Brault2012], with speeds greater than 0.5m/s were used to record initial response after T0. Additionally, reaction times were recorded at the instance of the initial response. Similar to the perception task, participants were provided a period of familiarisation to adapt to the perception-action task.

Similarly, for each block of visual appearance, these conditions were presented randomly within and between subjects. In total, each participant performed 48 trials (3 appearances x 16 motions). The duration of the experiment per participant, including training and resting periods, was 15 minutes.

A.2.7 Analysis

Perception responses and perception-action belt motion were post-processed using customised MATLAB scripts (Mathworks 2016b), responses were then expressed as a percentage of success (mean \pm SD). We set the level of significance to $\alpha = 0.05$. A Kolmogorov-Smirnov test was performed to evaluate whether data followed a normal distribution. For both experiments, the dependent variable was the rate of success, and a general linear mixed model analysis was used to determine the effect of appearance, type of motion (DM and NDM) and cut off times for the perception task and to determine the effect of appearance and motion for the perception-action task. Mauchly's test of sphericity was used for assumption, and a Greenhouse-Geisser was used as a correction when sphericity had been violated. Finally, effect sizes were computed as partial eta squared η_p^2 and pairwise comparisons were used for further post-hoc analysis.

A.3 Perception results

A.3.1 Overall performance

Overall, there was a main effect of expertise ($F(1,14) = 31.119$, $p < 0.001$, $\eta_p^2 = 0.69$), appearance ($F(2,28) = 127.826$, $p < 0.001$, $\eta_p^2 = 0.90$), cut off times ($F(1.232,17.247) = 33.115$, $p < 0.001$, $\eta_p^2 = 0.70$) and motion ($F(1,14) = 541.149$, $p < 0.001$, $\eta_p^2 = 0.98$). Overall, experts were more successful ($75.30 \pm 31.92\%$) than novices ($61.27 \pm 38.13\%$), appearance CG had a smaller success rate ($48.57 \pm 35.72\%$) than VH ($76.43 \pm 31.67\%$) and HC ($77.21 \pm 33.69\%$), cut off time T3 had the greatest rate of success ($75.65 \pm 35.83\%$), then T2 ($68.75 \pm 35.31\%$) and T1 had the lowest rate of success ($57.81 \pm 35.46\%$), and non-deceptive motion was greater ($92.27 \pm 14.41\%$) than the deceptive motion ($42.53 \pm 34.23\%$).

Figure A.3 presents the success rate for each individual condition, there was no four-way interaction between all dependent variables; visual appearance, cuts off times, motion type and expertise level ($F(4,56) = 0.391$, $p = 0.814$). From this we can observe during NDM, whilst interacting with CG, an increasing rate of success from T1 to T3 for both experts and novices, whilst interacting with VH or HC the rate of success is similar for T1, T2 and T3. During DM, whilst interacting with CG, we observe a decreasing rate of success from T1 to T3 for experts and a similar response for novices from T1 to T2 and T3, while VH and HC interactions show an increase of success rate from T1 to T2 and T3 for both experts and novices. Additionally we observe that experts and novices had similar rates of success for NDM, for DM experts had a greater rate of success than novices except while interacting with CG at T3.

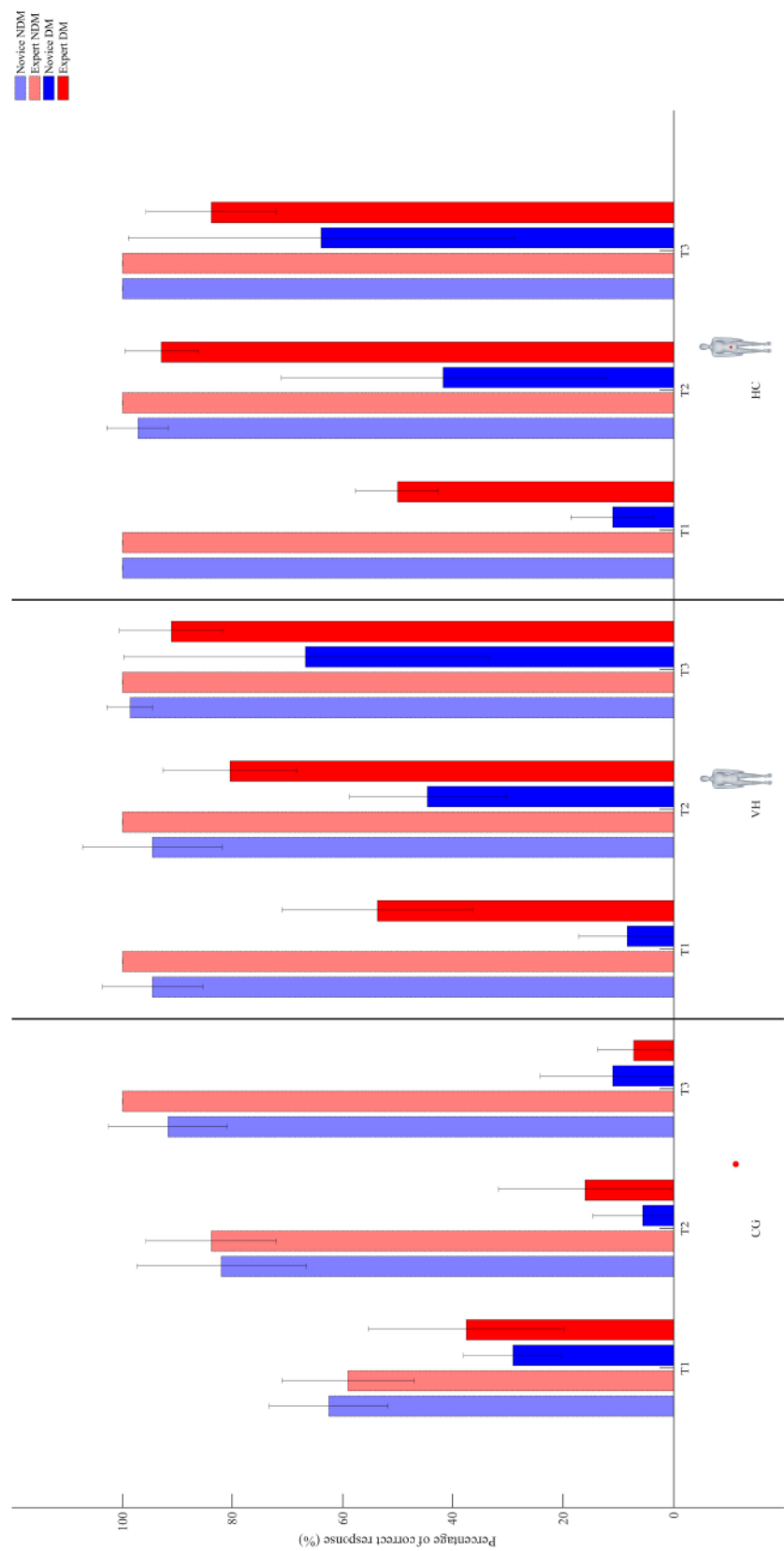


Figure A.3 - Mean±SD percentage of success for four-way interaction between expertise, appearance, cut off times and motion during the perception task

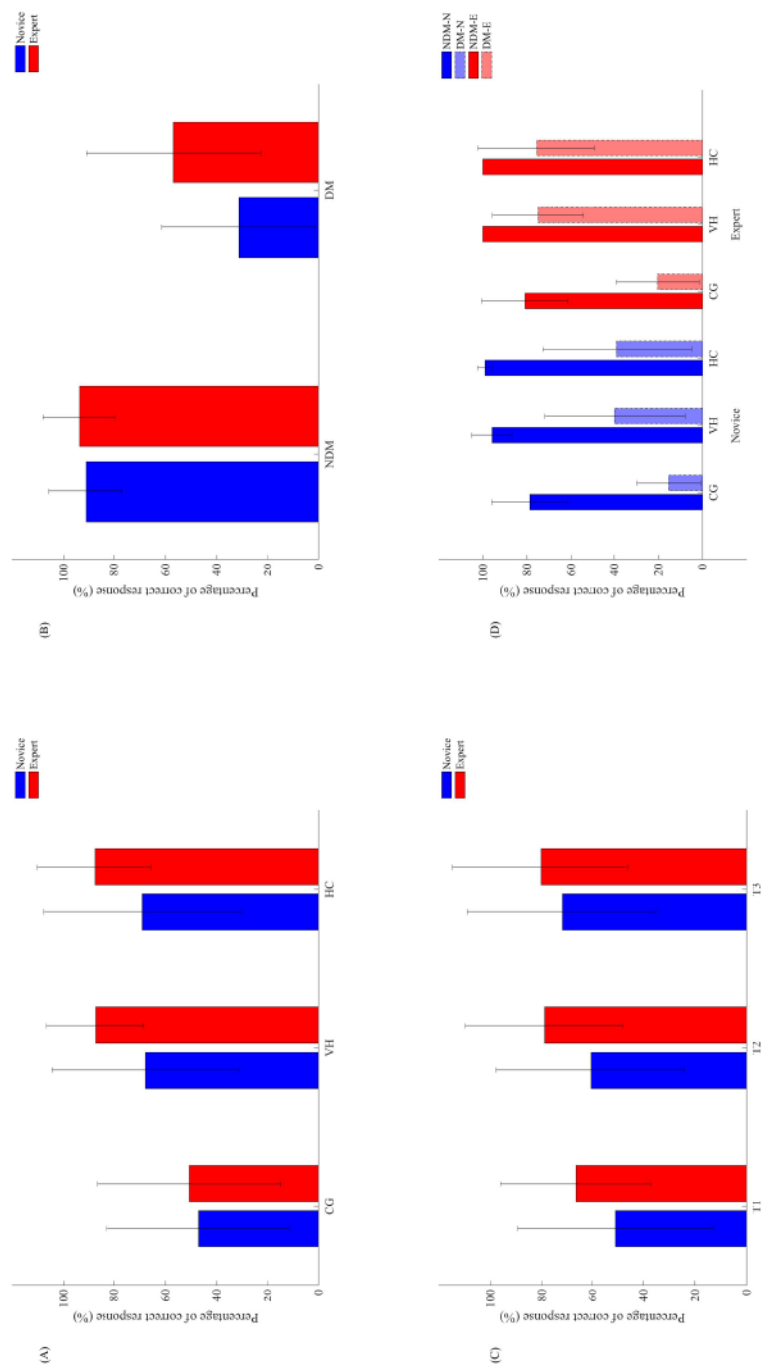


Figure A.4 - Mean±SD percentage of success when considering effect of expertise during the perception task, for interactions between level (novices (N) blue and experts (E) red) and appearance (A), motion (DM and NDM) (B), cut off time (C), and the interaction between level, appearance and motion (D).

A.3.2 Expertise

Further investigating the main effect of expertise, there was a significant two-way interaction between the visual appearance and the expertise (Figure A.4A) of the participant ($F(2,28) = 9.166$, $p < 0.001$, $\eta_p^2 = 0.40$); where we observe similar rates of success for experts ($50.60 \pm 36.10\%$) and novices ($46.99 \pm 35.68\%$) whilst interacting with CG, and experts were more successful than novices whilst interacting with VH ($87.50 \pm 19.13\%$ and $67.82 \pm 36.63\%$, respectively) and HC ($87.80 \pm 22.34\%$ and $68.98 \pm 38.60\%$, respectively).

There was a significant two-way interaction between motion (Figure A.4B) and expertise ($F(1,14) = 31.144$, $p < 0.001$, $\eta_p^2 = 0.69$); where we observe similar rates of success for experts and novices during NDM ($93.65 \pm 14.35\%$ and $91.20 \pm 14.45\%$, respectively), while experts were more successful than novices for DM ($56.94 \pm 34.11\%$ and $31.33 \pm 30.05\%$, respectively).

However, there was no significant two-way interaction between cut off times (Figure A.4C) and expertise ($F(1.232,17.247) = 2.710$, $p = 0.112$); we observe that experts were continually more successful than novices for T1 ($66.67 \pm 29.43\%$ and $50.93 \pm 38.38\%$, respectively), T2 ($78.87 \pm 30.80\%$ and $60.88 \pm 36.83\%$, respectively) and T3 ($80.36 \pm 34.28\%$ and $71.99 \pm 36.90\%$, respectively).

When considering the three-way interaction between expertise, appearance and motion (Figure A.4D), there was a significance ($F(1.443,28) = 7.795$, $p = 0.006$, $\eta_p^2 = 0.36$); where we observe that experts and novices had an increased rate of success when interacting with VH (100% and $95.83 \pm 9.17\%$, respectively) and HC (100% and $99.07 \pm 3.34\%$, respectively) than CG ($80.95 \pm 19.61\%$ and $78.70 \pm 17.27\%$, respectively) during NDM, however, experts had a greater rate of success from interacting with CG ($20.24 \pm 18.74\%$) to VH ($75 \pm 20.54\%$) and HC ($75.60 \pm 26.66\%$) during DM than novices ($15.28 \pm 14.43\%$, $39.81 \pm 31.97\%$ and $38.89 \pm 33.85\%$, respectively).

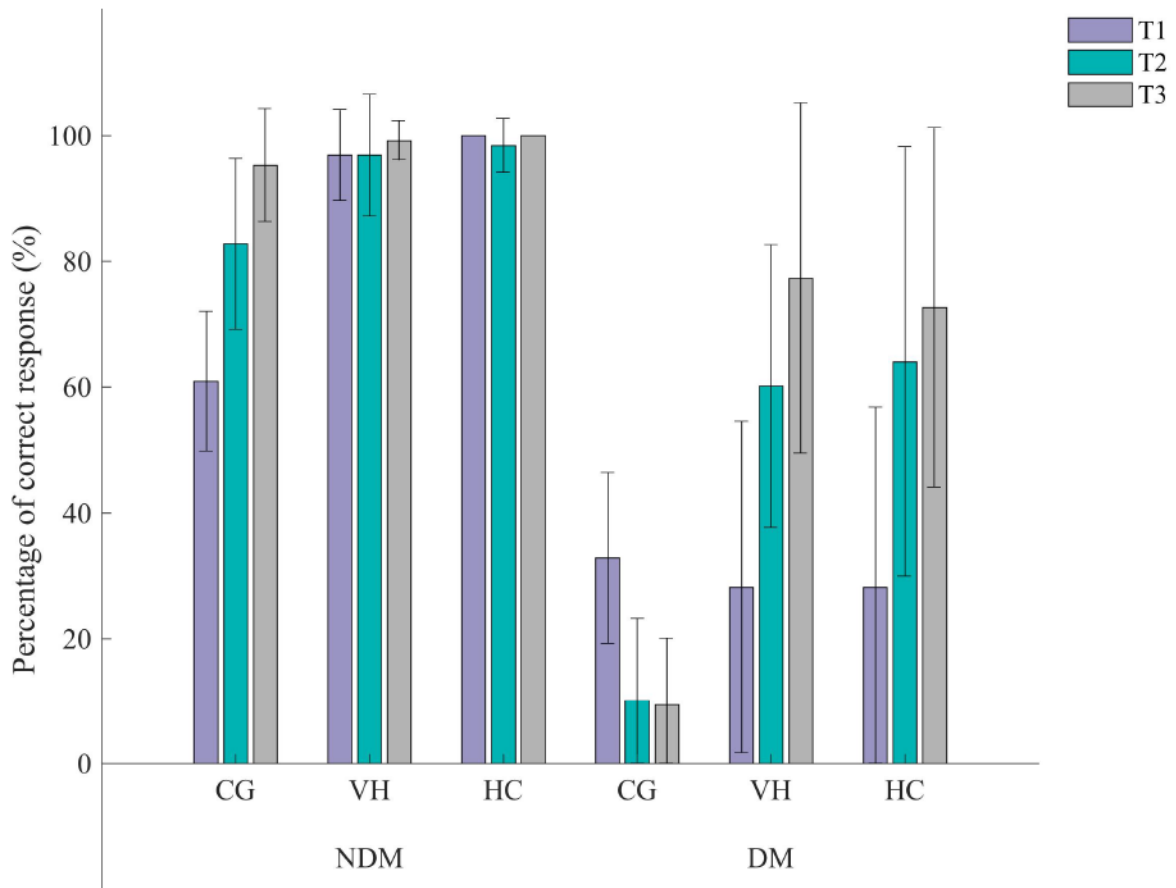


Figure A.5 - Mean \pm SD percentage of success for the interaction between appearance, motion and cut off times during the perception task.

A.3.3 Appearance

Irrespective of expertise, there was a significant two-way interaction between the visual appearance and cut off times ($F(4,56) = 9.971$, $p < 0.001$, $\eta_p^2 = 0.42$); where we observe that the rates of success were fewer whilst interacting with CG for T1 ($46.88 \pm 18.78\%$), T2 ($46.48 \pm 39.17\%$) and T3 ($52.34 \pm 44.73\%$) than VH and HC, which had similar rates of success for T1 ($62.50 \pm 39.78\%$ and $64.06 \pm 41.61\%$, respectively), T2 ($78.52 \pm 25.25\%$ and $81.25 \pm 29.61\%$, respectively) and T3 ($88.28 \pm 22.44\%$ and $86.33 \pm 24.25\%$, respectively).

Additionally, there was a significant two-way interaction between the visual appearance and motion ($F(1.443,28) = 13.969$, $p < 0.001$, $\eta_p^2 = 0.50$); where we observe that CG during NDM ($79.69 \pm 18.16\%$) had a lower rate of success than VH ($97.66 \pm 7.13\%$) and HC ($99.48 \pm 2.52\%$), during DM this difference became greater between CG and the VH and HC counterparts ($17.45 \pm 16.46\%$, $55.21 \pm 32.50\%$ and $54.95 \pm 35.71\%$, respectively).

Developing from the two-way interactions, there was an interaction between appearance, cut off times and motion ($F(4,56) = 41.932$, $p < 0.001$, $\eta_p^2 = 0.75$) (Figure A.5); where, during NDM the rate of success was similar for VH and HC at T1 ($96.88 \pm 7.22\%$ and 100% , respectively), T2 ($96.88 \pm 9.68\%$ and $98.44 \pm 4.27\%$, respectively) and T3 ($99.22 \pm 3.13\%$ and 100% , respectively), where CG increased cut off times ($60.94 \pm 11.06\%$, $82.81 \pm 13.60\%$ and $95.31 \pm 8.98\%$, respectively). During DM, at T1, CG, VH and HC were similar ($32.81 \pm 13.60\%$, $28.13 \pm 26.42\%$ and $28.13 \pm 28.69\%$, respectively), at T2, CG had a smaller success rate ($10.16 \pm 13.09\%$) than VH ($60.16 \pm 22.46\%$) and HC ($64.06 \pm 34.12\%$) and at T3, CG had a smaller success rate ($9.38 \pm 10.70\%$) than VH ($77.34 \pm 27.85\%$) and HC ($72.66 \pm 28.58\%$). The rate of success during NDM for all appearances and cut off times was greater than those observed during DM.

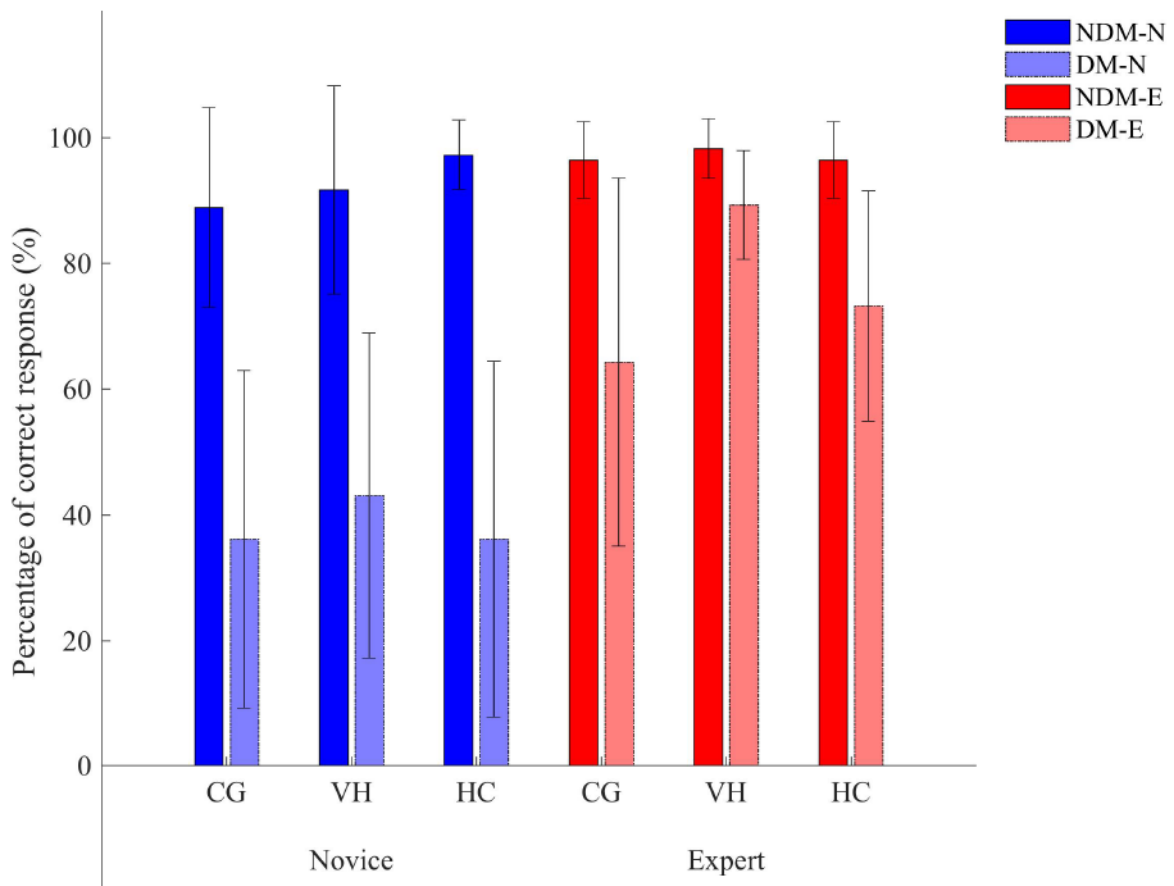


Figure A.6 - Mean \pm SD percentage of success during the perception-action tasks, showing the overall three-way interaction for novices (N, blue), and experts (E, red), during DM and NDM while interacting with CG, VH, or HC.

A.4 Perception-Action results

A.4.1 Performance

Overall, there was a main effect of expertise ($F(1,14) = 9.744$, $p=0.008$, $\eta_p^2=0.41$), experts had a greater rate of success ($86.01\pm19.25\%$) than novices ($65.63\pm32.79\%$). There was a main effect of motion ($F(1,14) = 77.260$, $p<0.001$, $\eta_p^2=0.85$), NDM had a greater rate of success ($94.53\pm10.91\%$) than DM ($54.69\pm30.58\%$). Additionally, there was a main effect of visual appearance ($F(1.427,28) = 4.693$, $p=0.031$, $\eta_p^2=0.25$) between CG ($70.31\pm32.03\%$), VH ($78.91\pm28.12\%$) and HC ($74.61\pm31.19\%$).

There was no three-way interaction (Figure A.6) between expertise, visual appearance and motion ($F(2,28) = 1.131$, $p=0.337$). From this we observe that experts and novices had no significant difference for rate of success ($96.43\pm6.10\%$ and $88.89\pm15.87\%$, respectively) whilst interacting with CG during NDM and ($64.29\pm29.25\%$ and $36.11\pm26.84\%$, respectively) during DM. Interactions with VH for experts ($98.21\pm4.72\%$) and novices ($91.67\pm16.54\%$) had no significant difference during NDM, also interactions with HC ($96.43\pm6.10\%$ and $97.22\pm5.51\%$, respectively) reported no difference. During DM, experts had a greater rate of success than novices whilst interacting with VH ($89.29\pm8.63\%$ and $43.06\pm25.85\%$, respectively) and whilst interacting with HC ($73.21\pm18.30\%$ and $36.11\pm28.26\%$, respectively).

Considering two-way interactions, there was no significant interaction between visual appearance and expertise ($F(1.427,28) = 1.320$, $p=0.280$)(Figure A.7A), where we observe that experts had a greater rate of success whilst interacting with CG, VH and HC ($80.36\pm26.27\%$, $93.75\pm8.13\%$ and $84.82\pm17.80\%$, respectively) than novices ($62.50\pm34.57\%$, $67.36\pm32.69\%$ and $66.67\pm37.13\%$, respectively).

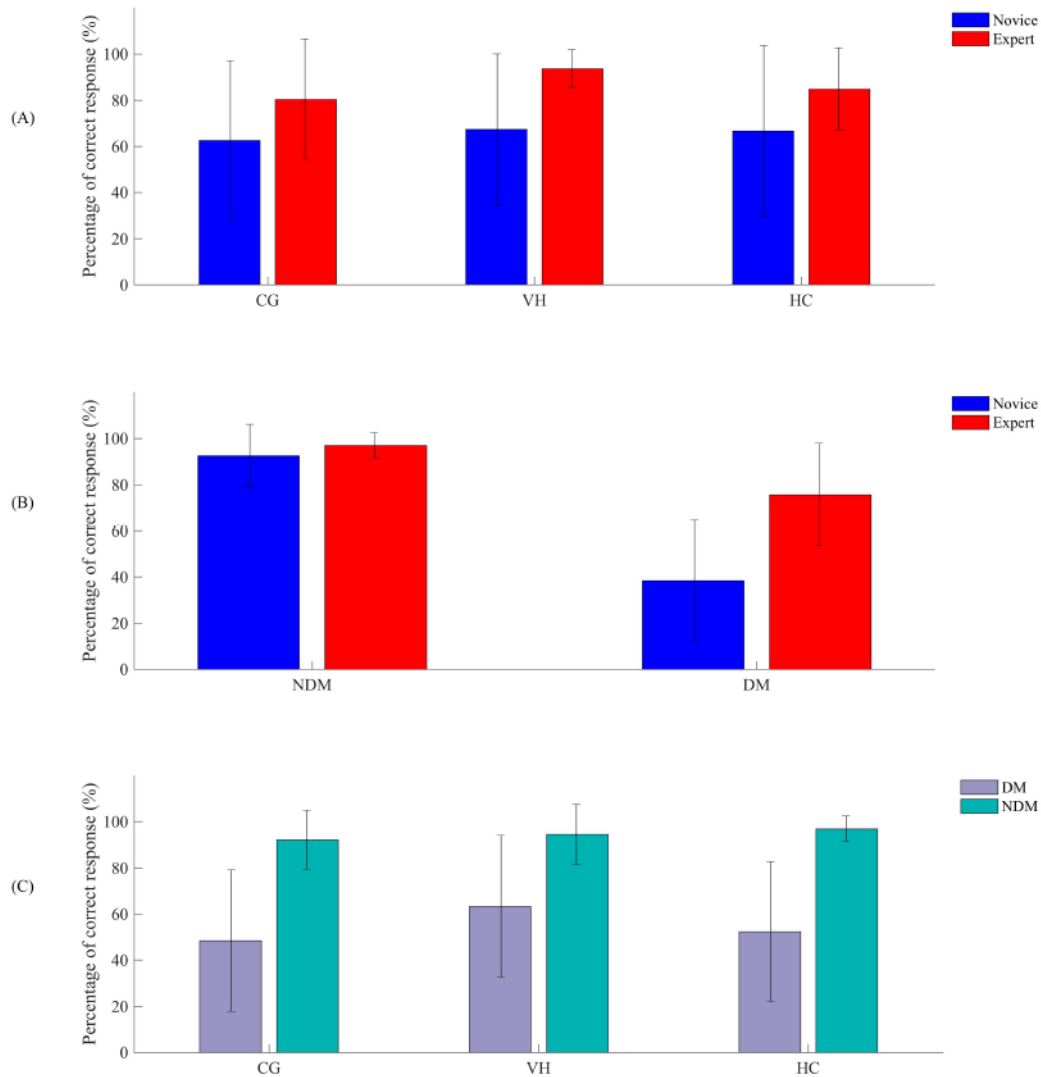


Figure A.7 - Mean \pm SD percentage of success when considering effects observed for interactions during the perception-action task between level and appearance (A), level and motion (B) and appearance and motion (C).

However, there was a significant interaction between motion and expertise ($F(1,14) = 14.490$, $p=0.002$, $\eta_p^2=0.51$)(Figure A.7B), where we observe that experts and novices had greater rates of success during NDM ($97.02\pm5.46\%$ and $92.59\pm13.54\%$, respectively) than during DM where experts had a greater rate of success ($75.60\pm22.18\%$) than novices ($38.43\pm26.16\%$).

There was no significant interaction between visual appearance and motion ($F(2,28) = 2.499$, $p=0.100$)(Figure A.7C), where the rate of success was greater during NDM for CG, VH and HC ($92.19\pm12.81\%$, $94.53\pm12.88\%$ and $96.88\pm5.59\%$, respectively) than during DM ($48.44\pm30.58\%$, $63.28\pm30.78\%$ and $52.34\pm30.35\%$, respectively).

A.4.2 Reaction time

There was no significant three-way interaction between expertise, appearance and motion (Figure A.8) on reaction times ($F(2,28) = 0.405$, $p=0.671$). Where we observe that experts generally had slower reaction times during DM (CG = $0.84\pm0.09s$, VH = $0.66\pm0.03s$, and HC = $0.61\pm0.06s$) and NDM (CG = $0.71\pm0.07s$, VH = $0.54\pm0.06s$, and HC = $0.52\pm0.08s$) than novices during DM (CG = $0.70\pm0.17s$, VH = $0.50\pm0.20s$, and HC = $0.53\pm0.19s$) and NDM (CG = $0.60\pm0.13s$, VH = $0.44\pm0.19s$, and HC = $0.45\pm0.15s$). Figures A.9 and A.10 presents the mean medio-lateral displacement of the defender as a function of normalised time, showing average correct and incorrect responses for both novices and experts.

Independently, there was no main effect of expertise ($F(1,14) = 2.906$, $p=0.110$) where experts had a reaction time of $0.65\pm0.13s$ and novices had a reaction time of $0.54\pm0.19s$. There was an effect of appearance ($F(2,28) = 89.224$, $p<0.001$, $\eta_p^2=0.86$), CG had a slower reaction time ($0.71\pm0.15s$) than VH ($0.53\pm0.16s$) and HC ($0.52\pm0.14s$). Finally, there was a main effect of motion ($F(1,14) = 36.839$, $p<0.001$, $\eta_p^2=0.73$), where DM had slower reaction times ($0.63\pm0.18s$) than NDM ($0.54\pm0.15s$).

There were no significant two-way interaction between expertise and motion ($F(1,14) = 1.204$, $p=0.291$), expertise and appearance ($F(2,28) = 1.540$, $p=0.232$) or motion and appearance ($F(2,28) = 1.537$, $p=0.233$). Where we observe that novices and experts

had slower reaction times during DM (0.58 ± 0.20 s and 0.70 ± 0.12 s, respectively) than during NDM (0.50 ± 0.17 s and 0.59 ± 0.11 s, respectively). For both novices and experts CG had the slowest reaction time (0.65 ± 0.16 s and 0.78 ± 0.10 s, respectively), VH and HC had similar reaction times for novices (0.47 ± 0.19 s and 0.49 ± 0.17 s, respectively) and experts (0.60 ± 0.08 s and 0.57 ± 0.08 s, respectively). Similarly, CG during DM and NDM had the slowest reaction times (0.76 ± 0.15 s and 0.65 ± 0.12 s, respectively) while VH and HC had similar reaction times during DM (0.57 ± 0.17 s and 0.56 ± 0.15 s, respectively) and NDM (0.48 ± 0.15 s and 0.48 ± 0.13 s, respectively). Observations of the two-way interactions are presented in figure A.11

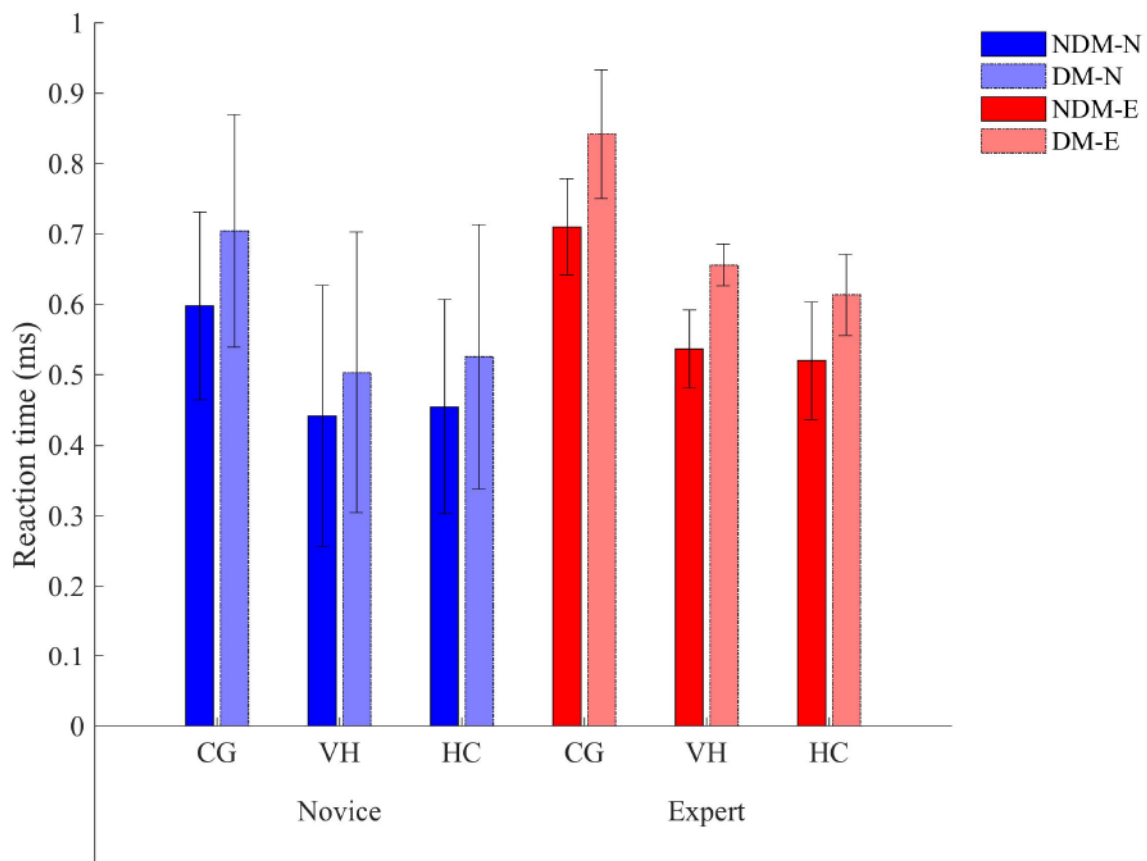


Figure A.8 - Mean \pm SD reaction times during the perception-action tasks, showing the overall three-way interaction for novices (N, blue), and experts (E, red), during DM and NDM while interacting with CG, VH, or HC.

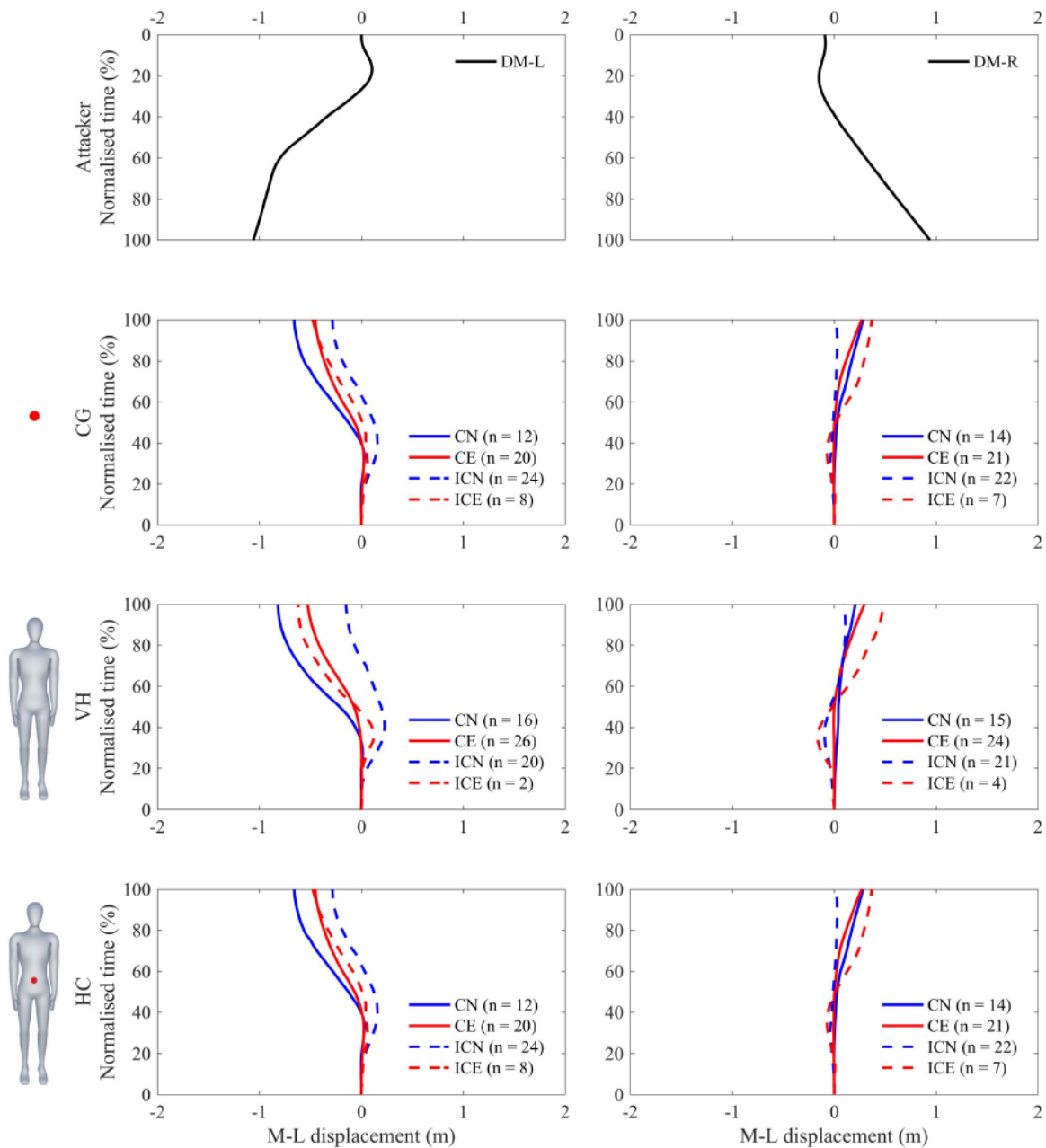


Figure A.9 - Average medio-lateral displacement during normalised time of expert (red) and novice (blue) defenders in successfully (solid line) and unsuccessfully (dashed line) detecting final crossing direction of the attackers motion (top). Columns (left - right) represent the motion of the attacker; DM-L and DM-R, and Rows (top - bottom) represent the visual appearance of the attacker; CG, VH, and HC.

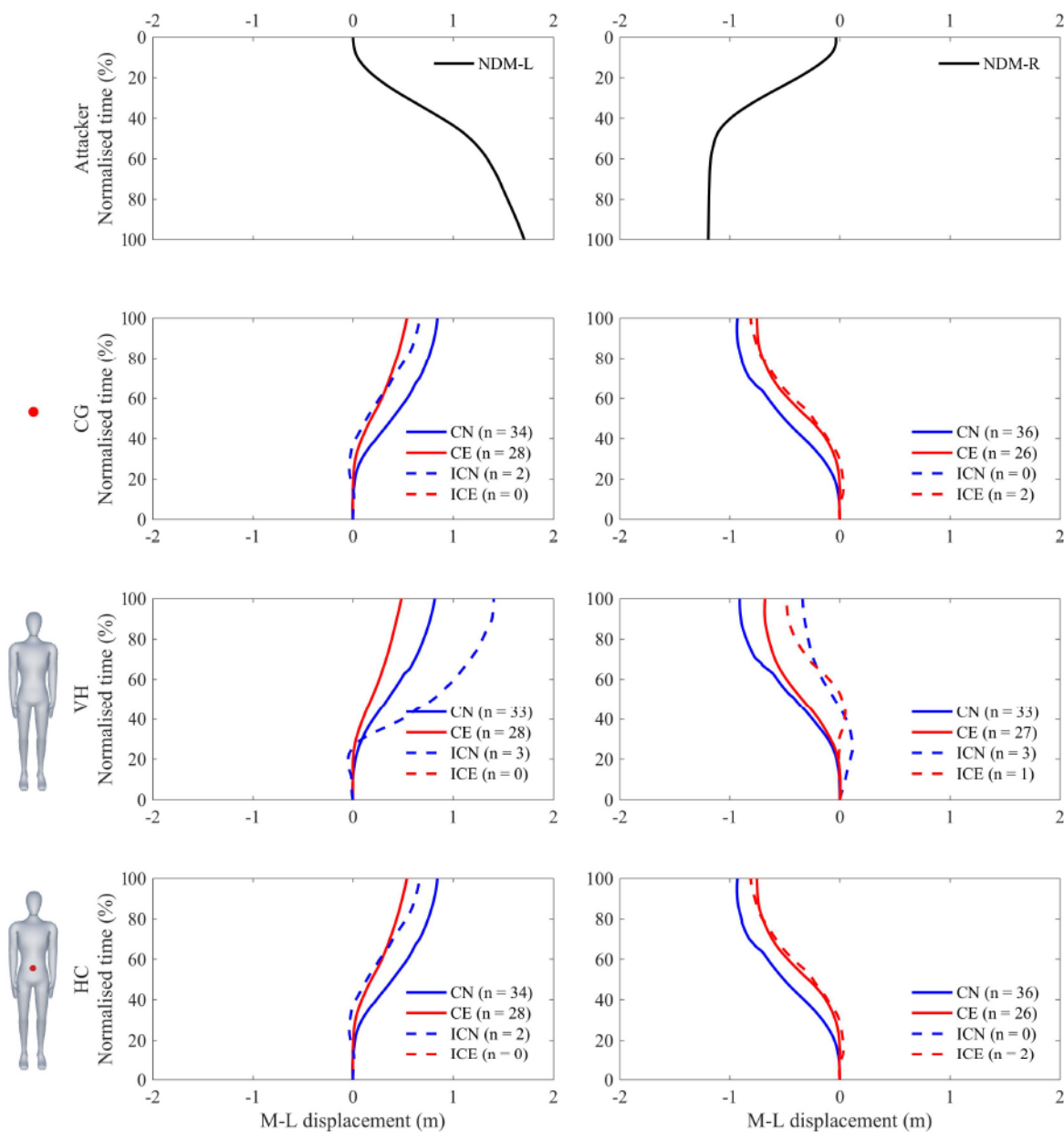


Figure A.10 - Average medio-lateral displacement during normalised time of expert (red) and novice (blue) defenders in successfully (solid line) and unsuccessfully (dashed line) detecting final crossing direction of the attackers motion (top). Columns (left - right) represent the motion of the attacker; NDM-L and NDM-R, and Rows (top - bottom) represent the visual appearance of the attacker; CG, VH, and HC.

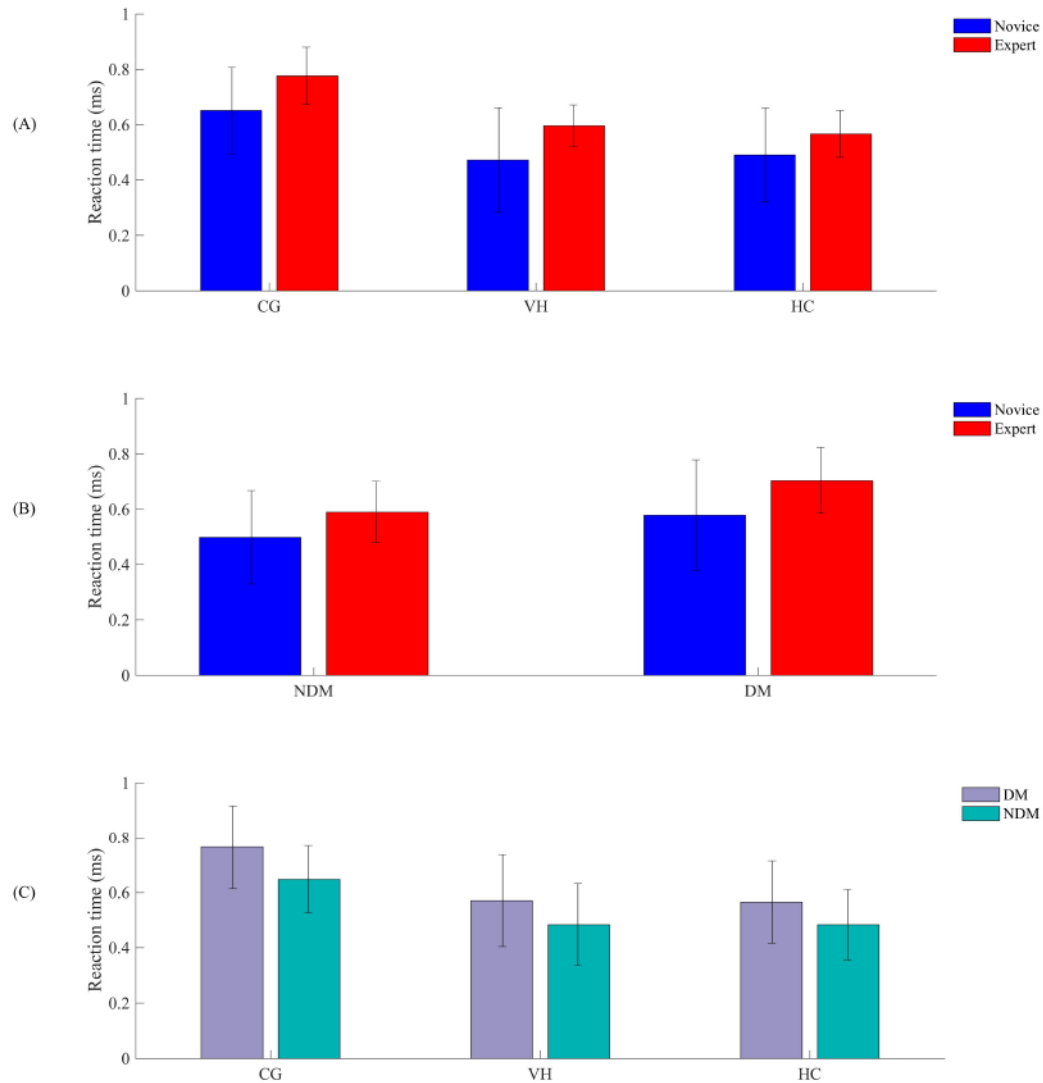


Figure A.11 - Mean \pm SD reaction times from interactions between level and appearance (A), level and motion (B) and motion and appearance (C).

A.5 Discussion

The present study focused on the visual cues conveyed by an attacker within a rugby dyad. We replicated an attacker-defender dyad, similar to [Brault2012], through virtual reality. In this paper, they implemented such a scenario using head-mounted displays (HMD), and they concluded that there is a relationship between attacker CG and expert defender rate of success. Developing from this, we focused on the visual representation of an attacker, a general full body, a full body with CG visible or only the CG of the attacker being present. We then evaluated the influence of these visual manipulations under two types of task, a perception only task and a perception-action task. We had hypothesised that CG alone would not impede the performance of experts and we had further hypothesised that the presence of CG with a full body representation would improve the performance of novices. From our results, we observed that actually, CG impeded the performance of experts. Further, we observed the CG did not act as an aid as there were no performance differences between HC and VH conditions for novices. We will discuss these findings and the influences of the other independent variables from our study.

A.5.1 Expertise Performance

Previously, Brault *et al.* [Brault2012] reported that experts were more sensitive in attuning their perceptual skills to more *honest* signals, specifying the medio-lateral displacement of the CG, while the novices were more attuned to deceptive, the otherwise *dishonest* signals, referring to upper trunk and shoulder rotation. Additionally, they reported that experts gained a majority of correct responses sooner than novices, suggesting that experts could accurately anticipate the final crossing direction of the

attacker with less information. While, during an action response task, experts waited significantly longer than novices before initiating their interception movement. The delayed response in reaction time that we observed within this work was observed for both novices and experts, with experts initiating displacement later than novices. The delayed responses observed by experts has previously been associated to a method of gaining more reliable information about the perceived action [Güldenpenning2017], this is coherent with our findings, experts waited longer than novices. However, greater reaction times were also observed for novices while interacting with CG than VH and HC, where they may well be incorporating a similar method of gaining more reliable information. The observed differences between novices and experts in this study may be further explained by the action capabilities of experts, such as being physically able to cover greater distances in shorter times [Oudejans1996, Dicks2010b, Navia2018].

Within our study, experts were more successful in identifying the future passing direction of an opponent than novices. These findings were consistent for both perception and perception-action tasks. Novices and experts were equally successful in determining the passage of the attacker, irrespective of visual appearance or cut off times during NDM. The difference in expertise only became distinguishable during DM, where performance for both experts and novices significantly decreased, experts were superior to novices in anticipating deceptive motion. These findings are in accordance with previous literature, that experts have a greater rate of success in identifying and correctly acting up deceptive motion within rugby [Jackson2006, Brault2010, Brault2012, Mori2013, Wright2014], cricket [Renshaw2000, Brenton2016], handball [Cañal-Bruland2010] and tennis [Sinnett2010].

A.5.2 Appearance Performance

Where [Brault2012] previously hypothesised a correlation between CG and performance, we have not produced supporting evidence for this. Our findings report a detrimental effect on performance while interacting with CG. First, in the perception only task, experts and novices had similar performance scores while interacting with CG but experts regained their advantage of expertise while interacting with VH and HC when compared to novices. While novices did improve during interactions with VH and HC compared to CG, they did not improve with the aid of HC when compared to VH. Moreover, the detrimental effect from CG was observable during NDM, and during DM the success rate in performance decreased the longer the stimulus was visible. Second, in the perception-action task, experts regained their advantage by maintaining a greater success rate than novices for all visual appearances. During the perception-action task, both experts and novices were most successful while interacting with VH. Novices had a similar success rate between VH and HC, while experts performed best with VH.

In non-competitive settings, [Meerhoff2014] and [Lynch2017] both reported advantages of full body representations as opposed to global motion visual cues. Meerhoff *et al.* [Meerhoff2014] reported temporal advantages in completing a mimicry task while interacting with local motion cues (i.e., arms and legs) or a large sphere (i.e., global motion cue) the same height as the virtual human. Lynch *et al.* [Lynch2017] also reported advantages of full body representation with local cues as opposed to interactions with global motion cues only. Where cues were not bound to a subjective preference of visual appearance, rather, the perceived action-opportunities. Specifically, their visual appearances of local motion cues produced similar results while global motion cues varied. Our findings are in accordance with these previous findings, global motion cues alone lack sufficient information for reproducible and repeatable performances as observed for local motion cues. Additionally, there was no advantage with the simultaneous presence of global and local motion cues.

A.5.3 Timing

During the perception-action task experts generally took longer to react to the stimuli, and CG and DM required longer reaction times. Moreover, both novices and experts required more time to observe CG, both for NDM and DM. Further, during the perception task there was an effect of cut off times, overall performance improved with longer exposure for both experts and novices. This trend of improvement in performance was observed for both VH and HC, however performance with CG did not improve with time. Rather, when considering visual appearance with DM and cut off times the success rate lowered after T1.

Our findings of reaction time during the perception-action task were similar to those of [Brault2012], experts took longer to act on a decision, they attributed these findings to a superiority in expertise, that is, experts minimised the number of motion errors in the wrong direction by delaying their response. This could also explain the delayed response observed for both experts and novices whilst interacting with CG, both groups delayed their responses to minimise errors in the wrong direction. However, this does not fully explain the differences observed between experts and novices if both are adopting similar strategies.

Meerhoff *et al.* [Meerhoff2014] also reported a temporal advantage of local motion cues (i.e., arms and legs) during a non-competitive setting; participants whilst interacting with a large sphere, the same height as the virtual human, had delayed responses in producing a mirrored or mimicked action of the visual display. Further, Lynch *et al.* [Lynch2017] reported similar findings during an orthogonal collision avoidance task. Participants, while interacting with a small red sphere, delayed their action response than during other interactions of global (i.e., a cylinder) or local motion cues (i.e., virtual human). They attributed this delayed response to a later threshold in the optical expansion than larger obstacles and the action-opportunities perceived by the participant.

Although, in a head on approaching task, Savelsbergh *et al.* [Savelsbergh1991] has previously shown a correlation of time to contact and the rate of expansion, where participants adjusted their hand apertures to catch a luminous ball. Considering these findings, we suggest that indeed both experts and novices adopted a delayed response to minimise errors whilst interacting with CG. This condition had indeed limited visual information with a low rate of expansion, creating uncertainty about the future passing direction of the attacker. This could possibly explain the inverted performance observed in the perception study where success rate dropped as cut off time increased during CG.

Finally, the observed differences between novices and experts could be explained by experience based on perceived action - opportunities [Hommel2001, Rizzolatti2001, Schütz-Bosbach2007]. That is, experts contain the appropriate motor repertoire from previous experience to associate from perception to required action. In part, this could explain the observed difference between perception and perception-action tasks; experts were unaccustomed in perceiving global motion of CG alone, however, during perception-action, they access their motor repertoire when physically required to intercept CG. Indeed, interacting with CG would not be habitual for both experts and novices; however, experts are familiar with the attacker-defender task and their action capabilities.

A.5.4 Limitations

An initial limitation in direct comparison to the previous study of [Brault2012] would be the change of apparatus. Previously, [Brault2012] completed their virtual reality study through the application of head mounted displays, while we have conducted our study using a computer assisted virtual environment. Both approaches have been previously validated and applied in ecological perception studies [Loomis1999, Brault2012], with known limitations [Loomis2003, Banton2005]. Head mounted displays have previously

been reported to have a reduced field of view and an increased impact on inducing simulator sickness compared to immersive environments [Creem-Regehr2005, Sharples2008]. A second limitation of the study could be attributed to the reaction time responses. Within our experimental setup we recorded reaction times and initiation responses from the moment of toe off before attacking direction reorientation defined as T0. Theoretically, as the stimulus was present prior to T0, participants could have performed an initial movement before an actual change in direction. However, we only considered responses and reaction times after T0 as the stimulus prior the reorientation provided no additional information on passing direction, this is in accordance with the paper of [Brault2012], but it could be interesting to evaluate if reaction times appeared before T0 for some players, mainly novices. Finally, we observed differences in overall reaction times in comparison to [Brault2012]. We attributed this general difference of mean reaction times to possible variances in the distance at which T0 occurs, while we maintained a similar methodology in the determination of T0 as [Brault2012], there was no specification of distance of the attacker from the defender at T0.

A.6 Conclusion

To our knowledge, this is a first paper to investigate the effect of visualised CG and performance in a rugby attacker-defender dyad. Our findings were in agreement with previous literature, experts more accurately detected the side an attacker would pass than novices, and that performance is hindered by deceptive motion such as a side-step in rugby. However, global motion cues alone were not sufficient in correctly detecting attacker direction. The rate of success was least for both experts and novices during deceptive motion whilst interacting with CG. The inclusion of CG on VH (HC condition) had no additional effect on performance or reaction times for both novices or experts in comparison with VH alone. During the perception-action task both novices and experts

adopted a delayed reaction response whilst interacting with CG. Additionally, experts had delayed reaction responses compared to novices for all visual appearances. We attribute this difference to sport specific action-opportunities, experts being trained and adapted to the attacker-defender dyad and may access and use an associated motor repertoire to delay their responses for increased certainty prior to initiation of motion. In comparison to [Brault2012] it appears that the global displacement of the whole body is necessary, however, the introduction of CG combined with VH (HC), was inhibitory on overall performance for experts. This suggests the introduction of CG as a training aid in attacker-defender dyad is not a relevant cue. Future work could consider the use of eye tracking as a method of detailing the notions of global and local cues, alternatively, the introduction of rigid attackers, without articulations of the joints, may provide insight. Where we have been unable to identify a possible training aid through the visual representation of CG, global displacement of a whole body, without articulation, may be a simplification of the interaction and a greater impact on training applications.

Annexe B

Synthèse Française



Figure B.1 - La vie urbaine, une foule de personnes marchant dans de multiples directions et réalisant différentes formes d'interaction.

B.1 Introduction

Bien que la locomotion puisse être considérée comme une tâche élémentaire et automatique de la vie quotidienne, elle n'en demeure pas moins une tâche complexe qui permet de se déplacer vers un but en toute sécurité [Winter1991]. Dans ce cadre, l'étude de la locomotion humaine représente un champ de recherche très vaste impliquant les disciplines telles que les neurosciences, la psychologie, les sciences du sport, la médecine ou encore l'informatique.

Comme l'illustre la Figure B.1 dans un espace urbain très fréquenté, un déplacement réussi correspond à la fois à la capacité d'orienter et de mouvoir son corps dans la direction désirée mais également d'interagir avec l'environnement, notamment en tenant compte des différents éléments le constituant (éléments fixes ou mobiles) et la nature des interactions possibles avec ces éléments. Ces interactions peuvent prendre diverses formes comme l'illustre la Figure B.2 dans une tâche d'interaction avec un autre marcheur ou dans une tâche sportive plus dynamique et plus complexe d'un point de vue des contraintes spatio temporelles. Le marcheur peut par exemple ainsi aller à la rencontre de quelqu'un, marcher avec, le suivre ou encore éviter toute collision avec le marcheur. Pour chacune de ces tâches, la perception de l'environnement qui entoure le marcheur est nécessaire pour recueillir les informations sur les caractéristiques de l'environnement ainsi que les positions et déplacements relatifs de l'individu par rapport aux éléments de l'environnement. Ceci permet à l'observateur de produire une action adaptée à la situation, cette action modifiant ce que perçoit l'observateur. Gibson parlait ainsi d'un couplage fort entre la perception et l'action dans lequel il est nécessaire de percevoir pour agir et d'agir afin de percevoir [Gibson1979]. Ce lien fort entre la perception et l'action a été étudié ainsi dans diverses situations comme la montée d'escaliers [Warren1984], le passage de portes [Cinelli2008b], ou encore l'évitement de collision entre deux marcheurs [Olivier2012].

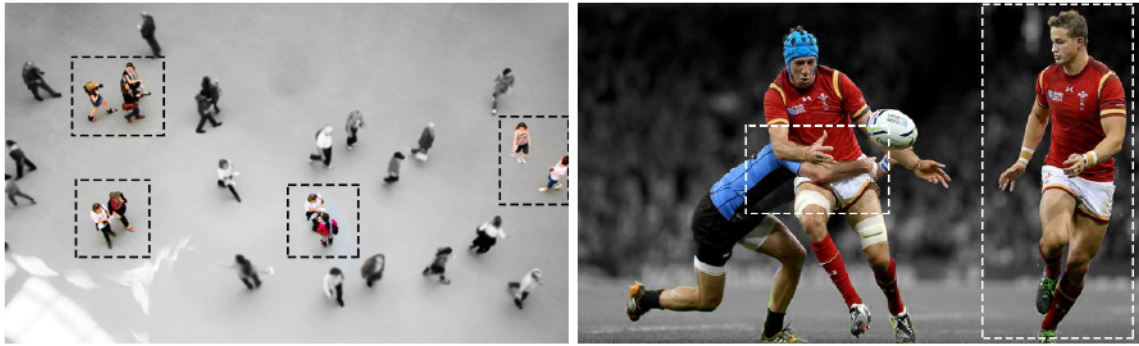


Figure B.2 - Deux exemples d'environnements de couplage perception-action. A gauche, une scène de ville présentant quatre formes possibles d'interaction, dans le sens inverse des aiguilles d'une montre depuis le haut à gauche : suivre, marcher avec quelqu'un, aller à la rencontre d'une personne et éviter une collision. A droite) Un exemple d'interception réussie (joueur en train d'être plaqué) et un coéquipier en soutien.

L'être humain est particulièrement sensible aux indices visuels fournis par le mouvement de la personne avec qui il interagit. Par l'observation du mouvement d'un autre marcheur, l'être humain est capable de déterminer les caractéristiques futures de l'interaction, et d'anticiper l'événement à venir par des adaptations possibles à son état actuel. Cette habileté à percevoir les caractéristiques du mouvement de l'autre marcheur est très sensible car l'observateur est capable d'identifier les états émotionnels d'un marcheur sur la base de son mouvement, ou encore son genre, son intention de feinte [Montepare1987, Runeson1983a], et ceci même lorsque les indices sont extraits d'une représentation très simplifiée du mouvement comme un ensemble de points lumineux (Point Light Display) [Troje2002]. Les indices locaux tels que le regard peuvent également être vecteurs d'informations importantes, où le regard a été caractérisé comme un facteur d'interaction sociale [Kleinke1986] et considéré comme une forme de communication non verbale [Senju2009]. L'identification des mécanismes sous-jacents, qui sont les indices perceptuels requis pour une perception correcte du mouvement, permettrait de réaliser des progrès significatifs dans la compréhension du comportement humain.

Dans ce cadre, cette thèse vise à répondre aux questions suivantes : quels sont les indices visuels qu'un individu perçoit à partir du mouvement des autres ? Quels sont les modèles permettant de déterminer les états futurs de l'interaction ? Quels sont les mécanismes d'interprétation des indices perçus mis en jeu ? Afin de répondre à ces questions, nous avons considéré un paradigme simple d'évitement de collision entre deux marcheurs, tâche qui fait partie des synergies motrices de base de la vie quotidienne. Considérant des tâches d'interaction, afin de garantir un contrôle expérimental fin, l'ensemble des expérimentations développées durant cette thèse ont été réalisés en réalité virtuelle. L'utilisation de la réalité virtuelle est un outil validé qui permet de manipuler les détails fins d'un environnement donné et de tirer des conclusions sur les effets de ces manipulations. Nous avons ainsi conduit trois études. La première étude s'est concentrée sur la nature des indices visuels utilisés sur le mouvement de l'autre en s'interrogeant sur le fait que l'information soit extraite d'une représentation globale du mouvement ou d'indices locaux au sein de la représentation globale. La deuxième étude s'est ensuite intéressée à l'influence du rayon de courbure de la trajectoire, en se demandant si les états futurs étaient extrapolés sur la base d'une représentation rectiligne ou curviligne du mouvement. Enfin, la troisième étude s'est penchée sur des paramètres plus sociaux de l'interaction à travers l'influence du comportement du regard de l'autre marcheur sur l'interaction. En résumé, les trois études combinées ont examiné le lien entre les indices visuels disponibles dans l'environnement et le comportement d'évitement de collisions.

La thèse est structurée de la manière suivante : Le chapitre 1 passe en revue la littérature actuelle, en mettant l'accent sur les fondements théoriques de la thèse, la perception de l'environnement, l'interaction avec l'environnement et le couplage des technologies informatiques pour analyser le couplage perception-action. Par la suite, sur la base des travaux de la littérature, les objectifs de la thèse sont détaillés avant de présenter les trois chapitres qui se réfèrent aux études expérimentales. Le chapitre 3 est le premier travail réalisé en relation avec la thèse, se concentrant sur la nature des indices visuels,

en particulier, en examinant si l'information est extraite du déplacement global ou des indices de mouvement local. Le chapitre 4 est le deuxième travail de la thèse et est centré sur l'influence des caractéristiques de la trajectoire du marcheur observé en s'intéressant notamment aux différences entre une trajectoire curviligne ou rectiligne. Le chapitre 5 est la dernière étude de la thèse, et s'intéresse aux aspects sociaux de l'interaction, à savoir l'influence du comportement du regard de l'autre marcheur sur l'interaction. Enfin, une conclusion générale des trois études et des perspectives sont présentées. Une étude complémentaire sur la nature de l'information visuelle utilisées dans un cadre plus dynamique d'une dyade rugby attaque-défenseur est disponible en annexe A, qui présente un champ d'application possible à partir du chapitre 3.

B.2 Objectifs



Figure B.3 - Vue d'ensemble de deux chemins qui se croisent et les indices visuels sur le marcheur observé considérés dans cette thèse. De gauche à droite, une représentation globale d'un marcheur, deux représentations abstraites et locales d'un marcheur, et deux représentations de l'orientation de la tête et du regard du marcheur.

Cette thèse et les travaux qui lui sont associés sont centrés sur les interactions entre un marcheur et son environnement. Dans ce contexte, nous visons à développer une meilleure compréhension des mécanismes perceptuels sous-jacents qui peuvent être impliqués lors d'une tâche d'évitement de collision entre deux marcheurs qui se croisent. Une revue de la littérature a démontré que durant sa tâche locomotrice, le marcheur extrait du flux optique les informations pertinentes qui lui permettent de se déplacer en toute sécurité dans son environnement. En particulier, il est nécessaire d'identifier si une collision se produira dans le futur et si oui quand elle aura lieu. Les réponses à ces deux questions fondamentales, s'appuient sur des indices visuels de mouvement global tels que les mouvements parallaxiques différentiels ou le taux d'expansion de l'obstacle sur la rétine. De nombreux travaux ont été menés sur la perception des caractéristiques du mouvement observé, mettant en évidence que le système visuel est performant pour

détecter des changements de direction, les indices de mouvements globaux étant basés sur une hypothèse de vitesses constantes. Le système visuel serait limité dans la perception de l'accélération, mais néanmoins, l'observateur humain reste capables d'adapter son mouvement afin d'interagir de façon adaptée avec les obstacles ayant différentes caractéristiques de mouvement. De plus, il a été démontré que le mouvement biologique est très riche avec des indices de mouvement local qui peuvent être utilisés pour identifier le genre de l'individu à partir d'un nombre limité de points lumineux correspondant à des repères anatomiques. Alors que les indices de mouvement locaux peuvent fournir des avantages temporels supplémentaires au cours des interactions, les indices de mouvement globaux sont suggérés comme source de signaux plus honnêtes.

L'évitement de collisions entre deux marcheurs a gagné en intérêt ces dernières années. En particulier, les auteurs ont développé de nouvelles métriques pour caractériser l'interaction, et ont analysé différents facteurs d'influence comme par exemple l'ordre de passage ou encore l'angle de croisement lors de trajectoires rectilignes sur les stratégies mises en place par les marcheurs. Les protocoles mis en place impliquent des obstacles prenant différentes apparences ou ayant des mouvements passifs ou réactifs. Les environnements considérés sont soit réels, ou alors virtuels. Cependant, de nombreuses questions sont encore sans réponse à ce jour et doivent faire l'objet d'un examen plus approfondi. En particulier, elles concernent la nature de l'information visuelle (globale ou locale) perçue et utilisée pour éviter une collision, la manière d'extrapoler le mouvement futur du marcheur observé ou encore l'influence de facteurs humains impliqués dans l'interaction, tels que le comportement du regard. **L'objectif principal de la thèse est donc de développer les connaissances sur les mécanismes perceptuels sous-jacents impliqués dans la perception de l'interaction entre deux marcheurs lors d'une tâche d'évitement de collision.**

L'apparence visuelle d'un obstacle a une influence significative sur la nature de l'information visuelle disponible et donc sur le comportement observé. Par exemple, lorsqu'un marcheur franchit une ouverture matérialisée par des poteaux ou des humains en conditions

réelles, il privilégiera de plus grandes distances dans le cas humain. Alors qu'au cours d'une tâche d'évitement de collision, les différences de comportement d'évitement sont signalées lors de l'interaction avec un robot à roues passif ou réactif. De plus, dans la réalité virtuelle, l'espace personnel et l'espace péripersonnel (c.-à-d. la portée des bras) sont plus petits pour les humains virtuels que pour les robots ou les cylindres virtuels. Ces différences notables suggèrent l'importance de l'apparence d'un objet et son influence sur les réponses comportementales. Ces différences de comportement peuvent bien être attribuées à des différences dans l'information visuelle disponible. Il a déjà été démontré que le mouvement global seul est suffisant pour mener à bien une tâche, cependant, les indices de mouvement local ont fourni un avantage temporel. Par conséquent, la première étude de la thèse se concentre sur la nature de l'information visuelle d'un obstacle virtuel pendant une tâche d'évitement d'une collision. Pour ce faire, l'apparence visuelle de l'obstacle est manipulée pour limiter les repères visuels disponibles. **Ce travail vise à déterminer si les indices pertinents sont basés sur le mouvement global ou sur les mouvements de segments locaux (c'est-à-dire le taux de pas des jambes).**

Après l'achèvement de la première étude, la thèse progresse vers la deuxième étude, qui s'oriente vers le chemin parcouru par le marcheur virtuel et l'évolution de l'interaction faite par le participant. En ce qui concerne la littérature sur l'évitement des collisions, lors d'une interaction orthogonale, une extrapolation linéaire du vecteur vitesse actuelle fournit une distance minimale prédite au croisement. Le calcul de cette distance de franchissement prévue pour chaque pas de temps fournit une évolution de l'interaction entre les deux marcheurs et met en évidence trois étapes d'interaction (c.-à-d. observation, réaction et régulation) avec anticipation. De plus, cela prouve qu'au cours d'une traversée orthogonale, la tâche peut être extrapolée linéairement par les marcheurs pour prédire l'instance de traversée. Cependant, au cours d'une tâche d'interception d'une bille suivant une trajectoire curviligne, il a été démontré que la tâche est accomplie prospectivement par des changements constants dans l'angle de gisement. Les différents

travaux ont fait varier le paradigme de l'évitement des collisions entre deux marcheurs avec des angles d'approche alternatifs, et avec des confédérés ou des robots à roues. Pour chaque cas, la tâche consistait à demander à un participant de marcher vers un but et d'éviter tout obstacle qui pourrait se trouver sur une trajectoire sujette aux collisions. Le marcheur, le confédéré ou le robot appariés ont reçu des instructions similaires (suivre une trajectoire rectiligne vers un but), les confédérés ayant reçu l'instruction de faire correspondre la vitesse du participant, de toujours s'assurer d'une collision future prévue ou d'être entraînés à marcher à vitesse fixe. De plus, lorsque nous nous déplaçons dans des environnements encombrés, dans lesquels nous résidons, un chemin peut être curviligne par opposition à un chemin rectiligne. Comme le prouvent les sports de ballon et les tâches d'interception dans la littérature, il est possible d'intercepter un objet en suivant une trajectoire curviligne. Cependant, le système visuel a été signalé comme étant insensible aux accélérations pour les estimations temporelles et spatiales futures. **A cette fin, l'étude deux s'intéresse à l'influence d'une trajectoire curviligne d'un marcheur virtuel sur les stratégies d'évitement de collision et s'intéresse à l'évolution de la distance minimale prévue au croisement. Le but de ce travail est de mieux comprendre la nature des indices de la trajectoire perçue, en particulier si un observateur peut ou non percevoir et prédire le risque futur de collision à partir de trajectoires curvilignes.** Auparavant, il a été démontré que le risque futur de collision pouvait être déduit de l'extrapolation linéaire des vecteurs vitesse de chaque marcheur, mais il reste à savoir si cela est vrai pour les trajectoires curvilignes ou si un modèle plus complexe qui prend en compte les accélérations doit encore être exploré.

Enfin, les interactions entre deux marcheurs sans contrainte ont présenté plusieurs résultats, tout d'abord l'extrapolation linéaire de la position et du cap des deux marcheurs a présenté la distance de franchissement prévue, lorsque cette distance est inférieure à une valeur seuil, les deux marcheurs se sont adaptés pour assurer un passage en toute sécurité. Deuxièmement, sans communication verbale entre les deux marcheurs, les deux rôles étaient assignés : l'un passerait en premier et l'autre passerait en second.

D'autres recherches sur l'attribution des rôles des ordres de croisement ont suggéré que les rôles sont attribués au poste actuel pendant la phase d'observation, qu'il n'y a pas d'influence des facteurs humains (p. ex. âge, sexe et taille) ou des traits de personnalité (p. ex. introverti et extraverti). Troisièmement, aucune inversion des rôles assignés n'a été rapportée, c'est-à-dire que pendant la période d'observation, les deux marcheurs ont assigné des rôles pour traverser en premier ou en second et ont maintenu ce rôle pour traverser en premier ou en second. Alors que, lors de l'interaction avec un robot passif, des inversions ont été rapportées, et considérées comme une réponse de suradaptation). De plus, les distances finales observées entre un marcheur et un robot sont plus grandes que celles observées entre deux marcheurs. L'analyse de la littérature a mis l'accent sur un effet possible de la communication sociale non verbale, d'un comportement passif ou d'une combinaison des deux. En considérant la tâche détaillée aux participants, la forme la plus probable de communication non verbale serait exprimée à travers les yeux et les expressions faciales. Là où il a déjà été démontré que lorsque deux individus se regardent l'un l'autre, les deux influencent implicitement la perception que chacun a de l'autre, avec un regard mutuel formant une interaction sociale par le biais de l'excitation émotionnelle et de l'intention. Le regard a déjà prouvé qu'il augmente le sentiment d'immersion dans les environnements virtuels. Cependant, la plupart des études portant sur le comportement du regard se sont concentrées sur les interactions frontales. Des études ont commencé à examiner l'influence des comportements d'évitement réciproque au cours d'une tâche d'évitement des collisions avec des résultats prometteurs. **La troisième étude est alors une continuation dans la même direction, introduisant le regard comme repère non verbal pendant l'évitement des collisions, dans cette étude nous avons inclus des essais avec ou sans comportement d'évitement réciproque pour étudier plus avant les effets du comportement du regard.**

B.3 Méthodes

B.3.1 Participants

Le personnel universitaire et les étudiants en bonne santé ont participé aux études liées à la thèse. Tous les participants avaient une vision normale ou corrigée à la normale et n'avaient pas d'antécédents de maladie ou de déficience qui auraient pu affecter leur capacité de participation. Un formulaire de consentement a été fourni par tous les participants avant l'expérimentation et les études étaient conformes aux normes de la Déclaration d'Helsinki.

B.3.2 Dispositifs

Les expériences ont eu lieu dans des environnements virtuels assistés par ordinateur (CAVE) ; celui de 9m de large, 3m de haut et 3m de profondeur, qui était équipé de 13 projecteurs avec une résolution totale de 15MPixels et la stéréoscopie active a été réalisée avec les lunettes portables Volfony ActiveEyes Pro Radiofrequency. Les lunettes ont été suivies par un système de suivi ART composé de 16 caméras. L'autre CAVE mesurait 12m de large, 4m de haut et 4m de profondeur. Il était équipé de 4 projecteurs Christie Mirage 4K 3D et la stéréoscopie active a été réalisée avec les lunettes portatives Volfony ActiveEyes Pro Radiofrequency. Les lunettes ont été suivies par 6 caméras Vicon Bonita. Les affichages d'environnement 3D et les animations de personnages (Figure B.4) ont été conçus dans le moteur de jeu Unity. Le rendu multi-surface a été effectué par le plugin MiddleVR. Un joystick a été utilisé par les participants pour se déplacer dans l'environnement virtuel. La loi de contrôle associée à la vitesse virtuelle était celle utilisée par Olivier et al. [Olivier2017]. La position neutre

du joystick produirait un déplacement de base de $1,4\text{m}\cdot\text{s}^{-1}$ avec une vitesse angulaire nulle, qui ressemble à une vitesse de marche normative typique [Bohannon1997]. Toute action sur le joystick par la suite produit une adaptation de la trajectoire virtuelle. L'axe longitudinal a contrôlé la vitesse linéairement à partir de $0,8\text{m}\cdot\text{s}^{-1}$ à $2,0\text{m}\cdot\text{s}^{-1}$, et la vitesse de rotation angulaire contrôlée par l'axe latéral linéairement à partir de $-25\text{deg}\cdot\text{s}^{-1}$ à $+25\text{deg}\cdot\text{s}^{-1}$.

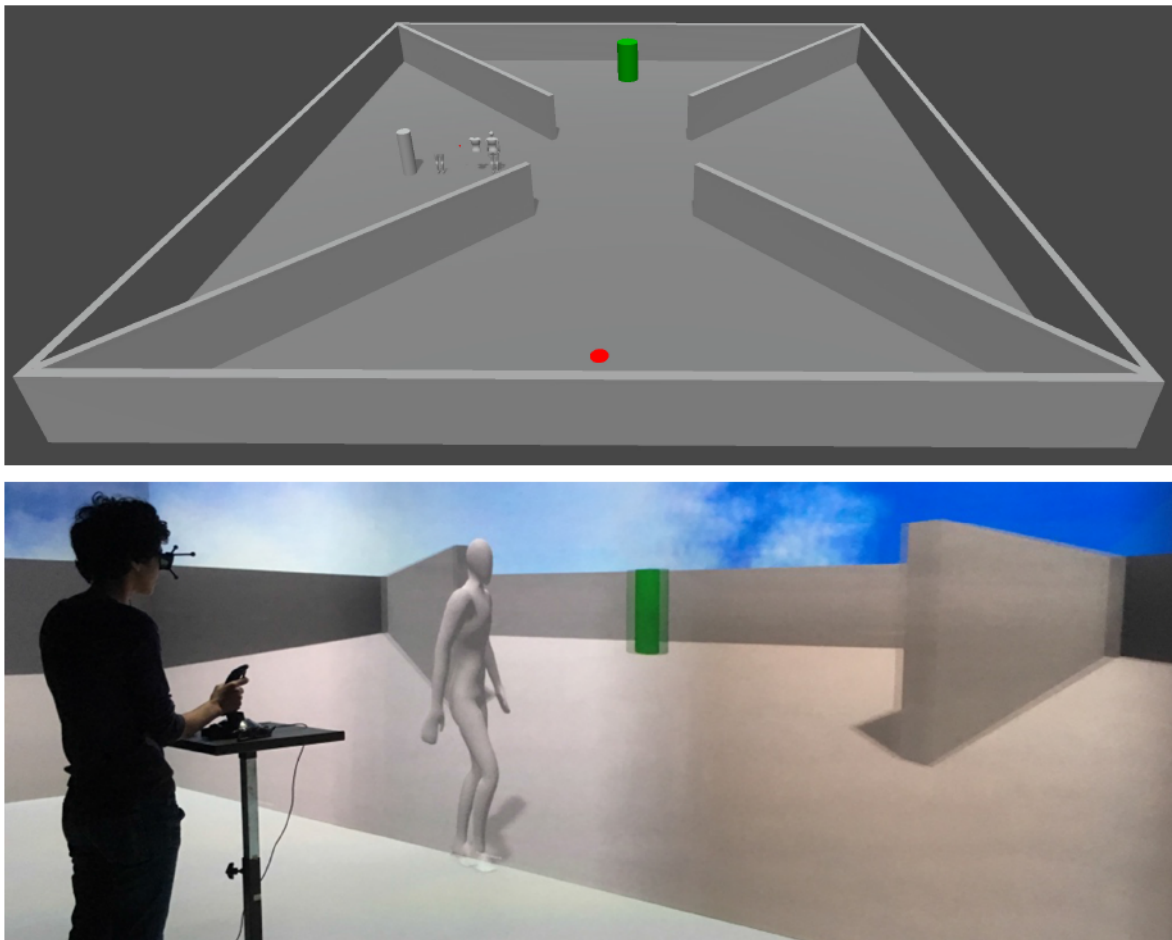


Figure B.4 - En haut). Vue d'ensemble de l'environnement virtuel utilisé pour l'expérience, d'une position de départ rouge, d'un objectif vert à atteindre et de la variété des apparences d'obstacles à une position de départ obstruée à gauche. En bas). Perspective à la troisième personne du participant tout en évitant la situation de contrôle total du corps avec l'objectif vert en arrière-plan.



Cette thèse portait sur trois études distinctes visant à étudier les mécanismes perceptuels sous-jacents qui peuvent être impliqués dans une tâche d'évitement des collisions. À cette fin, la tâche de chaque expérience individuelle était similaire et, par conséquent, la tâche générale est détaillée ci-dessous. Par la suite, le plan expérimental de chaque étude est détaillé dans les sections qui suivent la tâche.

B.3.3 Tâches

Les participants ont été plongés dans un environnement virtuel (Figure B.4), où on leur a demandé de se tenir debout à un endroit désigné représenté dans le plancher de l'environnement immersif. La tâche consistait se déplacer dans l'environnement, à l'aide d'un joystick, pour atteindre un objectif (un cylindre vert) à l'autre bout de la pièce. On leur a demandé d'éviter les collisions potentielles avec tout obstacle virtuel qui apparaîtrait sur leur chemin. L'obstacle virtuel se déplaçait le long d'une trajectoire qui se croisait perpendiculairement aux trajectoires des participants. Nous avons placé des murs d'occlusion dans l'environnement pour contrôler le moment où les participants pouvaient percevoir le personnage virtuel ($MPD_{t_{see}}$). Cela a permis aux participants d'atteindre la vitesse de base en simulant un état stable de marche confortable avant l'interaction. Tout au long de l'expérimentation, tous les obstacles virtuels avaient une vitesse constante. L'état d'équilibre initial du participant et la vitesse de l'obstacle virtuel ont été fixés selon l'étude de la vitesse normative de marche à $1,4\text{m}\cdot\text{s}^{-1}$ [Bohannon1997]. Là où la vitesse de l'obstacle virtuel est restée constante tout au long du parcours, les participants ont pu adapter leur vitesse et leur trajectoire après $MPD_{t_{see}}$ à l'aide du joystick.

B.3.4 Mise en place expérimentale

B.3.4.1 Comportement d'évitement des collisions entre marcheurs : indices de mouvement global et local

Pour la première étude (chapitre 3), le plan expérimental a été mis en place en utilisant un plan carré latin, l'expérimentation a été divisée en cinq blocs aléatoires d'apparence (Figure B.5). À l'intérieur de chaque bloc d'apparence, les obstacles avancent à partir de la droite ou de la gauche occultée du participant. Nous avons également contrôlé le danger potentiel de l'interaction pour évaluer si l'apparence visuelle de l'obstacle a un effet sur la perception de la situation. La position de départ de l'obstacle contrôlait le risque futur de collision déterminé par $MPD_{t_{see}}$, qui est l'instant où le participant peut d'abord voir l'obstacle [Olivier2012]. Un total de 5 distances de croisement ont été choisies pour l'expérience, variant le risque de collision : deux distances à haut risque, où une collision se produirait si aucune adaptation n'est mise en œuvre (0,1 et 0,3m), une distance intermédiaire (0,6m) qui ne nécessiterait aucune adaptation, selon ce qui est réellement observé entre deux piétons, mais une inversion est rapportée lors de l'interaction avec les robots [Vassallo2017], et enfin deux distances à faible risque, où aucune collision ne se produirait si aucune adaptation n'est mise en œuvre (0,9 et 1,2m). De plus, nous avons contrôlé l'ordre de croisement initial à $MPD_{t_{see}}$ où l'obstacle passerait devant ou derrière le participant à ces distances aléatoires de risque de collision. Pour chaque bloc d'apparence visuelle conditionnelle, les participants ont bénéficié d'une courte période de familiarisation consistant en cinq essais de risques variables de collision avec l'apparence conditionnelle spécifiée.

Dans chaque bloc d'apparence visuelle, ces conditions ont été présentées au hasard aux participants. Par conséquent, chaque participant a effectué 100 essais (5 apparitions \times 2 côtés de croisement (gauche-droite) \times 5 $MPD_{t_{see}}$ \times 2 ordres de croisement).

La durée de l'expérience par participant, y compris la familiarisation et le remplissage du questionnaire, était d'une heure.

B.3.4.1.1 Conditions

Notre objectif est d'étudier le rôle de l'information globale par rapport à l'information locale sur le mouvement des obstacles dans une tâche d'évitement des collisions. Pour ce faire, nous avons manipulé l'apparence visuelle de l'obstacle en mouvement en utilisant les conditions suivantes, comme l'illustre la figure 3.2:

1. Corps entier : Un mannequin mobile avec une largeur d'épaule de 37cm et une largeur de hanche de 27cm, a été rendu sans visage pour éviter toute influence de l'émotion et du regard. De plus, le mouvement a été animé comme un cycle de marche répété et neutre.
2. Jambes : Si l'on considère que le placement des pieds est un contact direct avec le sol, les pieds et les jambes seuls peuvent fournir des informations locales perceptuelles pour éviter les collisions. Ainsi, toute l'information locale sur le haut du corps a été supprimée avec seulement le placement des pieds et le mouvement des jambes. Seuls le positionnement et la foulée pouvaient être perçus ; la segmentation des jambes était sous les hanches pour supprimer toute information sur l'orientation de la hanche.
3. Tronc : Le tronc étant le plus grand aspect visible du corps humain, nous avons choisi d'utiliser cette segmentation, sans jambes ni bras, afin d'éliminer toute information sur le taux d'oscillation et de ne présenter que l'orientation. De plus, la hanche a été une fois de plus exclue de la segmentation, car un taux de foulée pourrait autrement être perçu par les oscillations de la hanche.
4. Cylindre : Pour supprimer toutes les informations d'orientation et de pas, un cylindre entoure entièrement le contrôle complet du corps dans une position statique. Le cylindre a ensuite été codé avec la même trajectoire et le même profil de vitesse

que l'état du corps entier.

5. Sphère : Avec les récentes découvertes de Brault et de ses collègues [Brault2012] suggérant une forte corrélation entre le centre de gravité (COG) et l'interception lors d'une tâche sportive trompeuse en termes de succès, nous avons choisi d'enlever toute information d'encapsulage et d'utiliser une petite sphère (8cm de diamètre) comme apparence de COG. Il s'agissait également de supprimer toutes les informations d'orientation et de foulée, et similaire au tronc, mais contrairement à la segmentation des jambes, il n'y avait pas de contact avec le sol.

Notez que la condition 1) sert de condition de contrôle. Les conditions 2) et 3) étudient le rôle des signaux de mouvement locaux transmis par les membres humains et le torse. Enfin, les conditions 4) et 5) éliminent complètement les repères de mouvement locaux et affichent les repères de mouvement globaux à travers différentes représentations géométriques de l'obstacle.

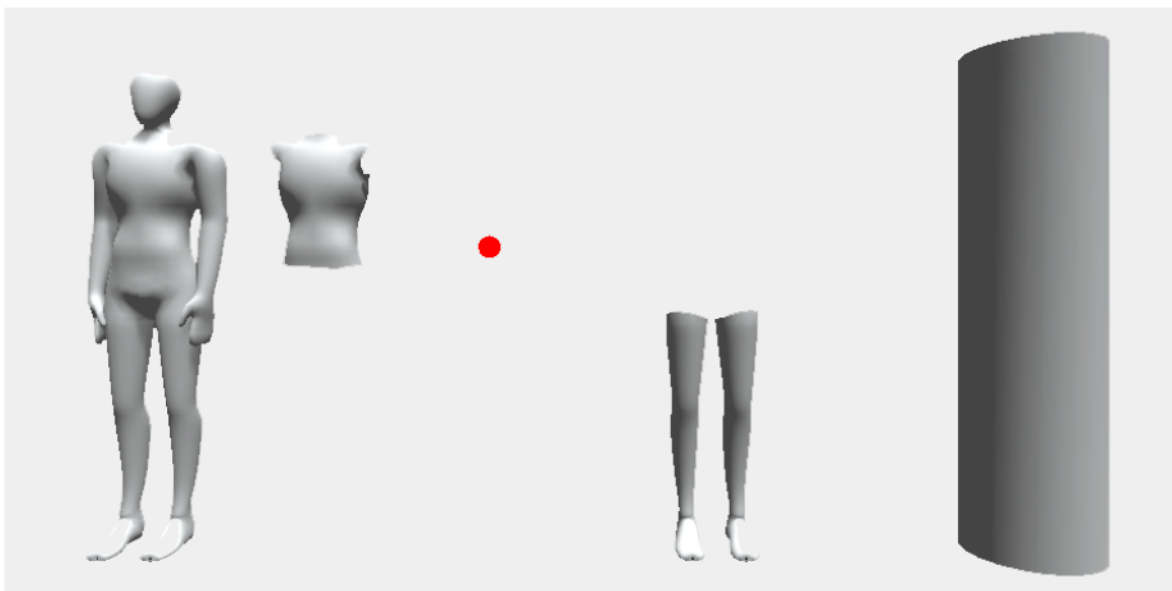


Figure B.5 - Apparences visuelles utilisées comme indices visuels des apparences locales et globales de gauche à droite, corps entier, tronc, tronc, COG, jambes et cylindre.

B.3.4.2 Influence de la courbure de la trajectoire sur le comportement d'évitement des collisions

Pour la deuxième étude (chapitre 4), l'installation expérimentale a été conçue de telle sorte que les participants ont commencé chaque essai à partir d'une position de départ dans un corridor, ce qui les a empêchés de percevoir la position de départ de la marchette virtuelle. Lorsque le participant est sorti du corridor, un marcheur virtuel s'est avancé de la droite ou de la gauche du participant. Nous avons contrôlé le danger potentiel de l'interaction pour évaluer si le rayon d'approche a un effet sur la perception de la situation. Pour ce faire, le déplacement de la position de départ du marcheur virtuel a déterminé le risque de collision future à $MPD_{t_{see}}$, qui est l'instant où le participant peut d'abord voir le marcheur virtuel [Olivier2012]. Au total, quatre distances de croisement ont été choisies afin de varier le risque de collision future : deux distances à haut risque (0 et 0,3 m), une distance de risque intermédiaire (0,6 m) et une distance à faible risque (0,9 m). Dans les collisions à haut risque, une collision se produisait si le participant n'adaptait pas sa trajectoire. Dans le cas des distances intermédiaires et à faible risque, le participant n'a pas nécessairement dû s'adapter pour éviter une collision. Il convient de noter qu'aux distances intermédiaires, on a observé que les humains ne s'adaptent pas dans les interactions entre humains ; cependant, dans les interactions entre humains et robots et entre humains et obstacles virtuels (en mouvement), les humains ont eu tendance à s'adapter et à inverser l'ordre de croisement [Vassallo2017, Lynch2017, Lynch2017, Lynch2018]. De plus, nous avons réglementé l'ordre de passage initial : le marcheur virtuel traverserait soit devant ou derrière le participant à ces distances aléatoires (sauf pour $MPD_{t_{see}} = 0\text{m}$). Enfin, le marcheur virtuel a avancé en utilisant une trajectoire fixe, un total de trois trajectoires ont été choisies (Figure B.6) : deux trajectoires curvilignes avec un rayon fixe de 5m ou 10m, et une trajectoire rectiligne de contrôle. La vitesse tangentielle (c.-à-d. la vitesse linéaire le long de la courbure de la trajectoire) a été fixée à $1,4 \text{ m}\cdot\text{s}^{-1}$, soit la même vitesse que la vitesse de base

du participant et la vitesse des marcheurs virtuels sur la trajectoire linéaire. Tous les chemins courbes étaient signés négatifs (à l'avant) et positifs (derrière) pour indiquer la direction à partir de laquelle le marcheur virtuel avançait :

- **N5** Le marcheur virtuel s'est avancé devant le participant, s'approchant d'eux, avec un rayon de 5m de chemin curviligne.
- **N10** Semblable à N5, le marcheur virtuel s'est avancé devant le participant, s'approchant de lui, avec une trajectoire curviligne d'un rayon de 10m.
- **P5** Le marcheur virtuel s'est avancé par derrière le participant, s'approchant de lui, avec un rayon de 5m de rayon curviligne.
- **P10** Semblable à P5, le marcheur virtuel s'est avancé devant le participant, s'approchant de lui, avec une trajectoire curviligne d'un rayon de 10m.
- **INF** Étant donné un rayon infini, la trajectoire du marcheur virtuel était rectiligne, une condition de contrôle. Pour équilibrer les conditions expérimentales, l'INF a été répété deux fois, selon l'approche par courbe signée.

Au total, chaque participant a effectué 168 essais ($6 \text{ voies} \times 7 \text{ MPD}_{t_{see}} \times 2 \text{ côtés de croisement (gauche-droite)} \times 2 \text{ répétitions}$). Toutes les conditions et leurs répétitions ont été présentées dans un ordre totalement aléatoire. Avant les essais expérimentaux, les participants ont effectué six essais de familiarisation à des conditions aléatoires, les participants se sont familiarisés avec le comportement du marcheur virtuel et leurs propres capacités d'adaptation au mouvement du joystick. La durée de l'expérience par participant, y compris la familiarisation et le remplissage du questionnaire, était d'environ une heure.

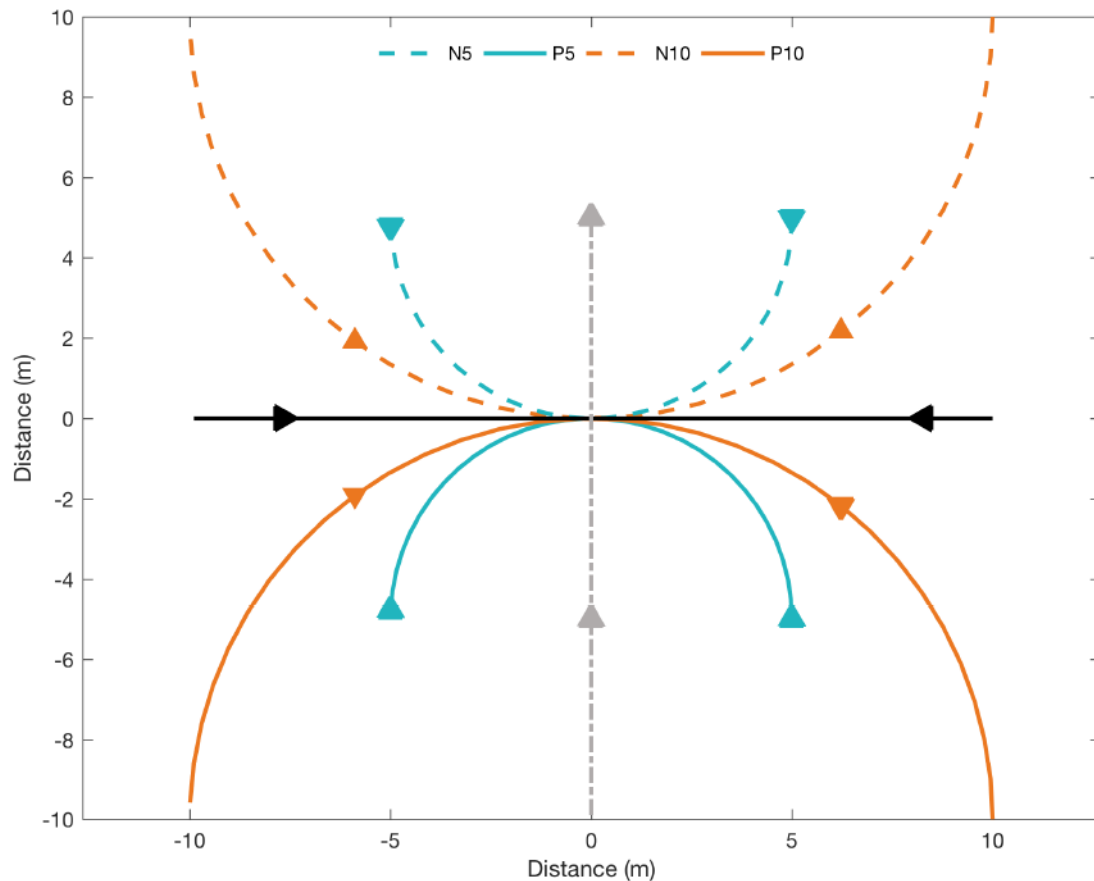


Figure B.6 - Exemples des courbes présentées à partir de la configuration. La ligne grise est la trajectoire hypothétique du participant sans adaptation, la ligne noire est la trajectoire rectiligne du marcheur virtuel, les lignes bleues sont les trajectoires du marcheur virtuel avec un rayon de 5m, les courbes orange sont les trajectoires du marcheur virtuel avec un rayon de 10m. Les lignes pleines sont pour les trajectoires de derrière le participant, les lignes pointillées sont à l'avant. Le marcheur virtuel s'est approché de la gauche ou de la droite.

B.3.4.3 Effet du comportement du regard humain virtuel lors d'une tâche d'évitement de collisions orthogonales

Pour la troisième étude (chapitre 5), le plan expérimental a été mis en place en tenant compte de deux facteurs principaux, à savoir le regard avec un comportement de rotation de la tête et le comportement d'évitement réciproque du personnage virtuel, qui ont été manipulés dans notre étude. Chaque facteur comporte deux niveaux décrits ci-dessous :

1) Comportement du regard (Figure B.7) : Pour le premier niveau **No Gaze (NG)**, le personnage virtuel ne regarde pas le participant mais tout droit devant, comme un intervenant stéréotypé qui ne formule pas d'interactions sociales avec le participant. Pour le deuxième niveau, **Gaze (G)**, le personnage virtuel regarde le participant. Plus précisément, le personnage regarde d'abord vers l'avenir, puis, 0.2s après MPD_{tsee} , il dirige son regard vers la tête des participants. Pendant 1,5s, le personnage se fixe sur le participant avant de retourner le regard dans le sens de la marche. Le comportement du regard est réalisé en animant les composantes de l'œil, de la tête et du cou (par rotation de la tête et des épaules) du personnage virtuel, sur la base des travaux antérieurs de [Grillon2009].

2) Comportement d'évitement : Pour le premier niveau **No Avoidance (NA)**, le personnage virtuel a maintenu un chemin droit vers son but à une vitesse constante. Pour le deuxième niveau **Avoidance (A)**, le personnage virtuel a adapté son chemin pour assurer un passage sûr au futur point de passage prévu en utilisant l'algorithme RVO [Van Den Berg2011].

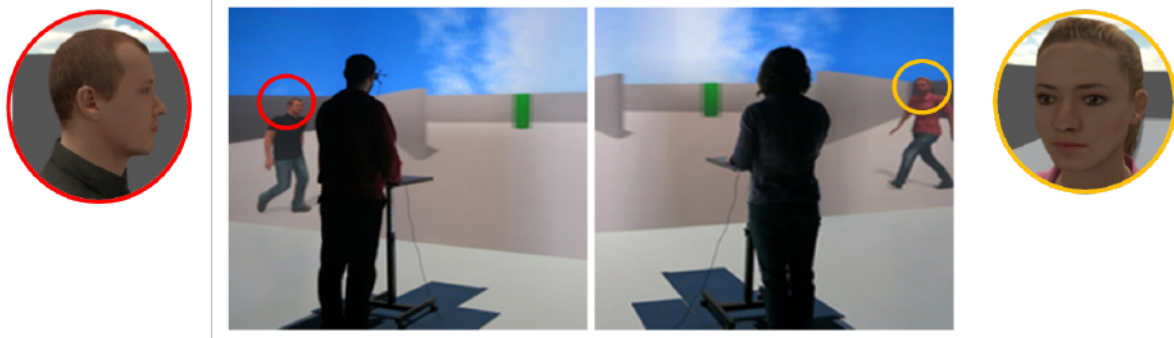


Figure B.7 - Perspective à la troisième personne des participants se déplaçant dans un environnement virtuel ; le participant masculin interagit sans regard (à gauche, cercle rouge) et la participante féminine interagit avec le regard (à droite, cercle orange).

Nous avons combiné ces deux facteurs de sorte que nous avons les conditions suivantes : No Gaze + No Avoidance (*NGNA*), No Gaze + Avoidance (*NGA*), Gaze + No Avoidance (*GNA*), Gaze + Avoidance (*GNA*), Gaze + Avoidance (*GA*).

Dans cette étude, le personnage virtuel avancerait à partir de la droite ou de la gauche occultée du participant. Nous avons contrôlé le danger potentiel de l'interaction pour évaluer si le comportement du regard avait un effet sur la perception de la situation. Le risque futur de collision a été calculé à l'aide de la variable Distance minimale prévue (*DMP*) définie précédemment par [Olivier2012]. Il a été défini au début de l'interaction en contrôlant la vitesse de base et le cap du participant jusqu'à t_{see} , et en contrôlant en outre la position de départ du personnage, qui avait la même vitesse de base que le participant et un cap constant [Olivier2012]. Le participant et le personnage virtuel ont été localisés à 9,5 m du point d'intersection, à un cap et à une vitesse constants, les deux arrivent au même moment. Pour nos conditions expérimentales, nous compensons la position de départ du personnage, au lieu de compenser le temps de départ. Un total de 5 futures distances de croisement calculées à t_{see} ($MPD_{t_{see}}$) ont été choisies, variant le risque initial de collision dans l'interaction ; 2 distances à haut risque, où une collision se produirait si aucune adaptation n'est mise en œuvre (0,1 et 0,3m), une distance intermédiaire (0.6m) qui ne nécessiterait aucune adaptation, ce qui est réellement observé entre deux piétons, mais une inversion est rapportée lors de l'interaction avec des robots et des personnages virtuels [Vassallo2017, Lynch2017], et enfin 2 distances

à faible risque, où aucune collision ne se produirait si aucune adaptation n'est mise en œuvre (0,9 et 1,2m). De plus, nous avons contrôlé l'ordre de croisement initial à t_{see} où le personnage virtuel passerait le participant soit devant ($MPD_{t_{see}} < 0$ ou derrière ($MPD_{t_{see}} > 0$) à ces distances aléatoires de risque de collision.

Chaque participant a effectué 80 essais aléatoires (4 réponses comportementales \times 2 côtés de croisement (gauche-droite) \times 5 MPD \times 2 ordres de croisement). À la fin de l'expérience, nous avons demandé aux participants d'indiquer les paramètres qu'ils pensaient que nous avions évalués au cours de cette étude. Nous avons également recueilli des commentaires autodéclarés. La durée de l'expérience par participant était d'une heure.

B.4 Comportement d'évitement des collisions entre marcheurs : indices de mouvement global et local

B.4.1 Objectif et contributions de la première étude

La première étude se concentre sur les indices visuels qui transmettent des informations pertinentes pour une estimation précise du mouvement global des autres, en particulier, que ces indices visuels soient extraits des parties locales du corps ou de la perception globale du mouvement du corps. Pour manipuler l'aspect visuel tout en préservant strictement la cinématique des interactions (c'est-à-dire le mouvement relatif de l'obstacle par rapport aux participants), nous avons développé une expérience en réalité virtuelle. La réalité virtuelle est une nouvelle approche qui s'est avérée être un outil puissant pour la perception écologique et la recherche-action [Loomis1999]. Les avantages de la réalité virtuelle comprennent la capacité de découpler les variables covariantes naturelles, l'augmentation du contrôle expérimental et la manipulation des détails finis. La perception et l'action à travers la réalité virtuelle n'est pas sans limite [Fink2007]. Il a en effet été démontré qu'il existe une variance dans la perception de la profondeur [Loomis2003], qui n'est pas nécessairement liée au champ de vision restreint auquel on se réfère souvent lorsqu'on utilise des écrans montés sur la tête [Creem-Regehr2005]. De plus, en réalité virtuelle, la vitesse du regard vers l'avant est sous-estimée par rapport à la vitesse réelle [Banton2005].

Malgré ces différences notables au sein de la réalité virtuelle, les réponses comportementales se conforment à la réalité. Les marcheurs qui exécutent une tâche de locomotion dirigée vers un but dans la réalité reproduisent leur trajectoire en réalité virtuelle [Cirio2013]. En ce qui concerne l'évitement des collisions, la validation de

la réponse comportementale a été rapportée dans la préservation de l'espace personnel [Gérin-Lajoie2008] et des méthodes interactives utilisant de grands écrans immersifs ont été développées [Olivier2017]. La réalité virtuelle s'est avérée être un outil important dans l'exploitation de situations complexes telles que le sport de compétition [Brault2012], le contrôle de mouvement [Fink2007] et la simulation de foule [Bruneau2015]. La réalité virtuelle est donc un outil robuste et fiable pour approfondir la compréhension de l'évitement des collisions.

L'expérience de réalité virtuelle met un obstacle dynamique sur une trajectoire de collision avec un participant. L'apparence visuelle de l'obstacle dynamique est modifiée entre les essais. Une situation de contrôle, l'obstacle dynamique est un personnage virtuel ambulant. Dans ce cas, nous sommes en mesure de comparer les résultats obtenus en réalité virtuelle avec les données réelles enregistrées lors d'interactions entre deux humains réels.

Le travail a contribué de différentes manières :

1. Nous étudions expérimentalement la nature de l'information visuelle utilisée par un marcheur, en particulier dans le cadre d'une tâche d'évitement des collisions. Nous démontrons que le mouvement global est une source d'information suffisante pour éviter avec succès les obstacles, tandis que le mouvement local contient des détails supplémentaires.
2. A partir de ces résultats, nous fournissons des recommandations pour la conception de plates-formes de réalité virtuelle afin d'effectuer des études de locomotion humaine dans le contexte des interactions.

B.4.2 Discussion

L'objectif de la première étude était d'étudier la nature de l'information provenant des mouvements d'obstacles utilisés lors des interactions entre les marcheurs. Nous avons conçu une tâche d'évitement des collisions orthogonales dans la réalité virtuelle, semblable à Olivier et ses collègues [Olivier2012] qui ont formé une méthode pour décrire l'interaction interpersonnelle dans des conditions réelles. Nous nous sommes concentrés sur les indices de mouvement global et local en manipulant l'apparence visuelle des obstacles. Nous avons évalué l'influence de cette manipulation sur la stratégie d'adaptation, en nous concentrant notre analyse sur le *MPD*, la distance prévue de l'approche la plus proche.

B.4.2.1 Adaptation qualitative du mouvement

Toutes les apparences d'obstacles ont conduit à une adaptation du mouvement qualitativement similaire. Presque aucune collision et peu d'inversions de l'ordre de passage à niveau ont été observées. Le comportement d'évitement des collisions présentait trois phases distinctes d'évitement : observation, le participant percevait l'obstacle mais n'agissait pas actuellement sur celui-ci ; réaction, le participant modifiait sa trajectoire pour augmenter la distance future de l'approche la plus proche ; réglementation, une fois la distance de sécurité obtenue, la distance était maintenue constante ou même légèrement diminuée. Tous les essais d'évitement des collisions ont été résolus par anticipation. Ces résultats correspondent à ceux observés dans des conditions réelles [Olivier2012], ainsi que dans des environnements virtuels avec un marcheur virtuel [Olivier2017]. La manipulation de l'apparence visuelle n'a montré aucun effet sur la capacité humaine de mener à bien une tâche d'évitement des collisions orthogonales : les humains ont réussi à éviter les collisions indépendamment de l'apparence globale ou locale de l'obstacle.

Contrairement à [Olivier2012, Olivier2013] et [Vassallo2017], qui n'ont rapporté aucune adaptation de trajectoire au-dessus d'une distance de croisement future de 1m, cette étude ne présente aucun seuil de risque de collision (c'est-à-dire les valeurs initiales MPD). Nous avons toujours observé une adaptation d'évitement de la trajectoire, ceci est en accord avec [Olivier2017]. L'absence d'un seuil supérieur au sein de notre dispositif expérimental pourrait s'expliquer en partie par un changement de perception de la distance dans la réalité virtuelle [Loomis2003, Lampton1995, Plumert2005], ainsi que par l'espace personnel accru pendant l'immersion [Gérin-Lajoie2008, Argelaguet-Sanz2015].

B.4.2.2 Ordre de croisement

Après avoir examiné l'ordre de croisement initial, les résultats ont montré un effet d'apparence visuelle d'obstacle sur le nombre d'inversions de l'ordre de croisement. Semblable à une étude précédente impliquant un robot à roues [Vassallo2017], nous avons noté des inversions (de 5% à 20%) de l'ordre de croisement pour les essais où il était prévu qu'un marcheur croise en premier et finalement croise en second. Le taux d'inversion était le plus élevé pour le cylindre et le moins élevé pour le corps entier et les jambes. Des configurations expérimentales similaires avec des apparences d'obstacles variables ont produit des réponses comportementales variables. Les travaux de [Olivier2012, Olivier2013] n'ont rapporté aucune inversion entre deux humains dans des conditions réelles, un ordre de croisement a émergé à $MPD_{t_{see}}$ et est resté. Cependant, Vassallo et ses collègues [Vassallo2017] ont signalé des inversions d'ordre de croisement après $MPD_{t_{see}}$. Le rôle de l'inversion a été interprété comme une réponse comportementale extrême pour la préservation de l'espace personnel, déclarant qu'une inversion est une réponse énergétique inefficace sur la trajectoire prévue. Ils ont suggéré que cette réaction pourrait s'expliquer par le niveau de danger perçu du robot ainsi que par le manque d'expérience en matière d'évitement des collisions avec des robots à roues. L'immersion dans des environnements virtuels réduit le danger

physique, d'autres réponses comportementales orientées vers un objectif dans la réalité virtuelle ont déjà été validées [Cirio2013, Olivier2017]. Considérant les résultats rapportés ici et précédemment, nous pouvons émettre l'hypothèse que le fait de soutenir la communication sociale non verbale aide les marcheurs à maintenir l'ordre de croisement après $MPD_{t_{see}}$. De plus, la taille de l'obstacle et l'incertitude du comportement peuvent influencer davantage le taux d'inversion.

B.4.2.3 Adaptation quantitative du mouvement

Nos résultats ont fait état d'une différence significative de la distance de croisement tout en interagissant avec les apparences visuelles globales du mouvement. La distance de croisement était plus grande lors de l'interaction avec le cylindre (1,24 m) et plus petite lors de l'interaction avec le COG (0,96 m) par rapport au corps entier (1,17 m). Nous notons que dans un réglage d'évitement des collisions orthogonales, la variation de l'apparence visuelle par rapport au contrôle de l'apparence visuelle du corps entier n'a pas affecté la stratégie d'évitement.

L'évolution du MPD au fil du temps pendant les étapes interactives de la tâche d'évitement des collisions a montré une différence significative par rapport à l'état du corps entier pour les deux aspects du mouvement global (c'est-à-dire le COG et le cylindre). Après que 22% du temps normalisé de $MPD_{t_{see}}$ à $MPD_{t_{cross}}$, les participants ont suivi une trajectoire qui s'est traduite par une distance de croisement plus petite dans l'état COG par rapport au corps entier. En revanche, après 47% du temps normalisé, les participants ont suivi une trajectoire qui leur a permis de franchir une plus grande distance à partir du cylindre. En ce qui concerne les trois phases distinctes d'évitement, le COG avait la plus longue période d'observation en temps normalisé de 10% (Figure 3.3). Par la suite, une différence significative dans l'évolution du MPD avec le corps entier a été observée à partir de 22% (Figure 3.4). Bien que l'évitement des obstacles ait été ef-

fectué avec succès avec l'aspect COG (sphère de 8 cm), suggérant que le changement d'angle de relèvement fournissait suffisamment d'informations pour éviter les obstacles dynamiques, la période d'observation avant d'initier une réponse était significativement plus longue, et la distance de croisement était significativement plus petite que pour les obstacles plus grands. Cela peut suggérer que l'expansion optique a également joué un rôle important dans le chronométrage de la réponse d'évitement : l'expansion optique d'un objet de 8 cm atteint le seuil beaucoup plus tard que celle d'un objet de grande taille. Ces résultats impliquent que l'évitement des obstacles peut ne pas être contrôlé par le seul changement d'angle de roulement, bien qu'il soit efficace dans l'auto-organisation émergente au sein des foules [Ondřej2010].

Le cylindre, cependant, reproduisait une période d'observation similaire à celle du corps entier, une différence significative se produisant à partir de 47% où le marcheur est susceptible de s'être suradapté en raison de la plus grande distance de croisement. Ce résultat est en accord avec [Iachini2014] qui a rapporté une plus grande distance d'interaction tout en rencontrant un cylindre par rapport à un corps humain. Ils ont établi un lien entre leurs conclusions et les aspects sociaux de l'interaction. Cependant, dans notre cas, nos résultats peuvent être interprétés par : la différence dans la dimension sociale des interactions avec un cylindre ou un personnage, ou une certaine incertitude dans la perception de la taille et du mouvement du cylindre.

B.4.2.4 Informations locales ou globales

Les participants ont rempli un questionnaire concernant leur expérience subjective de chaque apparition d'obstacle. Ils ont classé l'apparence visuelle dans l'ordre de préférence pour l'interaction. Il est intéressant de noter qu'il n'y avait pas de préférence unique. Cette réponse impartiale a été étayée par des questionnaires Likert inter-blocs qui n'ont pas non plus montré de biais dans l'apparence des obstacles.

Knorr et ses collègues [Knorr2016] ont rapporté que l'âge, la taille, le sexe et les facteurs sociaux de personnalité n'influencent pas les réponses comportementales d'une tâche d'évitement des collisions. La préférence subjective rapportée ici corrobore les réponses comportementales de Knorr et al. [Knorr2016]. Toutefois, Knorr et coll. n'ont pas fait état d'une analyse des préférences subjectives. Étonnamment, les réponses comportementales que nous avons observées aux informations globales et locales sur le mouvement contredisent ces résultats. Nos résultats ont montré que selon l'apparence de l'obstacle, les participants éviteraient l'obstacle à une distance différente. Ces résultats suggèrent donc que le comportement d'évitement n'est pas lié à une préférence subjective de l'apparence visuelle, mais plutôt que l'apparence visuelle modifie les occasions d'action perçues d'un agent, comme en témoigne sa réaction comportementale. C'est-à-dire que la plus grande surface englobée par le cylindre permet une plus grande distance de croisement, alors que le COG a un plus petit volume et permet donc une plus petite distance de croisement.

Meerhoff et al. [Meerhoff2014] ont étudié le rôle de l'information sur le mouvement global et local dans une tâche de régulation de distance non compétitive. Ils ont montré que même si la capacité de régler la distance n'était pas perturbée, lorsque seul le mouvement global était disponible, les participants ont réussi à obtenir un avantage temporel (c.-à-d. des réponses antérieures) lorsque le mouvement local et le mouvement global étaient disponibles. On pourrait donc supposer que l'information sur le mouvement local permet une estimation plus précise des mouvements d'une autre personne, mais l'utilité de cette information dépend de la nature de l'interaction (compétitive ou non compétitive). Dans notre étude, nous avons constaté que les conditions de cylindre induisaient une plus grande distance de croisement. Cependant, nos résultats COG contrastent avec les résultats de [Meerhoff2014], ce qui peut s'expliquer par la taille de l'objet. Meerhoff et ses collègues [Meerhoff2014] ont utilisé un objet sphérique ayant le même diamètre que la hauteur de leur condition de contrôle du corps entier, alors que nous avons adopté une sphère plus petite pour représenter le COG. Étant

donné cette taille plus petite, cela aurait pu donner aux participants l'impression de pouvoir traverser à une distance plus petite, malgré l'incertitude supposée de l'absence d'information sur le mouvement local. De plus, dans notre analyse, nous avons considéré les réponses comportementales au centre d'un obstacle et à l'enveloppe d'un obstacle, c'est-à-dire le point circonférentiel de l'obstacle le plus proche du marcheur. L'analyse de la réponse comportementale à l'enveloppe de l'obstacle a été omise car il n'y avait pas de différence par rapport au centre de l'obstacle. Cependant, la fréquence des collisions a été considérablement augmentée tout en traitant le COG à l'intérieur d'un corps entier invisible. Cela confirme que les occasions d'action sont liées aux apparences visuelles directement perçues dans le réseau optique.

B.4.2.5 Conclusion

Nous avons étudié le mouvement d'un personnage virtuel passif avec des indices visuels globaux et locaux lors d'une tâche d'évitement de collision orthogonale. Nos constatations ont montré que la nature de l'apparence visuelle avait effectivement une incidence sur la distance finale du passage à niveau. Les apparences de mouvement global du COG et du cylindre étaient plus petites et plus grandes respectivement d'après les apparences de mouvement local. Qualitativement, toutes les apparences visuelles reproduisaient des adaptations de mouvement similaires. Les participants ont anticipé les collisions futures par l'observation, la réaction et les réponses réglementaires. De plus, l'apparence visuelle n'a eu aucun effet sur le nombre de collisions ou d'inversions de l'ordre de passage à niveau. Nous associons la variance de la distance de croisement à la perception des opportunités d'action du marcheur, la surface offerte par l'obstacle virtuel, plutôt que la dichotomie visuelle de l'information globale et locale. En résumé, le mouvement global fournit suffisamment d'informations pour éviter les collisions, mais les variantes de mouvement local reproduisent des réponses plus précises et répétables.

B.5 Influence de la courbure de la trajectoire sur le comportement d'évitement des collisions

B.5.1 Objectifs et contributions de la deuxième étude

Cette étude a examiné l'influence de la trajectoire d'un marcheur virtuel pour l'estimation précise de la détection des collisions potentielles entre deux marcheurs. Plus précisément, nous avons cherché à savoir si une trajectoire curviligne influençait le choix du moment et le comportement d'évitement entre deux marcheurs par rapport à une trajectoire rectiligne. Les êtres humains interagissent dans des environnements dynamiques sur une base quotidienne, répondant à ce que chaque environnement offre. Par exemple, les espaces publics et bondés permettent aux humains de régler leurs distances interpersonnelles afin d'éviter les collisions. Dans le cas d'une interaction d'évitement des collisions par paires, l'environnement peut se permettre de passer en premier (devant) ou en second (derrière) d'un autre marcheur, avec ou sans évitement des collisions. Dans le cas des trajectoires rectilignes, les comportements d'évitement des collisions ont été largement rapportés [Olivier2012, Olivier2013, Basili2013, Huber2014, Knorr2016, Olivier2017]. De plus, il a été démontré que les occasions d'action perçues par les marcheurs pourraient être accordées sur la base d'une distance minimale prédite [Olivier2012, Olivier2013]. La distance minimale prévue (*MPD*) extrapolera linéairement la vitesse et l'orientation instantanées, ce qui représente la distance prévue la plus proche que deux marcheurs passeront si aucune adaptation n'est effectuée par l'un ou l'autre marcheur (c.-à-d., basée sur une vitesse et une trajectoire constantes). En outre, *MPD* quantifie la notion de *risque de collision*, où des adaptations du *MPD* sont observées lorsque la distance de croisement prévue est inférieure à la distance de contact ; un seuil de 1m a été rapporté [Olivier2012]. De plus, au cours de l'évolution du *MPD*, trois phases distinctes ont été identifiées

: l'observation, la réaction et la régulation. Ces résultats ont montré que pour une trajectoire rectiligne, le *MPD* peut être utilisé dans la prédiction du risque futur de collision. Lorsque le risque est faible, aucun comportement d'évitement n'est observé, mais lorsque le risque est élevé, le comportement d'évitement est observé. Cependant, dans des conditions réelles, les humains ne suivent pas toujours des trajectoires rectilignes à vitesse constante. Cela soulève deux questions, la première étant de savoir si une tâche d'évitement des collisions avec des trajectoires curvilignes peut être aussi bien exécutée, comme cela a été démontré précédemment pour les trajectoires rectilignes. Deuxièmement, la question de savoir si le *MPD* est un moyen pertinent pour éviter les collisions avec des trajectoires non linéaires.

Le système visuel a déjà été montré comme sensible aux changements directionnels de l'automobilisme et du mouvement des objets dans les trajectoires rectilignes et curvilignes [Bastin2006b, Bastin2008, Bosco2012, Delle Monache2015], et sensible à la perception de la vitesse mais plutôt insensible à l'accélération [Watamaniuk2003, Zaal2012]. Il a déjà été démontré que la vitesse des marcheurs peut être contrôlée prospectivement en utilisant une stratégie d'angle de relèvement constant tout en interceptant une balle qui suit une trajectoire médiolatérale le long d'une courbe de 5m et 10m de rayon [Bastin2006b]. De plus, il a été démontré que la vitesse des marcheurs était plus affectée par la courbure d'une boule en vol que par la manipulation du taux d'expansion [Bastin2008]. Cependant, dans ces expériences, la validité écologique peut avoir été affectée car les marcheurs ont été contraints à un seul axe de déplacement. De plus, les participants ont effectué une tâche d'interception, on ne sait pas dans quelle mesure ces résultats s'appliquent au déplacement piétonnier dans le cadre d'une tâche d'évitement des collisions.

Il est difficile de manipuler expérimentalement la trajectoire d'un marcheur passif pour suivre une trajectoire curviligne sans aide visuelle et de répéter la trajectoire curviligne avec une accélération constante pour assurer une vitesse constante à la tangente de la trajectoire curviligne dans la vie réelle et la reproductibilité serait une limitation. La réal-

ité virtuelle est une nouvelle approche qui a déjà été utilisée pour étudier la locomotion et les interactions [Bruneau2015, Lynch2017, Olivier2017] car elle s'est avérée être un outil puissant pour la perception écologique et la recherche-action [Loomis1999]. Bien que la réalité virtuelle ne soit pas sans limites (voir [Pan2018] pour une revue), les réponses comportementales observées dans la réalité virtuelle sont conformes à la réalité. Par exemple, les tâches de locomotion orientées vers un but ont été validées pour la reproductibilité des trajectoires stéréotypées [Cirio2013], malgré les différentes méthodes interactives [Olivier2017]. De plus, en ce qui concerne les tâches d'évitement des collisions, la préservation de l'espace personnel et des réactions comportementales d'évitement similaires ont été signalées [Gérin-Lajoie2008, Argelaguet-Sanz2015, Olivier2017]. C'est pourquoi nous avons développé et réalisé l'expérience en réalité virtuelle.

Nous abordons la question de savoir si l'évitement des collisions des marcheurs sur des trajectoires courbes est perturbé (c.-à-d., de mauvaises adaptations conduisant à une collision). Lorsqu'il a été démontré que lorsque la distance future de l'approche la plus proche est inférieure à un seuil d'un mètre de trajectoires linéaires, les marcheurs adaptent leur trajectoire en prévision de l'évitement des collisions. Dans ce contexte, la prédiction du risque futur de collision suit l'hypothèse d'une vitesse constante. Cependant, dans le cas d'une trajectoire courbe, il y a une accélération constante pour changer constamment de direction, et il n'est pas clair si cela est pris en compte dans la prédiction des collisions futures (c.f., figure B.8). Par ailleurs, lorsque l'on considère la nature de la courbe, si le comportement d'évitement des collisions est effectivement perturbé, les réponses comportementales peuvent s'appuyer sur des repères visuels comme l'orientation de la marche par rapport à l'observateur. Par conséquent, une analyse supplémentaire de l'orientation de la marche serait intéressante. Nous émettons l'hypothèse que le comportement d'évitement des collisions sera en effet perturbé par des trajectoires curvilignes, ce qui indiquerait que les marcheurs utilisent une extrapolation linéaire en supposant une vitesse constante pour anticiper les collisions futures.

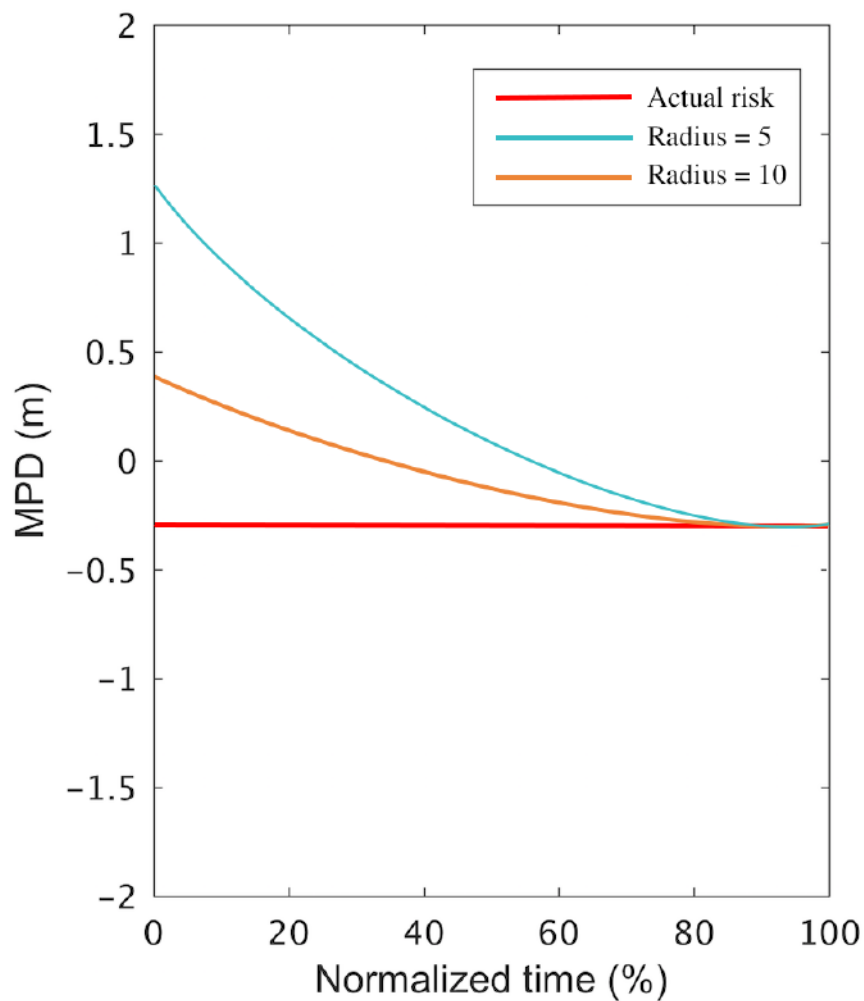


Figure B.8 - Exemple de vitesse constante *MPD* prédisant le risque futur pour les trajectoires courbes. La ligne bleue serait l'extrapolation d'une trajectoire suivant une courbe de 5 m de rayon. La ligne orange serait l'extrapolation d'une trajectoire suivant une courbe de 10 m de rayon. La ligne rouge indique la progression acutale du risque sans adaptation.

B.5.2 Discussion

Le but de la présente étude était d'examiner le comportement d'évitement des collisions lors de l'interaction avec un marcheur virtuel ayant une accélération constante et produisant une trajectoire curviligne en comparaison avec une trajectoire rectiligne à vitesse constante. Nous avons conçu une tâche d'évitement des collisions dans la réalité virtuelle, en utilisant une trajectoire rectiligne, similaire aux études précédentes [Olivier2012, Olivier2013, Basili2013, Olivier2013, Olivier2017], comme situation de contrôle. De plus, nous nous sommes concentrés sur les trajectoires curvilignes qui croisent perpendiculairement la trajectoire du participant, comme étude initiale des trajectoires curvilignes sur le comportement d'évitement des collisions, nous avons utilisé des trajectoires à rayons fixes. Pour ce faire, nous avons évalué l'influence des trajectoires curvilignes sur le comportement d'adaptation et la synchronisation d'événements spécifiques, notre analyse s'est concentrée sur la distance minimale prévue de l'approche la plus proche entre deux marcheurs.

B.5.2.1 Adaptation qualitative du mouvement

Les interactions avec tous les chemins de marcheurs virtuels, rectilignes et curvilignes, ont conduit à des adaptations de mouvement qualitativement similaires. Sur les 3501 essais possibles, une adaptation a eu lieu dans presque tous les essais. Pour chaque condition de la marche virtuelle, le comportement de prévention des collisions du participant a présenté trois phases distinctes d'interaction : l'observation, la réaction et la régulation. L'observation sous-entend que les participants percevaient le marcheur virtuel mais n'agissaient pas en fonction de l'information visuelle présentée. Au cours de la phase de réaction, les participants ont modifié leur propre trajectoire, en augmentant leur distance de croisement future prévue de l'approche la plus proche avec le marcheur

virtuel pour permettre une traversée en toute sécurité. Une fois la distance de croisement future d'approche minimale obtenue, les participants ont commencé l'étape de régulation, en maintenant la distance prévue ou en la diminuant légèrement jusqu'à ce que le passage en toute sécurité. Ces résultats sont similaires à ceux observés entre deux marcheurs ayant des trajectoires linéaires, en réalité [Olivier2012, Olivier2013], entre un marcheur et un robot à roues [Vassallo2017, Vassallo2018], et en réalité virtuelle [Olivier2017, Lynch2017, Lynch2017, Lynch2018]. Ces résultats suggèrent que, tout en interagissant avec un marcheur virtuel avec une accélération constante ou sans accélération, la stratégie d'évitement des collisions est globalement similaire. Les possibilités d'action perçues par les futures distances de croisement prévues sont observées, une adaptation est nécessairement faite et la tâche est anticipée par la réglementation du *MPD*.

B.5.2.2 Adaptation quantitative du mouvement

Distance de croisement. Nos résultats ont montré un effet principal de la marche virtuelle sur la distance de croisement, la condition P5 (1.27 ± 0.33 m) avait une distance de croisement significativement plus petite que INF (1.37 ± 0.27 m), P10 (1.35 ± 0.31 m) et N10 (1.38 ± 0.32 m). Les distances de croisement rapportées ici sont plus grandes que celles précédemment rapportées dans la réalité virtuelle [Olivier2017, Lynch2017, Lynch2017, Lynch2018] et plus grandes que celles observées dans la réalité [Olivier2012, Vassallo2017, Vassallo2018]. Lorsque nous comparons notre dispositif expérimental de l'essai témoin à ceux qui ont été signalés précédemment, nous pouvons émettre l'hypothèse que le corridor, qui a été utilisé à des fins d'occlusion dans cette étude, peut avoir influencé le comportement d'évitement. Ces résultats confirment que les participants ont perçu les différences de la marche virtuelle et ont adapté avec succès leurs trajectoires pour éviter les collisions. En effet, la distance finale du passage à niveau P5 était nettement inférieure à INF, P10 et N10, mais cette distance n'a pas

donné lieu à une collision. Dans l'ensemble, peu de collisions ont été signalées ; sur le nombre total de collisions, l'état P5 a signalé beaucoup plus de collisions que l'état INF. A partir de ces résultats, nous pouvons résumer que lorsque le marcheur virtuel suit une trajectoire curviligne avec un rayon de 5 m et s'approche par derrière le participant, le comportement d'évitement global produit une distance de croisement plus petite et une probabilité accrue d'une collision. Nous pouvons émettre l'hypothèse que pour la condition P5, les participants peuvent avoir eu besoin de plus de temps pour percevoir la tâche ou, inversement, percevoir que la tâche a été résolue plus tôt, et potentiellement de manière incorrecte. Notre analyse comprenait l'évolution du *MPD* et la synchronisation d'événements spécifiques au cours de l'interaction, nous discutons donc de la direction de cet effet observé plus tard.

Inversions d'ordre de croisement. En considérant les inversions de l'ordre de croisement initial, nos résultats ont montré un effet de trajectoire. Semblable aux enquêtes impliquant un robot à roues [Vassallo2017] et dans la réalité virtuelle [Lynch2017], nous avons observé des inversions allant de 3% à 20%. D'après nos résultats, INF avait le nombre d'inversions le plus faible et était similaire aux études précédentes [Lynch2017], alors que N5 avait le plus grand nombre d'inversions.

Dans un cadre rectiligne entre deux marcheurs dans la vie réelle, aucune inversion n'a été rapportée [Olivier2012, Olivier2013], l'ordre de croisement qui était présent à $MPD_{t_{see}}$ a été maintenu par les deux marcheurs. Le rôle d'une inversion était auparavant interprété comme une réponse comportementale extrême pour la préservation de l'espace personnel du danger physique car il est inefficace en termes d'énergie [Vassallo2017], mais les études écologiques à travers la réalité virtuelle réduisent le danger physique. Par conséquent, l'inversion de l'ordre de croisement a été attribuée plus tard aux indices de communication sociale non verbale sous-jacents qui peuvent aider au maintien de l'ordre de croisement après $MPD_{t_{see}}$ [Lynch2017]. Le nombre d'inversions a été réduit par la suite lorsque les marcheurs ont interagi avec un robot à roues qui a collaboré à la tâche d'évitement des collisions [Vassallo2018]. Bien que ces résultats n'aient pas été

reproduits pour les marcheurs virtuels qui ont collaboré à la tâche avec et sans regard [Lynch2018].

Nos résultats avaient une gamme d'inversions similaire à celles rapportées précédemment [Lynch2017], la présence d'inversions dans notre étude et leur accord avec les études précédentes prouve l'exactitude de la perception de la situation. De plus, le nombre rapporté d'inversions entre les conditions INF, P10, N10 et P5 suggère que les ordres de croisement dans ces conditions étaient facilement perçus et permettaient des comportements d'évitement similaires. Cependant, la condition N5 avait beaucoup plus d'inversions, ce résultat suggère que les participants ont soit perçu plus facilement la trajectoire et ont adopté un comportement d'évitement pour passer derrière le marcheur virtuel, soit ils ont eu besoin d'une plus longue durée pour percevoir et s'adapter à la trajectoire du marcheur virtuel afin d'assurer un passage en toute sécurité. Dans les sections suivantes, nous détaillons et discutons de la chronologie des événements au cours de l'interaction.

Évolution de la MPD. Nous avons comparé l'évolution de R_{MPD} et C_{MPD} sur une période normalisée, qui était l'étape d'interaction de la tâche d'évitement des collisions entre MPD_{tsee} et MPD_{tcross} . Pour cette analyse, le nombre limité d'essais qui ont signalé une collision ou une inversion a été exclu, alors qu'en général, un essai avec une collision ou une inversion suggère que les caractéristiques de l'interaction n'étaient pas bien perçues. Lorsque cette analyse devait comparer spécifiquement la pertinence et l'évolution du MPD pour les essais réussis seulement.

L'évolution de C_{MPD} a montré des différences significatives pour des trajets d'un rayon de 5 m par rapport à R_{MPD} . Le C_{MPD} pour P5 était significativement différent de R_{MPD} après 39% du temps normalisé d'interaction, les participants ont adapté leur trajectoire qui a eu pour résultat une augmentation moins graduelle de C_{MPD} ; la différence observée n'était plus présente après 65% du temps normalisé. De plus, le C_{MPD} pour N5 était significativement différent de R_{MPD} après 46% du temps nor-

malisé. Les participants ont suivi une trajectoire qui a entraîné une augmentation moins graduelle de C_{MPD} que R_{MPD} , ce qui a eu pour effet de réduire la distance de croisement lorsque l'on envisage des essais sans modification de l'ordre de croisement. Ces résultats soutiennent notre hypothèse, une trajectoire avec une accélération constante qui suit une trajectoire avec un rayon de 5m perturbée et un comportement d'évitement des collisions par rapport à une trajectoire sans accélération. Cependant, ceci n'était vrai que pour un rayon de 5m, il n'y avait pas de différence significative pour l'accélération constante d'une trajectoire d'un rayon de 10m à partir de la trajectoire rectiligne. Cela suggère qu'une accélération constante était plus difficile à percevoir pour une trajectoire courbe de 5m. Cependant, à partir des similitudes observées dans l'évolution des courbes MPD , nous avons démontré que MPD est un moyen pertinent de disposer d'une vitesse constante et de trajectoires d'accélération constante pour les tâches d'évitement des collisions.

Timing. Tous les trajets présentaient les trois phases distinctes du comportement d'évitement des collisions au cours de l'évolution du MPD , observable dans la figure 4.7. Des études antérieures ont caractérisé l'évolution du MPD en calculant sa dérivée temporelle, en identifiant un changement de signe de la dérivée temporelle du MPD et en comparant ensuite les valeurs correspondantes du MPD [Olivier2012, Lynch2017]. Pour élucider les trois étapes de l'interaction, nous avons fixé un seuil de différence absolue de MPD supérieur à 0,15m, à partir de $MPD_{t_{see}}$ pour le temps de réaction (c'est-à-dire le terminus de l'étape d'observation) et de $MPD_{t_{cross}}$ pour le temps de régulation, qui a duré 1,5s. Nous avons choisi un seuil de MPD absolu de 0,15m comme étant à l'intérieur de l'écart-type précédemment rapporté au moment de la réglementation [Olivier2012]. Le seuil fixé a été validé en observant la différence entre le temps de régulation et la durée totale, le temps de régulation a été enregistré environ 0,8s avant le croisement, ce qui était similaire aux résultats précédents [Olivier2012]. Nous avons observé que P5 avait une période d'observation plus longue que INF, P10 et N10. De plus, N5 avait une période d'observation beaucoup plus longue que N10. De plus, nous interprétons

l'instance de régulation enregistrée comme la combinaison des étapes d'observation et d'adaptation ; après l'instant de régulation enregistrée, aucune autre adaptation du *MPD* supérieure au seuil de 0,15m n'a été observée. D'après nos résultats, nous avons observé un effet principal de trajectoire ; N5 a eu un temps de régulation plus tardif de toutes les autres conditions. Si l'on considère les différences entre le temps de réaction et le temps de régulation, on peut résumer que P5 a nécessité des périodes d'observation plus longues pour la collecte d'informations visuelles et donc retardé leur adaptation, mais le comportement d'évitement pendant la phase de réaction de P5 a été résolu plus tôt et la distance finale de traversée a été plus courte. Par contre, N5 n'était pas significativement plus long que INF pendant la période d'observation mais avait une durée de régulation plus tardive ; N5 était initialement perçu de la même manière que INF, mais N5 avait besoin de plus de temps pour atteindre une distance de régulation confortable, bien que cela n'ait pas d'influence sur la distance de croisement. Ces résultats appuient notre hypothèse, où le temps de réaction pour la condition P5 suggère que l'accélération constante est initialement mal perçue, puis la durée plus longue de l'adaptation et plus tard le temps de régulation de N5 suggère que l'accélération constante a été mal perçue.

D'après les différences observées dans la synchronisation des événements ; P5 avait une période d'observation plus longue que INF, et N5 avait besoin de plus de temps avant d'obtenir une distance de régulation. Nous avons considéré l'analyse supplémentaire de C_{MPD} de R_{MPD} et l'orientation du marcheur virtuel à chaque événement respectivement chronométré. Il permet d'inférer l'information visuelle présentée au participant. Dans l'ensemble, il n'y avait pas d'effet principal du trajet sur le *MPD* au moment de la réaction, la plus longue durée d'observation pour P5 n'a pas eu d'effet sur la distance de croisement prévue. Toutefois, l'observation plus longue et la durée d'adaptation plus courte qui a produit le temps de régulation similaire de P5 à partir de l'INF avait influencé la distance de croisement future prévue au moment de la régulation. Le *MPD* le plus court à la régulation est également observé par la distance finale de croisement

plus courte de P5. Au contraire, N5 avait une durée similaire pour la phase d'observation de l'interaction et a pris beaucoup plus de temps pendant la période d'adaptation, ce qui a produit un temps de régulation de N5 significativement plus long à partir de INF. Toutefois, l'adaptation plus longue n'a pas eu d'effet significatif sur le *MPD* au moment de la réglementation ou sur la distance finale de N5 par rapport à INF.

Angle orientation. En considérant l'orientation de la marche virtuelle, nos résultats ont montré que l'angle absolu normalisé pour P10 et N10 étaient similaires. Les participants ont commencé leurs adaptations avec le même type d'informations visuelles de la marche virtuelle. L'effet significatif d'un temps de réaction plus long pour P5 peut également être observé dans l'orientation normalisée absolue de la marche virtuelle au temps de réaction, P5 était significativement différent de INF et N5. Cependant, la différence entre P5 et N5 tend à ne pas être significativement différente ($p=0,049$). Compte tenu de ce qui précède, nous pouvons suggérer que les participants ont commencé leurs adaptations avec une quantité similaire d'informations visuelles de la marche virtuelle suivant une trajectoire fixée à un rayon de 5m indépendamment de la direction d'approche. De même, l'orientation de la marche virtuelle au moment de la régulation était similaire entre P5 et N5, et similaire entre P10 et N10. De plus, on a utilisé le même type d'information visuelle pour déterminer un temps de régulation pour chaque taille de courbe, indépendamment de la direction d'approche. Ces résultats sont intéressants dans la mesure où le même type d'informations visuelles peut être utilisé pour la prise de décision entre les étapes d'adaptation. Toutefois, nos constatations font encore état de différences quant à la distance finale du passage à niveau et au moment des adaptations. Nous émettons l'hypothèse que les différences signalées peuvent avoir été influencées par la direction d'approche du marcheur virtuel. Il a été rapporté que l'espace personnel est asymétrique entre l'axe antéro-postérieur et l'axe médiolatéral [Gérin-Lajoie2005], ce qui a été discuté pour son influence du risque d'être plus petit lors du premier croisement et plus grand lors du croisement du second [Olivier2013]. A partir des effets d'interaction de la distance finale du croisement et des angles d'orientation normalisés,

nous pouvons observer la quantité d'informations visuelles et la distance de croisement a été influencée par la direction d'approche du marcheur virtuel.

B.5.2.3 Rectiligne et curviligne.

Les résultats de cette étude démontrent que les participants ont réussi à exécuter une tâche d'évitement des collisions lorsqu'ils interagissent avec un humain virtuel marchant sur une trajectoire rectiligne de vitesse constante et une trajectoire curviligne d'accélération constante. Ceci est confirmé par le questionnaire de fin d'expérience que les participants ont rempli concernant le mouvement du marcheur virtuel, l'interaction avec le marcheur virtuel, la facilité de la tâche et les réponses aux questions ouvertes qui se référaient souvent à la trajectoire du marcheur virtuel.

La capacité de détecter avec succès les trajectoires curvilignes a déjà été démontrée lors de tâches d'interception [Bastin2006b, Bosco2012] et ces capacités ont été présentées dans des paradigmes d'occlusion partielle (voir [Delle Monache2015] pour une revue). Cependant, à notre connaissance, il s'agit de la première étude qui a examiné l'interaction des trajectoires curvilignes entre deux marcheurs lors d'une tâche d'évitement de collision. Bosco et ses collègues [Bosco2012] ont étudié l'intégration de différents traitements de l'information dans le contrôle d'une action d'interception d'une balle qui suit une trajectoire de vol parabolique. Dans le cadre de leur conception expérimentale, les participants ont intercepté un ballon à l'aide d'une souris d'ordinateur et ont suivi la trajectoire sur un écran d'ordinateur. La trajectoire était soit continuellement présente, soit occultée peu de temps après l'atteinte de la hauteur maximale. De plus, la trajectoire de vol a été perturbée pendant la descente. La conception mixte de mesures répétées a permis la comparaison entre le contrôle visuel prospectif et les capacités prédictives [Bosco2012]. Leurs résultats ont montré que les participants s'appuyaient sur une combinaison de contrôle prospectif et prédictif lorsque les stimuli

visuels sont constamment présents, et qu'ils s'appuyaient davantage sur des mécanismes prédictifs lorsque les stimuli étaient occlus. Les participants avaient plus d'erreurs d'interception lorsqu'ils interagissaient initialement avec des trajectoires de vol perturbées et occultées. Cependant, l'une des implications de cette étude était l'interaction entre un écran d'ordinateur et la souris, la position finale du curseur de la souris aurait pu être spécifiée avant le moment de l'interception. Nos constatations sont en accord, les participants se sont fiés à une combinaison de contrôle prospectif et prédictif lorsqu'ils effectuent la tâche d'évitement des collisions. En effet, notre dispositif expérimental n'a pas été conçu pour élucider les différences entre le contrôle prospectif et le contrôle prédictif. Cependant, l'évolution du *MPD* et la distinction des trois étapes de l'interaction soutiennent l'hypothèse que les étapes initiales de l'interaction sont prédites. De plus, l'achèvement de l'adaptation avant le croisement et la présence d'une étape de régulation suggère que les étapes finales de la tâche ont été contrôlées prospectivement. Les travaux futurs consisteraient à envisager un paradigme d'occlusion temporelle au cours d'une tâche d'évitement des collisions afin d'étudier l'aspect prédictif de la commande.

Comme pour notre plan expérimental, Bastin et ses collègues [Bastin2006b] ont effectué une tâche d'interception d'un ballon qui suivait des trajectoires rectilignes ou curvilignes basées sur des courbes de rayon de 5 et 10m. De plus, la distance à laquelle la balle a intercepté la trajectoire du participant était décalée, de sorte que les participants devaient accélérer (1m), maintenir une vitesse constante (0m) ou décélérer (-1m) pour intercepter la balle avec succès. Dans leur conception, toutes les trajectoires de balle provenaient de l'avant du participant et s'approchaient de la droite. Les participants ont été attachés au cadre du tapis roulant afin de limiter l'adaptation du mouvement à la vitesse de marche [Bastin2006b]. Les résultats de leur étude ont montré une capacité de percevoir et d'intercepter une balle avec seulement des adaptations à la vitesse de marche. De plus, leurs résultats ont montré qu'une stratégie d'angle de relèvement constant pouvait expliquer les adaptations de déplacement au cours d'une tâche d'interception ; les participants contrôlaient prospectivement leurs actions en

maintenant un angle de relèvement invariant [Bastin2006b]. Bastin et ses collègues ont confirmé plus tard, en utilisant le même paradigme, que la stratégie de portance constante tenait compte de l'effet de courbure. De plus, la vitesse de marche des participants était également affectée par la courbe. [Bastin2008]. Nos résultats sont en accord avec le contrôle prospectif de la tâche, nous avons démontré pour une tâche d'évitement des collisions que les trajectoires curvilignes sont bien perçues. Nous avons en outre montré que la tâche peut être prévue à l'avance et qu'elle est accomplie grâce à un contrôle prospectif en prévision du croisement. Dans le cadre de notre étude, nous n'avons pas tenu compte de l'angle d'appui du participant pendant l'interaction ou de la théorie de l'angle d'appui constant. Compte tenu de la cohérence des angles d'orientation rapportés ici, il semblerait qu'un seuil constant d'angle de relèvement pourrait avoir été un repère visuel pour une prise de décision efficace.

Enfin, Olivier et ses collègues [Olivier2012] ont proposé *MPD* pour décrire les interactions interpersonnelles combinées pendant la prévention des collisions. L'extrapolation linéaire de la vitesse instantanée et de l'orientation à un futur point de passage entre deux marcheurs représente la distance future de l'approche la plus proche si aucune adaptation n'est effectuée. *MPD* quantifie la notion de *risque de collision*, les adaptations de *MPD* se produisent en effet lorsqu'il y a un risque de collision future [Olivier2012]. Lorsque la stratégie d'adaptation est réalisée par anticipation [Olivier2012] et dépend en outre des caractéristiques de l'interaction ; les travaux précédents ont pris en compte différents angles d'intersection avec des chemins rectilignes [Huber2014]. Dans le cadre de notre conception expérimentale, nous avons envisagé une adaptation du *MPD* pour les trajectoires curvilignes d'un rayon fixe afin d'exprimer l'interaction entre deux marcheurs. Nos résultats ont montré qualitativement et quantitativement que les participants ont prédit les distances de croisement futures et ont réussi à éviter les comportements d'évitement ; de plus, nos résultats ont montré que l'interaction avec les trajectoires curvilignes est réalisée par anticipation.

B.5.2.4 Limitations

Une limitation de notre conception expérimentale peut être observée dans les distances de croisement rapportées. Nous avons utilisé un marcheur virtuel passif car cela a permis un meilleur contrôle et une standardisation des conditions auxquelles les participants ont été exposés. Des études antérieures ont signalé une augmentation des distances finales de traversée, les différences observées ont été attribuées au comportement passif du marcheur virtuel ou robot [Olivier2017, Lynch2017, Lynch2017, Vassallo2017]. En réalité, un comportement d'évitement collaboratif d'un robot à roues a réduit de manière significative la distance de croisement finale [Vassallo2018]. Cependant, ces observations n'étaient pas cohérentes pour les marcheurs virtuels collaboratifs [Lynch2018]. Par conséquent, bien que les participants aient été informés de la passivité de la marche virtuelle et qu'ils ne devraient pas s'attendre à une coopération pendant la tâche d'évitement des collisions, cela a pu conduire à une adaptation excessive des comportements d'évitement des participants.

Alors que l'augmentation de la distance de croisement peut en effet être attribuée à la nature passive du mouvement de l'être humain virtuel ainsi qu'au changement de perception de la profondeur dans la réalité virtuelle, nos distances de croisement rapportées étaient plus grandes que celles rapportées précédemment pour les marcheurs virtuels passifs [Lynch2017, Olivier2017, Olivier2017, Lynch2018]. Ces différences observées peuvent être attribuées à l'utilisation d'un corridor d'occlusion par opposition à un plan d'étage ouvert avec des murs occlusifs [Olivier2012, Olivier2013, Olivier2013, Olivier2017, Lynch2017]. Le couloir d'occlusion permettait un meilleur contrôle et une standardisation de l'instant où les deux marcheurs étaient visibles ($MPD_{t_{see}}$). En effet, nous aurions pu maintenir un paradigme similaire à celui des études précédentes, mais il serait nécessaire de déplacer l'orientation, la taille et la position des murs occlusifs pour chaque condition, ce qui pourrait fournir des indices pour l'identification des conditions. Sinon, nous aurions pu concevoir l'expérience de manière à ce que la marche

virtuelle apparaisse à un endroit précis ; cependant, cela limiterait la validité écologique de l'interaction.

Enfin, nous avons d'abord étudié les effets des trajectoires curvilignes à rayons fixes sur le comportement d'évitement des collisions, à l'instar des études antérieures qui portaient sur la capacité d'intercepter des objets [Bastin2006b]. Cependant, lorsqu'on considère les trajectoires observées dans la réalité et la réalité virtuelle pour les tâches orientées vers un but [Hicheur2007, Cirio2013] et les trajectoires de vol de balle [Bosco2012, Craig2006], les trajectoires observées ne sont pas nécessairement uniformes avec une courbe radiale fixe. Lorsque l'on considère la trajectoire de la courbe fixe en combinaison avec le comportement passif de la marche virtuelle, ces deux limitations peuvent avoir entraîné une moins bonne validité écologique et réduit le sentiment de présence. Les travaux futurs devraient inclure la mesure du sens de la présence afin de déterminer si les trajectoires avec une accélération constante réduisent ou éventuellement augmentent le sens de la présence.

B.5.2.5 Conclusion

Cette étude a examiné l'influence de la trajectoire rectiligne et curviligne d'un marcheur virtuel passif sur le comportement d'évitement des collisions. Nous avons montré que la nature de l'information provenant du chemin du promeneur virtuel affectait en effet la distance de croisement et les étapes de l'évolution du *MPD*. Cependant, ces influences n'ont été observées que lorsque le marcheur virtuel a suivi une trajectoire avec une courbe de 5 m de rayon.

Lorsque le marcheur virtuel approché par derrière, le participant a eu une période d'observation plus longue, mais la durée de l'adaptation a été plus courte, ce qui a entraîné une distance de traversée finale plus courte. Inversement, lorsque le marcheur virtuel s'approchait de devant le participant, la durée de l'observation était similaire à un

chemin rectiligne, mais la durée de l'adaptation était plus longue. La durée plus longue de l'observation et de l'adaptation n'a pas eu d'influence sur la distance croisement.

Qualitativement, toutes les conditions expérimentales reproduisaient des adaptations de mouvement similaires ; les participants ont anticipé l'interaction par l'observation, la réaction et la régulation. Parmi le petit nombre d'essais qui ont fait l'objet d'une collision ou d'une inversion, P5 a eu le plus grand nombre de collisions et N5 a eu le plus grand nombre de collisions. Il n'y a pas eu d'effets significatifs d'une trajectoire curviligne de 10 m sur le nombre de collisions ou d'inversions de la condition de contrôle.

A partir de ces résultats, nous pouvons conclure qu'une accélération constante à partir d'une trajectoire courbe d'un rayon de 5 m perturbe le comportement d'évitement des collisions, mais ce n'était pas le cas pour la courbe d'un rayon de 10 m. Cependant, lorsque *MPD* tient compte de l'accélération constante d'une courbe radiale fixe, l'évolution de la tâche est résolue avec des adaptations qualitativement similaires. Cela donne à penser que le risque futur de collision a été prédit tôt dans l'interaction et qu'il a été contrôlé prospectivement par la suite et anticipé au cours d'une dernière étape de régulation avant le croisement. Cette étude offre une première tentative d'étudier comment un observateur interprète la trajectoire d'un autre marcheur. Nous avons discuté ici d'un contrôle prospectif qui tient compte de l'accélération, ce qui semble être un bon candidat pour modéliser la situation. Des travaux futurs sont nécessaires pour envisager d'autres trajectoires accélérées, par exemple, des accélérations constantes supplémentaires à partir de courbes de rayons de tailles différentes et la présence d'accélérations dans des conditions rectilignes.

B.6 Effet du comportement du regard humain virtuel lors d'une tâche d'évitement de collisions orthogonales

B.6.1 Objectifs et contributions de la troisième étude

La troisième étude a porté sur l'influence du comportement du regard sur une tâche d'évitement des collisions entre un personnage humain réel et un personnage humain virtuel. Contrairement aux travaux précédents, nous nous sommes concentrés sur l'effet du regard sur la cinématique des interactions avec deux questions en tête. La présence ou l'absence d'interception du regard changerait-elle la cinématique de l'évitement des collisions entre deux marcheurs ? Et par extension, comme la réalité virtuelle est aujourd'hui utilisée pour étudier la locomotion et les interactions [Bruneau2015, Lynch2017], est-il important de contrôler correctement le comportement du regard des personnages virtuels afin de ne pas biaiser les données expérimentales ainsi acquises ?

Pour répondre à ces questions, nous avons demandé aux participants d'effectuer une trajectoire dans un environnement virtuel et de contrôler un personnage virtuel pour croiser leur chemin. Parmi les essais, le personnage présenterait un risque variable de collision avec le sujet, le personnage regarderait ou non les sujets, et le personnage exécuterait ou non des manœuvres d'évitement.

Nous avons supposé que la présence ou l'absence d'interception du regard pendant la négociation de l'évitement des collisions aura un effet sur les trajectoires réalisées par un participant pour éviter un personnage virtuel. La première hypothèse (**H1**) est que l'absence d'interception du regard (c'est-à-dire parce que le personnage ne regarde pas le sujet) peut entraîner des manœuvres d'évitement plus importantes de

la part du participant, qui ne s'attend pas à une collaboration pour résoudre la tâche. Cependant, l'absence de regard peut être compensée par la présence de manœuvres d'évitement perçues dans le mouvement du personnage. Lequel de ces deux indices visuels joue le plus grand rôle ? La deuxième hypothèse **(H2)** est que si le repère visuel lié au regard ne joue aucun rôle important dans l'interaction, la distance de traversée ne sera pas influencée par le facteur regard (le sujet contrôle sa trajectoire en fonction du mouvement relatif du personnage, quel que soit le comportement du regard). Une dernière hypothèse **(H3)** est que, lorsqu'un stimulus incongru est affiché, c'est-à-dire lorsque le personnage regarde le participant mais ne les évite pas, nous pouvons observer un manque d'évitement de la part du participant qui devrait s'attendre à une collaboration (et donc, une collision potentielle ou des distances de croisement anormalement basses).

La contribution de ce travail est de démontrer que, dans le type de situation simple que nous avons considéré, la locomotion des personnages virtuels a fourni suffisamment d'informations pour que les participants puissent contrôler leur propre mouvement. La présence ou l'absence d'interception du regard n'a pas affecté leur mouvement. Ce résultat est détaillé dans les sections suivantes.

B.6.2 Discussion

B.6.2.1 Collisions

Table B.1 - Pourcentage total des collisions observées pour chaque valeur de MPD_{tsee} (en mètres) par rapport aux conditions de regard et d'évitement.

<i>mpd tsee</i>	% of Collisions			
	<i>GNA</i>	<i>NGNA</i>	<i>GA</i>	<i>NGA</i>
-1.2	0	0	0	0
-0.9	0	0	0	0
-0.6	0	2.94	0	0
-0.3	2.94	0	0	0
-0.1	5.88	2.94	0	0
0.1	2.94	11.76	0	0
0.3	5.88	5.88	0	0
0.6	0	0	0	0
0.9	0	0	0	0
1.2	0	0	0	0

Tout d'abord, nous avons inspecté la présence de collisions entre les participants et le personnage virtuel. Parmi les 1360 essais effectués par l'ensemble des participants, la tâche d'évitement des collisions a été exécutée avec succès : il y a eu 14 collisions entre le personnage et le participant, ce qui signifie que seulement 1% des essais effectués présentaient une collision. La figure B.1 illustre le pourcentage de collisions observées en fonction des valeurs de MPD_{tsee} ainsi que les conditions de regard et d'évitement. Évidemment, aucune collision n'a été observée dans la condition d'évitement puisque l'algorithme de navigation RVO a empêché le personnage d'entrer en collision avec l'utilisateur. Les collisions n'ont été observées que dans les essais de Non-évitement où MPD_{tsee} variait de -0,6m à 0,3m.

Il n'y a pas eu d'effet significatif du comportement du regard des personnages virtuels ($p > 0,05$) ni dans les conditions *NA* ni dans les conditions *A* lorsque l'on considère le nombre de collisions par participant pour tous les essais (valeur médiane : $GNA=0\%$ et $NGNA=0\%$, $GA=0\%$ et $NGA=0\%$) ou séparément pour chaque condition $MPD_{t_{see}}$ (c'est-à-dire, définissant le risque initial de collision).

Ces résultats ne sont pas conformes à l'hypothèse **(H3)**. En effet, dans la condition *GNA*, nous avons émis l'hypothèse que le regard du personnage virtuel permettrait aux participants de s'attendre à une collaboration dans la tâche d'évitement alors qu'il n'y en a pas. Dans l'hypothèse d'une collaboration, le participant n'adapterait pas suffisamment la trajectoire pour éviter le personnage, ce qui entraînerait davantage de collisions. Les comparaisons entre le regard et les conditions sans regard (resp. *GNA* et *NGNA*) ne montrent pas de différence significative dans le nombre de collisions. Par conséquent, il n'y avait presque aucune ambiguïté dans l'interprétation de la trajectoire du personnage virtuel quelles que soient les conditions du regard, permettant des passages sûrs même dans la plupart des situations sans que la stratégie d'évitement soit mise en œuvre par le personnage virtuel où le risque initial de collision était élevé ($-0,3m < MPD_{t_{see}} < 0,3m$).

B.6.2.2 Ordre de croisement

Deuxièmement, nous avons exploré les inversions de l'ordre de croisement entre le participant et le personnage virtuel. Parmi les 1360 essais, 165 essais ont présenté une inversion de l'ordre de croisement (c.-à-d. 12% au total). Le pourcentage d'inversions dépendant des valeurs de MPD_{tsee} par rapport aux conditions de regard et d'évitement est illustré sur la figure B.2. Des inversions ont été observées pour les valeurs de MPD_{tsee} allant de -0,6m à 0,6m. En particulier, nous avons trouvé un pourcentage élevé d'inversions dans la condition -0,1m, la moitié de ces essais enregistrant une inversion de l'ordre de croisement.

Table B.2 - Pourcentage total des inversions d'ordre de croisement observées pour chaque MPD_{tsee} (en mètres) par rapport aux conditions de regard et d'évitement.

<i>mpd tsee</i>	% of Inversions			
	<i>GNA</i>	<i>NGNA</i>	<i>GA</i>	<i>NGA</i>
-1.2	0	0	0	0
-0.9	0	0	0	0
-0.6	20.59	17.65	8.82	11.76
-0.3	32.35	17.65	38.24	29.41
-0.1	47.06	55.88	50	50
0.1	8.82	20.59	17.65	20.59
0.3	8.82	11.76	2.94	8.82
0.6	0	0	2.94	2.94
0.9	0	0	0	0
1.2	0	0	0	0

Compte tenu de l'influence de nos paramètres expérimentaux, le regard mutuel n'a pas eu d'effet significatif ($p > 0.05$) sur ces pourcentages ni dans les conditions *NA* ni dans les conditions *A* soit en considérant tous les essais ensemble ($GNA=10\%$ et $NGNA=10\%$, $GA=10\%$ et $NGA=15\%$) ou en effectuant les statistiques séparément pour chaque valeur MPD_{tsee} . Ces résultats sont en contradiction avec nos attentes, c'est-à-dire que dans les conditions du No Gaze, le participant ne s'attendrait pas à une collabor-

ation et céderait plus facilement, même s'il passe en premier. Alors que [Olivier2013] n'a rapporté aucune inversion dans l'évitement des collisions sans contrainte entre deux marcheurs réels, Vassallo et al. [Vassallo2017] a rapporté des inversions entre un marcheur et un robot lorsque les valeurs $MPD_{t_{see}}$ se situaient entre 0 et 0,8m. De même, Lynch et al. [Lynch2017] ont rapporté des inversions entre un utilisateur et un obstacle virtuel passif mais n'ont pas détaillé leurs résultats par rapport aux valeurs $MPD_{t_{see}}$. Olivier et al. [Olivier2013] ont attribué la résolution de tâche comme une communication non verbale entre deux marcheurs, où [Vassallo2017, Lynch2017] a présenté des sujets avec des partenaires non-communicatifs, un robot passif et des obstacles virtuels passifs respectivement. Alors que Vassallo et al. [Vassallo2017] ont suggéré un niveau de danger perçu, un manque d'expérience de l'interaction avec les robots ainsi que la nature passive du robot comme causes d'inversion, Lynch et al. [Lynch2017] ont attribué les inversions à un manque de communication non verbale et à l'incertitude du comportement. Nous avons étudié ici l'effet du comportement du regard et du comportement d'évitement réciproque lors d'une tâche d'évitement de collision avec un personnage virtuel. Comme pour les collisions, le comportement du regard n'a eu aucun effet. Peu d'inversions ont été signalées lorsque l'on considère tous les essais, mais un grand nombre d'inversions ont été signalées pour la condition -0,1m. Ce résultat peut être lié à celui observé précédemment dans [Olivier2017] impliquant l'interaction entre un participant et un personnage virtuel non réactif et neutre. Dans leur étude perceptuelle, les auteurs ont montré que les participants n'étaient pas assez précis pour prédire l'ordre de croisement futur lorsque $MPD_{t_{see}}$ était égal à -0,1m. Ils ont interprété cette inexactitude comme un déplacement vers l'avant dans l'espace de l'enveloppe corporelle perçue dans la réalité virtuelle. Nous pouvons alors émettre l'hypothèse que dans notre configuration, la perception du mouvement relatif du personnage virtuel par rapport à la position perçue par le participant était plus importante que le regard pour définir l'interaction.

B.6.2.3 Distance de passage

Les distances de croisement pour tous les essais considérés ensemble sont illustrées dans la Figure B.9. (la grande variabilité s'explique par le fait que nous traçons les valeurs pour toutes les conditions $MPD_{t_{see}}$).

Le comportement du regard du personnage virtuel n'a eu aucun effet significatif ($p > 0,05$) sur la distance de croisement finale, ni en conditions *NA* ni en conditions *A* ($GNA=1,22m$ et $NGNA=1,20m$, $GA=1,20m$ et $NGA=1,20m$) lorsque l'on considère tous les essais réalisés par les participants. C'est également vrai lorsqu'on considère les essais en ce qui concerne le risque initial de collision ($MPD_{t_{see}}$). Ces résultats valident notre hypothèse **(H2)**. Les distances finales de croisement rapportées ici sont similaires à celles de [Olivier2017, Lynch2017], qui sont plus grandes que celles observées dans la réalité [Olivier2012, Vassallo2017]. L'augmentation de la distance de croisement en VR peut avoir été causée par une perception immersive de la profondeur qui a été signalée principalement dans des études antérieures.

Gerin-Lajoie et al. [Gérin-Lajoie2008] ont comparé les différences de comportement et la préservation de l'espace personnel entre la réalité et la RV lors d'une tâche de contournement d'obstacles, il a été rapporté que la forme elliptique de l'espace personnel était similaire à la réalité bien que la taille ait augmenté dans la RV. De plus, la fidélité de l'environnement ou la perception de l'agence des personnages virtuels peut avoir affecté les réponses comportementales. Lorsque, compte tenu de l'effet du regard sur les personnages virtuels, le comportement est considérablement modifié si une personne croit interagir avec un avatar virtuel ou un marcheur virtuel [Bailenson2003]. Ce qui était en accord avec le sentiment d'être regardé, avec une fréquence cardiaque ralentie, des réponses conductrices de la peau et une réponse positive du cortex P3 frontal [Myllyneva2015]. Compte tenu de ces résultats antérieurs, les participants peuvent avoir adapté leur comportement à la croyance d'interagir avec un avatar plutôt qu'avec un

marcheur réciproque. Par conséquent, les participants peuvent avoir porté leur attention sur des variables perceptuelles, telles que l'angle de relèvement et l'expansion optique du mouvement du corps entier, qui sont suffisantes pour éviter les collisions à partir des indices de mouvement du corps entier [Lynch2017].

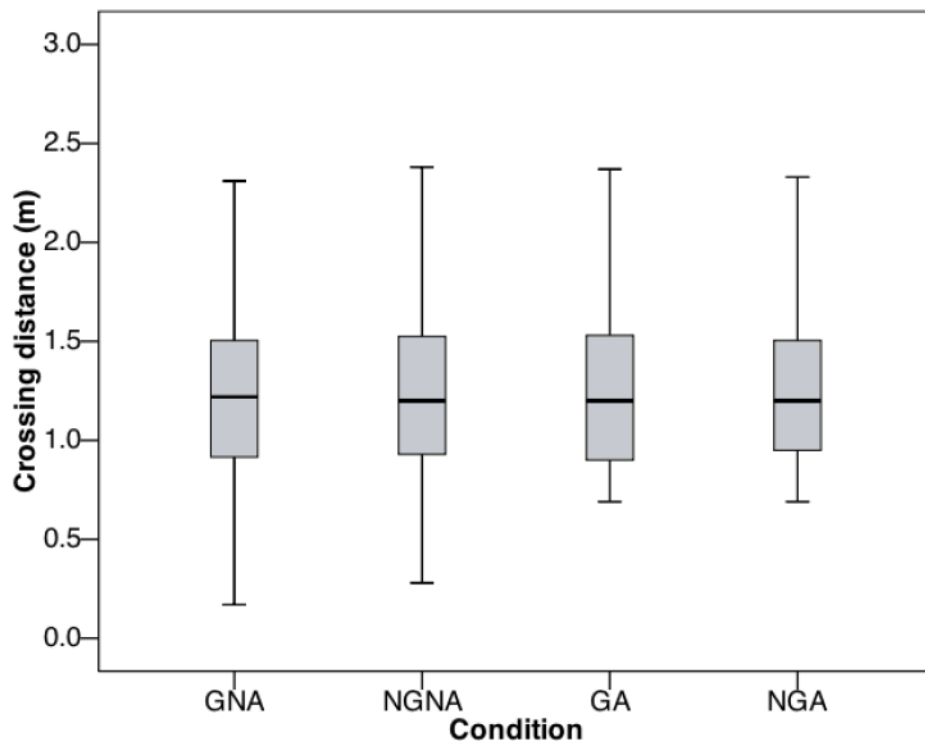


Figure B.9 - Boxplot de distance de croisement (médiane, 1er-3ème quartiles, valeurs min-max) en fonction du regard et du comportement d'évitement.

B.6.2.4 Évolution de la MPD

Enfin, nous avons étudié le comportement d'évitement des collisions pendant l'interaction en considérant l'évolution du *MPD* dans le temps. Pour chaque condition de regard et d'évitement, le comportement était conforme à ceux précédemment rapportés dans des conditions réelles et virtuelles [Olivier2012, Olivier2017, Lynch2017]. En effet, comme l'illustre la figure B.10 pour tous les essais, nous pouvons décrire pour chaque condition de la présente étude les trois phases distinctes de l'interaction : l'observation (la valeur du *MPD* est constante), la réaction (le *MPD* est augmenté) et la régulation (le

MPD est maintenu constant à une distance confortable). L'anticipation précédemment rapportée lors des interactions entre marcheurs réels est préservée puisque nous avons observé la phase de régulation qui a montré que la tâche est résolue avant la fin de l'interaction.

Quantitativement, l'analyse SPM a montré qu'il n'y avait pas d'effet significatif du comportement du regard sur les valeurs de $MPD(t)$ ou la durée de chaque phase, ni dans les conditions NA ni dans les conditions A ($p > 0,05$) lorsque l'on considère tous les essais ensemble (considérant la valeur absolue de MPD) comme illustré dans la Figure B.10 ou séparément par rapport aux valeurs initiales $MPD_{t_{see}}$. Ces résultats ne sont pas conformes à l'hypothèse **(H1)** et corroborent donc davantage l'hypothèse **(H2)**. Aucune différence n'a été rapportée tout au long de l'évolution du MPD , indépendamment de nos paramètres expérimentaux. Il est intéressant de noter que l'évolution du MPD dans le NA et dans les conditions du A étaient similaires. Cette similarité a été observée pour tous les $MPD_{t_{see}}$ initiaux sans différences significatives rapportées ($p > 0,05$), suggérant que les participants peuvent avoir dirigé leur attention sur des variables perceptuelles liées à la trajectoire [Lynch2017] plutôt que sur le comportement du regard du personnage à éviter.

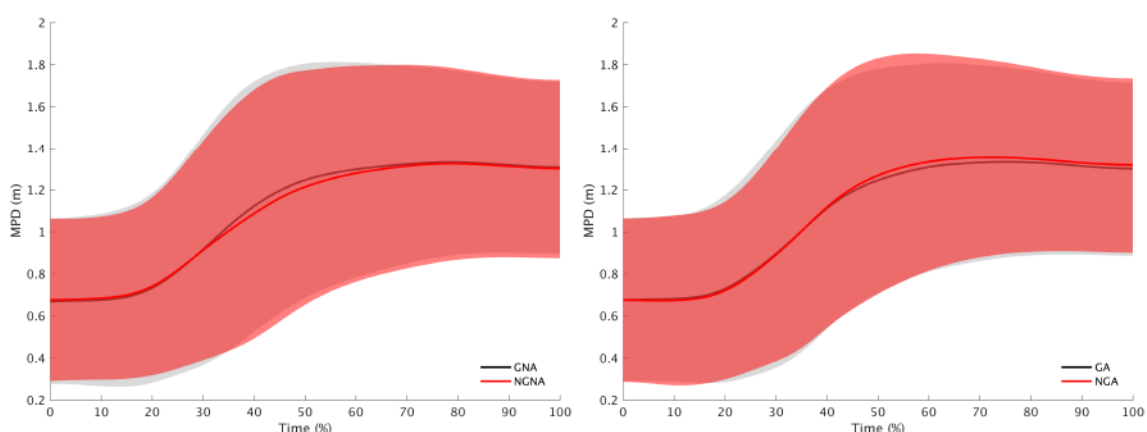


Figure B.10 - Analyse SPM de l'évolution du MPD , comparant l'effet du regard dans les conditions de No Avoidance (NA , à gauche) et Avoidance (A , à droite). Chaque graphique montre l'évolution du MPD avec le regard (ligne noire) et sans regard (ligne rouge), avec les nuages d'écart-type respectifs.

B.6.2.5 Conclusion

Les résultats de cette étude ont montré que le regard mutuel n'avait aucun effet sur le comportement d'évitement par paires, ni en interaction avec un personnage passif ni avec un personnage virtuel réactif. Nous croyons toujours que le regard joue un rôle important dans l'évitement des collisions, mais notre expérience n'a pas pu révéler un effet sur le comportement d'évitement. L'influence du regard peut dépendre des caractéristiques de cette tâche, comme la durée de l'interaction et sa complexité. Par ailleurs, les indices de mouvement du corps transmettaient suffisamment d'information pour résoudre cette tâche. Les travaux futurs devraient alors tenir compte des situations plus complexes et de l'utilisation du suivi oculaire, qui permet de spécifier les indices dérivés pour la prévision des collisions futures. Par exemple, nous pouvons immerger un utilisateur dans une foule avec des marcheurs virtuels qui regardent et d'autres qui ne regardent pas l'utilisateur. Cette situation permettrait d'examiner si la sélection des interactions au sein du quartier des usagers ainsi que leur trajectoire est influencée par le regard des marcheurs virtuels. Enfin, même si nous ne signalons pas d'effet significatif du regard sur le comportement d'évitement au sein de notre dispositif expérimental, nous continuons à soutenir qu'un comportement de regard devrait être inclus dans l'animation de personnages virtuels. Là où l'inclusion du regard a déjà été rapportée pour augmenter l'immersion [Narang2016] et dans notre expérience, même si aucun questionnaire de présence n'a été inclus, les participants ont reconnu le changement dans le comportement des personnages virtuels.

Scientific contributions

The following scientific contributions are associated with this thesis:

Publications

- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Cretual, A. and Olivier, A.-H. *Collision avoidance behavior between walkers: global and local motion cues*. IEEE Transactions on Visualization and Computer Graphics, In Press, 2017.
- ▶ Meerhoff, L. A., Pettré, J., Lynch, S. D., Cretual, A. and Olivier, A.-H. *Collision avoidance with multiple walkers: Sequential or simultaneous interactions?*. Frontiers: Movement Science and Sport Psychology, In review.

International conferences

- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Cretual, A. and Olivier, A.-H. *Collision avoidance behavior between walkers: global and local motion cues*. 2018 IEEE Virtual Reality, Reutlingen, Germany, 18 - 22 March, 2018.
- ▶ Lynch, S. D., Pettré, J., Bruneau, J., Kulpa, R., Cretual, A. and Olivier, A.-H. *Effects of virtual human gaze behaviour during an orthogonal collision avoidance walking task*. 2018 IEEE Virtual Reality, Reutlingen, Germany, 18 - 22 March, 2018.
- ▶ Meerhoff, L. A., Pettré, J., Kulpa, R., Lynch, S. D., Cretual, A. and Olivier, A.-H. *Simultaneous and sequential affordances of collision avoidance between multiple pedestrians*. ICPA 2017 - 19th biannual International Conference on Perception and Action, Séoul, South Korea, 5 - 8 July, 2017.

National conferences

- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Cretual, A. and Olivier, A.-H. *Effect of local limb cues in the prediction of global motion during collision avoidance*. ACAPS 2017 - 17ème Congrès de l'Association des Chercheurs en Activités Physiques et Sportives, Dijon, France, 29 - 31 October, 2017.
- ▶ Lynch, S. D., Pettré, J., Bruneau, J., Kulpa, R., Cretual, A. and Olivier, A.-H. *Effect of mutual gaze on collision avoidance behavior during human walking*. AFRV 2017 - L'Association française de Réalité Virtuelle, Augmentée, Mixte et d'Interaction 3D, Rennes, France, 11 - 13 October, 2017.
- ▶ Lynch, S. D., Kulpa, R., Meerhoff, L. A., Pettré, J., Cretual, A. and Olivier, A.-H. *Global Motion Provides Sufficient Information for Successful Collision Avoidance During a Locomotor Task Within Virtual Reality*. AFRV 2016 - L'Association française de Réalité Virtuelle, Augmentée, Mixte et d'Interaction 3D, Brest, France, 11 - 13 October, 2016.

Titre : Perception visuelle du mouvement humain dans les interactions lors de tâches locomotrices

Mots clés : Perception du mouvement, Évitement de collision, Locomotion, Regard, Interaction, Trajectoire

Résumé : Durant ses activités quotidiennes, un marcheur interagit avec son environnement et en particulier avec les autres marcheurs, notamment en évitant toute collision. La nature de l'information visuelle utilisée pour une interaction sans collision est une question encore très ouverte à ce jour. Dans ce cadre, cette thèse vise à répondre aux questions suivantes : quels sont les indices visuels qu'un individu perçoit à partir du mouvement des autres ? Quels sont les mécanismes d'interprétation possibles et les modèles utilisés pour déterminer les possibles risques de collision ? Afin de répondre à ces questions, nous avons mis en place des expérimentations impliquant des évitements de collision entre deux marcheurs en utilisant la réalité virtuelle, permettant un contrôle détaillé de l'environnement visuel et des informations visuelles disponibles. La première étude s'est concentrée sur la nature de l'information visuelle fournie par un autre marcheur, en particulier, si ces informations sont extraites d'une perception locale considérant les segments corporels, ou d'une perception globale du mouvement du corps. La deuxième étude s'est concentrée sur l'influence de la trajectoire de l'autre marcheur (en ligne droite ou en courbe) sur la capacité à estimer de façon précise un possible risque de collision. Enfin, la troisième étude s'est concentrée sur l'effet du contact visuel sur l'interaction entre les deux marcheurs. Nous avons présenté ici le couplage entre les possibilités d'action perçues et les possibilités offertes par la nature de l'information visuelle et démontré que les marcheurs peuvent détecter les collisions futures prévues lorsqu'un autre marcheur suit une trajectoire avec des accélérations constantes.

Title: Visual perception of human movement during walking task interactions

Keywords : Motion perception, Collision Avoidance, Locomotion, Gaze, Interaction, Trajectory

Abstract: During daily activities, a walker interacts with their environment, especially the other walkers, avoiding any collision with them. The nature of visual information that is used for a collision-free interaction requires further understanding. Specifically, the thesis aims to answer the following questions: what are the visual cues an individual perceives from the movement of others? What are the possible interpretation mechanisms and models used for determining future predicted crossing distances? To answer these questions, we designed experiments considering collision avoidance interactions between two walkers in virtual reality, allowing detailed control of the visual environment and the available visual information. The first study of the thesis focused on the nature of visual information provided from another walker, investigating whether these visual cues are extracted from local body parts or from global perception of the body motion. The second study investigated the influence of the walker's path (straight or curved), which the participant is interacting with for the accurate estimation of future risk of collision. Finally, the third study investigated whether eye contact influences the interaction. Here we have demonstrated the coupling of perceived action-opportunities affordances from the nature of visual information and evidenced that walkers can detect future predicted collisions when another walker follows a path with constant acceleration.