Obstacle Avoidance Behaviour during Locomotion: Strategy Changes as a Result of Visual Field Limitations

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Obstacle Avoidance Behaviour during Locomotion: Strategy Changes as a Result of Visual Field Limitations

Obstakelontwijkgedrag tijdens het lopen: strategieveranderingen als gevolg van gezichtsveldbeperkingen

(met een samenvatting in het Nederlands)

Proefschrift

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te Nieuwegein

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Contents

Chapter 1

Introduction

As humans, we constantly move through structured environments in which obstacles are present. According to the Oxford English Dictionary, an obstacle is *"something that blocks one's way or prevents or hinders progress"*. During goal oriented locomotion, this can be described as something that is located between your current position and your desired goal position. As such, these can be either dynamic or static as well as living or inanimate. Avoiding collision with obstacles is an everyday task for most people moving through structured environments. Although not desirable, accidental contact with an obstacle often does not have serious consequences. However, there are several situations when it does. For instance, elderly people can be severely injured by tripping over a shallow threshold or kerb. On the other end of the difficulty spectrum are professional athletes who attempt to run as fast as possible during hurdle or steeplechase racing (see Figure 1.1). The various goals lead to different strategies but the task remains similar.

Figure 1.1: Men's 110m hurdles at Golden League 2006, Gaz de France, Paris Saint-Denis.

In order to avoid colliding with obstacles, it is important to know both the dimensions as well as the spatial relations between different parts of the environment and the obstacles. Based on this information and the knowledge about our own bodily dimensions and action capabilities, it is possible to plan a certain avoidance manoeuvre. Subsequently, it is essential to perceive the changing spatial relations between our own body and the environment during the approach of the obstacle and the execution of the manoeuvre. It may be that the obstacle dimensions or position were initially misperceived or changed during the interval of approach. In such cases the preparation and execution of the bodily movements performed to avoid collision may need updating based on the current perception of the situation. For the most part, we rely on the visual system as an important source for this information. Impairment in the acquisition of visual information poses a threat to efficient and save locomotion through structured environments.

In this thesis I will present research investigating the effect of visual field limitation on obstacle avoidance behaviour. The remainder of the current chapter is used to introduce relevant concepts. In the final section of this chapter, I will present the research questions and outline of the thesis.

1.1 Adaptive locomotion

Several studies have argued that unobstructed locomotion is characterised by an energy conservation strategy where the goal is to minimise the amount of energy spent on walking. (Anderson & Pandy, 2001; Inman, 1966; Saunders, Inman, & Eberhart, 1953; Waters & Mulroy, 1999; Pierrynowski, Winter, & Norman, 1980). However, if there is an obstacle in the path, safe locomotion is threatened. Therefore, this energy efficient gait requires adjustment in order to safely avoid a collision. In order to decide if and how an obstacle can be overcome, several actions need to be performed.

First, it is required to identify the obstacle (i.e., what is it, what is it made of). Then, the position, dimensions and (possible) dynamics of the obstacle need to be estimated. This extraction of information regarding the state of the external world is known as exteroception. Then, based on the observer's current velocity and acceleration, combined with knowledge of his bodily dimensions, one can predict a possible collision. This information regarding the body relative to the environment is referred to as exproprioception (Patla, 1997, 1998). When such a collision is predicted, the situation requires a manoeuvring action in order to avoid it. In case of a low obstacle, one might decide to step on or over it. Alternatively, circumventing the obstacle or ducking underneath it might be better options in some situations. In this thesis, I will focus mainly on obstacle crossing and obstacle passing tasks. Although they are different in the required bodily movements, they rely for the most part on similar visual information.

1.1.1 Obstacle crossing

When it is decided to step over the obstacle, step length during the approach may need to be adjusted in order to clear the obstacle in a comfortable and safe way, perhaps involving a preference for left or right as the lead limb. Also, there may be a need to reduce overall locomotion speed to enable additional time to prepare for as well as execute the manoeuvre. This also reduces impact in case a collision does occur (Patla & Rietdyk, 1993).

During the actual crossing steps, both vertical and horizontal clearance need to be monitored and if necessary increased to keep a reasonable safety margin. For the lead limb this monitoring can be done visually. However, this is not possible for the trail limb, which is normally invisible during crossing. Only proprioceptive information is available during crossing, which appears to be the reason for the slightly larger clearance often observed for this limb.

Meanwhile postural equilibrium needs to be maintained and attention has to be paid to possible upcoming obstacles.

1.1.2 Obstacle passing

There may be several reasons why crossing an obstacle is not feasible. First, the size could simply not allow for it. Height and depth seem to be the most important dimensions in this regard. Second, the consequence of failing to clear it could be serious. The obstacle may be damaged or injured (in case of a baby or small pet). Also, the pedestrian could be injured or damage something he's carrying. Finally, one may prefer to pass instead of cross an obstacle because of time and energy efficiency considerations.

Passing an obstacle can be done by means of circumvention or steering past it. Although related, these actions are not identical. Circumvention requires a transient change in the positioning of the centre of mass (COM) while maintaining the underlying travel direction. Alternatively, during steering, the COM is guided in a new direction by reorientation of the head and torso, followed by mediolateral COM deviation and foot adjustments in the new direction (Hollands, Sorensen, & Patla, 2001; Vallis & McFadyen, 2003).

1.2 The human visual field

The visual field is defined as the space or range within which objects are visible to the immobile eyes at a given time. Although the spatial and temporal resolution of the different parts of the retina are important when investigating the role of vision in adaptive locomotion, in this thesis I will focus mainly on the extent of this field.

For humans this area is approximately 200° wide and 135° tall (Werner, 1991). As with most predatory animals, our eyes are positioned on the front of the head. This allows for binocular vision within a region of about 120° horizontally. However, the stereopsis resulting from this comes at the cost of a reduced visual field (Henson, 1993).

1.2.1 Causes for visual field limitation

There are several causes for a limitation of the visual field. One of these are eye diseases such as retinitis pigmentosa (RP) and glaucoma. Although they have very different causes, both can result in progressive visual field loss.

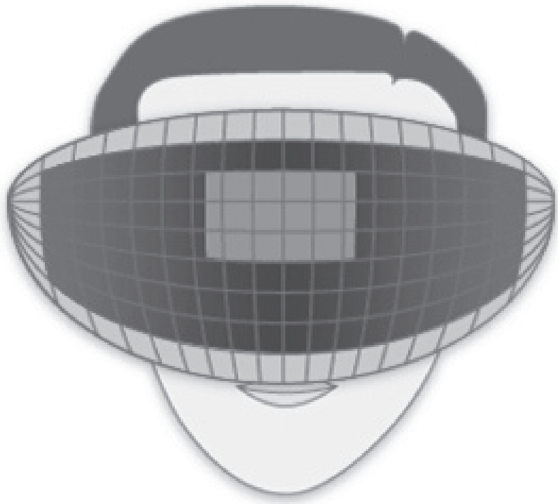


Figure 1.2: Schematic representation of different visual field sizes. The largest grey area indicates the unrestricted human visual field. The other two represent different sized viewing displays available for head-mounted displays.

Furthermore, age has been associated with a decline in visual field extent and sensitivity (Spry et al., 2001).

In addition to involuntary causes such as disease, size of our visual field can also be restricted by the use of optical devices. Dismounted soldiers performing night-time operations in urban terrain frequently deploy night-vision goggles (NVGs), the visual field of which is typically limited to 30°–40° (Inc, 2001). Other optical devices with a limited visual field are Head Mounted Displays (HMDs). Such devices present a virtual environment to the user by means of two small displays in front of the eyes. A head tracker is used to register changes in head orientation. The image presented to the user is then updated in accordance with this rotation in order to enable a sense of immersion. See Figure 1.3 for examples of such hardware.

Most commercially available HMDs offer limited viewing angles, often only 40° to 60° horizontally and 30° to 45° vertically (Arthur, 1996). Increasing the amount of peripheral information by extending the FoV of HMDs and NVGs is very costly, reduces their resolution or makes them heavier and therefore less comfortable to wear (Latham, 1999). Moreover, in virtual environment

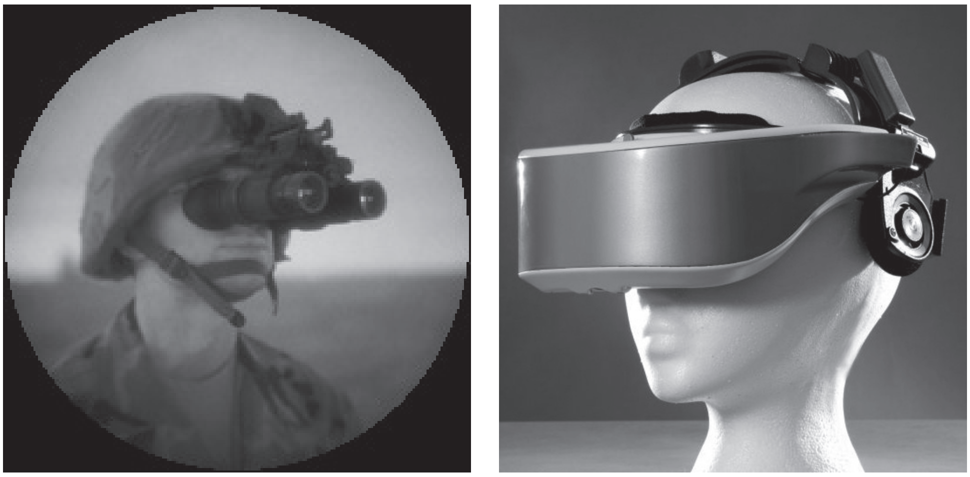


Figure 1.3: Example of a pair of night vision goggles (left) and head mounted display (right).

applications, a wider FoV yields greater sensations of motion sickness (Pausch, Crea, & Conway, 1992; Psotka, 1998). To determine a trade-off between human performance, cost and ergonomic aspects, it is necessary to know how limitation of the instantaneous visual field affects human locomotion through complex structured environments.

Moreover, there are everyday tasks during which the visual field is limited. For instance, when carrying large objects, both the lower limbs and the immediate ground surface in front of an observer is occluded. Also, wearing headgear such as a cap or hood also occludes part of the peripheral visual field. In addition, specific lighting conditions can be another cause of visual field limitation. When walking in the dark with a flashlight or towards a streetlight, one can see only that part of the environment which is illuminated.

1.2.2 Effects of visual field limitation

Dolezal (1982) was one of the first to describe how extensive visual field limitation affects everyday living. For 71 waking hours over 6 days he wore 30 cm long paper tubes restricting his field of view to 12°. He reports difficulty in visually tracking moving objects, forming a cognitive map and maintaining equilibrium. Also, he was often startled by objects and people suddenly entering his field of view and experienced problems with understanding events taking place over areas larger than his 12° view.

Moreover, limitation of the peripheral visual field has been associated with a number of other impairments. Specifically, observers tend to compensate for the reduction in their instantaneous visual field by making larger, but slower head movements (Wells & Venturino, 1990; Szoboszlay, Haworth, Reynolds, Lee, & Halmos, 1995). It is argued that these head movements are extended to counter the underestimation that otherwise results from an incomplete ground-surface integration (He, Wu, Ooi, Yarbrough, & Wu, 2004; Wu, Ooi, & He, 2004; Creem-Regehr, Willemsen, Gooch, & Thompson, 2005). Additionally, visual field restriction is known to affect the maintenance of postural balance (Paulus, Straube, & Brandt, 1984; Turano, Herdman, & Dagnelie, 1993) and spatial representation during navigation (Fortenbaugh, Hicks, Hao, & Turano, 2006, 2007). Impairment of any of the above mentioned subtasks may have a negative effect on safe and efficient obstacle avoidance behaviour.

1.3 Vision during adaptive locomotion

Gibson speaks of a "mobile retina" when discussing visually guided locomotion. He argues that visual scanning to explore appropriate information is achieved at the global level by locomotion, at the next level by head movements relative to the body, and finally by eye movements within the head (Gibson, 1966). Following this, several studies have investigated the role of vision during obstructed locomotion (i.e., when obstacles are present).

According to Patla and Vickers (1997, 2003b), two dominant gaze behaviours occur during adaptive locomotion: landing target fixation and travel gaze fixation. They argued that the latter is more dominant and consists of the eyes being directed at the ground ahead and not to a specific location. In accordance with this, Marigold and colleagues (2007; 2008) examined the lower body kinematics and gaze behaviour of participants stepping over obstacles that suddenly appeared in the pathway. They conclude that downward-directed saccades were rarely made and when present they were directed to the landing area and not to the obstacle. The conclusion was that peripheral visual information is sufficient for safe obstacle negotiation.

Other studies have investigated how lower visual field occlusion affects obstacle avoidance behaviour. Rietdyk and Rhea (2006b; 2007) showed that blocking the view of the lower limbs and immediate ground surface in front of an observer caused increases in horizontal toe-obstacle distance, toe clearance and toe clearance variability when stepping over an obstacle. However, they also found that the presence of obstacle position cues returned lead and trail foot placements to full vision values but obstacle dimension cues did not. These observations strengthen the argument that it is the visual expproprioceptive information, not visual exteroceptive information, that is used to fine tune the lower limb trajectory during obstacle avoidance.

Furthermore, Graci and colleagues (2009, 2010) also found increased toe clearance and stride length for a lower visual field occlusion when stepping over a low obstacle. In addition, they report that loss of the upper and lower peripheral visual fields together had a greater effect on adaptive gait compared with the loss of the lower visual field alone. This may be because of the greater impairment of optic flow.

1.4 Application areas

The work presented in this thesis investigates how artificial limitation of the visual field in healthy subjects affects their obstacle avoidance behaviour. Several application areas may benefit from the knowledge gained through these experiments.

1.4.1 Healthcare

Fall-associated fractures in older people are a significant source of morbidity (Sattin, 1992). A third to one half of people over 65 years old fall each year (Downton & Andrews, 1991). A recent study highlights the importance of the lower visual field in the risk of falling among older adults (Black, Wood, & Lovie-Kitchin, 2011). Because elderly people are confronted with a multitude of risk factors influencing visuomotor behaviour (i.e., impaired vision, deficits to the musculoskeletal system, and impairment of the proprioceptive and vestibular systems), it is difficult to investigate the relation between a single impairing factor and the resulting behaviour for this group. By investigating the (changes in) strategies associated with obstacle avoidance behaviour under restricted viewing conditions, we contribute to the understanding of human adaptive locomotion. In this thesis, the focus lies mainly on visual field limitation. However, other suboptimal visual conditions may have similar effects. Increased understanding of this behaviour may help predict which people run a high risk of falling. Furthermore, this may increase the effectiveness of programs aimed at fall in the elderly.

1.4.2 Virtual training applications

Immersive virtual environments are increasingly applied in training and rehearsing tasks involving human locomotion through complex structured environments (e.g., first responder actions, military operations in urban terrain). Compared to traditional training solutions, a virtual training has many benefits. For instance, a multitude of different layouts and scenarios can be created relatively easy and adjusted to the trainee's current level. Also, an extensive review of the training is available because of the many possible viewpoints. In such a setting a virtual environment is presented to the user by means of a head mounted display. The image presented in the HMD is updated according to the bodily movements of the user. In this way it is possible to explore the virtual environment by walking and looking around. The user's own body may also be digitally represented adding to the sensation of being present in that environment. As mentioned before, many of the commercially available HMDs have very limited viewing angles due to optical complexity and weight considerations. Insight into the effects of this restriction on obstacle avoidance behaviour can be used to formulate guidelines for the selection and development of these devices.

Another important aspect of virtual training applications are the non-playable characters. Typically, these have to navigate toward their desired locations in a human–like manner while avoiding collisions with other characters and objects in the environment. As a result, visually compelling and natural looking avoidance behaviour has become a necessity for interactive virtual environments. One way to achieve such realistic character motion is by using motion capture techniques to record human motion (Moeslund & Granum, 2001). Such an approach has the advantage of high spatial and temporal resolution of the recording. Also, the movement extracted in this way is by definition "natural" and can be transferred directly to a virtual character. However, there are also disadvantages to such an approach. It is very time consuming to record these data and it is therefore very costly. Another problem arises when additional recordings need to be made and the actor is no longer available. Moreover, it is simply impossible to record all possible movements. This approach lacks flexibility since only recorded movements can be shown.

In contrast to transferring motion capture data directly onto a character, it is also possible to use these data to construct a parameterised human motor behaviour model. Such a model (i.e., based on real world data) can then be used to increase the realism of a character's movement.

1.5 Research questions and outline

Below, the research questions and subsequent chapters are outlined. The chapters are based on original articles published in peer-reviewed journals.

1. *How do limitations of the horizontal and vertical viewing angles affect obstacle avoidance behaviour?*

   Chapter 2 discusses two experiments concerning the effect of the extent of the horizontal viewing angle on several obstacle avoidance tasks. Experiment 1 examines how a narrow visual field (30°–75° wide) influences steering behaviour. This is done by measuring speed and accuracy of manoeuvring through an environment with multiple vertical obstacles.

   Experiment 2 investigates if a wide viewing angle of 120° improves performance on the task tested in experiment 1. In addition, it addresses the possible generalisation of the effect of visual field extent to other obstacle avoidance tasks. Thereto, speed of movement was measured during locomotion through an obstacle course that required obstacle crossing, ducking, and avoiding walls.

   Chapter 3 presents a study investigating how the vertical and horizontal viewing angle affect obstacle avoidance behaviour independently. Little is known concerning the effect of lower visual field limitation. Therefore, a full factorial design of 4 horizontal angles and 5 vertical ones is employed to systematically investigate the role of both during obstructed locomotion.

   In addition, it was investigated if re–orientation of the visual field (i.e., downward or upward pitched) altered performance. If so, this could be an alternative way of improving performance with visual field limiting devices without the need for display enlargement.

2. *How does vertical viewing limitation affect body kinematics and strategy changes during an obstacle crossing task?*

   Chapter 4 discusses an experiment investigating how lower visual field occlusion affects obstacle crossing behaviour. Full–body motion capture is used to extract toe clearance, step length, and speed of movement while stepping over obstacles of different dimensions. These kinematic measures are then analysed to infer strategy changes induced by such limitation.

3. *Can similar strategy changes be found during a steering task and how are head movement and balancing affected by visual field limitation?*

   Chapter 5 presents a study similar in approach to the one discussed in Chapter 4. Here, it is investigated if similar strategy shifts can be observed when steering through a multi-obstacle environment. Furthermore, the role of head movements is examined by analysing both the speed and magnitude of yaw and pitch rotation. Also, step width was analysed to examine balancing impairment.

   Finally, chapter 6 gives a general discussion of the work presented in this thesis. Moreover, implications for relevant application areas are discussed.

Chapter 2

The influence of the horizontal viewing angle

This chapter is based on the following publications:

Toet A., Jansen S.E.M., Delleman N.J., (2007) Effects of field-of-view restrictions on speed and accuracy of manoeuvring. *Perceptual and Motor Skills, 105*, 1245-1256

Toet A., Jansen S.E.M., Delleman N.J., (2008) Effects of field-of-view restriction on manoeuvring in a 3-D environment. *Ergonomics, Vol. 51, No. 3*, 385-394

This chapter addresses the influence of limitation of the instantaneous horizontal visual field on manoeuvring through complex structured environments. Two experiments are presented here that explore the effects of limitation of the horizontal viewing angle on speed and accuracy of movement while avoiding collision with several obstacles.

2.1 Introduction

Appreciation of an object's qualities and of its spatial location depends on the processing of different kinds of visual information, which have separate cortical pathways (Mishkin, Ungerleider, & Macko, 1983). The dorsal path, also known as the *where path* leads to the inferior temporal cortex. The ventral (or *what path*) leads to the posterior parietal cortex.

Restricting the human visual field results in a predominant activation of the ventral cortical stream relative to the dorsal stream (Milner & Goodale, 2006), which may compromise an observer's ability to control heading or process spatial information (Patterson, Winterbottom, & Pierce, 2006). It has also been observed that restrictions of the instantaneous FoV influence distance estimates (Watt, Bradshaw, & Rushton, 2000). However, this effect is not found when head movements are allowed (Knapp & Loomis, 2004; Creem-Regehr et al., 2005). Even with a very small visual field (i.e., $< 40°$), observers can still accurately judge absolute distances by scanning the ground surface from near to far, but not in the reverse direction (Wu et al., 2004). Hence, it appears that the effects of instantaneous FoV limitation can be compensated to some degree through the construction of an effective FoV with a larger extent, which can be obtained by sweeping the instantaneous FOV over a larger region of space (i.e., through head movements) (Knapp & Loomis, 2004).

In addition, peripheral visual input is very important in the maintenance of postural equilibrium (Amblard & Carblanc, 1980; Turano et al., 1993). Manoeuvring through complex structured environments requires all three of the above mentioned subtasks (i.e., distance estimation, heading control, and balance maintenance). Any restriction of the peripheral visual field may therefore be detrimental for task performance.

This chapter describes two experiments that investigate the relationship between horizontal visual field restriction and human obstacle avoidance performance. During the first experiment, participants traversed an s-curved path in order to avoid collision with a three-wall setup. The field of view of participants was restricted by wearing opaque goggles with rectangular apertures of different sizes. Both speed and accuracy of movement were measured for four different levels of horizontal viewing angle, ranging from 30° to 75° combined with a vertical angle of 48°. In addition to the viewing conditions, wall-to-wall distance and direction of movement were also varied. It is hypothesised that the loss of peripheral visual field information degrades results in a reduction of the speed and accuracy of movement.

The second experiment extends this investigation by adding a wide angle viewing condition of 120° (H) x 48° (V) as well as a more complex environment that presents participants with a low hanging bar and floor bound obstacles, next to the three-wall setup presented in the first experiment. Since most of the above-mentioned tasks require the analysis of spatial relations between objects in the environment, the control of heading during locomotion through the environment, and the continuous maintenance of postural equilibrium, any restriction of the peripheral visual field may therefore be detrimental for performance on all three tasks. In addition, it is expected that the wide viewing angle of 120° increases performance compared to widest angle tested in experiment 1 (i.e., 75°).

2.2 Experiment 1

2.2.1 Methods

Participants

The procedures of this study were approved by the TNO Human Factors internal review board on experiments with human participants. Fifteen paid participants (8 male, 7 female) with an average age of 22.9 years ($SD = 2.8$) participated and gave informed consent. All participants had normal, or corrected to normal vision. Due to technical issues, data sets of three participants were incomplete, and therefore excluded from analyses.

Apparatus

Goggles. To restrict the field of view, opaque templates with rectangular apertures of different sizes were attached to plastic safety goggles from which the lenses had been removed (see Figure 2.1). By design, all apertures restricted the vertical extent of the field-of-view to 48°. Horizontal angular field-of-view sizes were respectively 30°, 45°, 60° and 75°. These dimensions correspond to field-of-view sizes that are typical for commercially available head-mounted displays and night vision goggles. The dimensions of the frames of the safety goggles did not allow for field-of-view sizes larger than 75°. In the unrestricted field-of-view condition, participants wore no field-of-view restricting device. This condition merely served to establish the optimal speed and accuracy (a performance baseline).

We tested both monocular and binocular visual field restrictions, since both conditions occur in practice (head-mounted displays are frequently binocular systems, whereas night vision goggles usually provide monocular vision). In the monocular conditions, a fully opaque slide was used to block visual information to one of the eyes.

We determined the (horizontal and vertical) physical aperture size of the templates from the geometry of the situation in which an observer, wearing the goggles fitted with the slides and with his head fixated, was placed in front of a vertical office wall to which two (horizontally or vertically separated) markers had been attached, such that the (horizontal or vertical) spatial interval defined by the markers just fitted in their field-of-view. The angular aperture sizes thus determined differed less than 4° among all subjects tested.

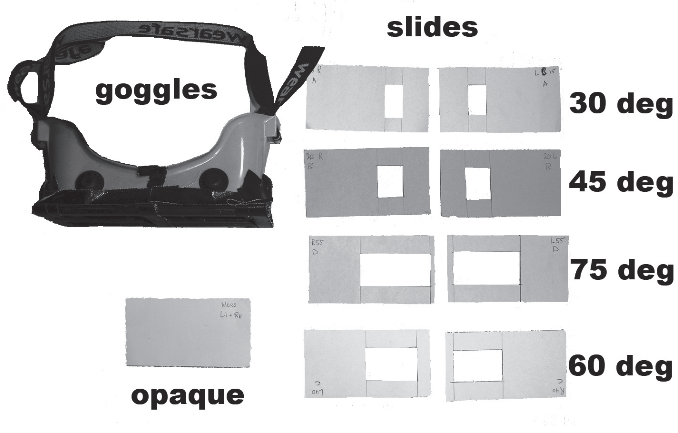


Figure 2.1: Top view of the pair of goggles and the set of aperture templates.

Environment. We created a course consisting of three partition-wall segments for office rooms. The wall segments were placed parallel to each other, one behind the other, such that the right side of the middle wall segment was located at the midpoint of the interval defined by the left sides of the outer two wall segments (see Figure 2.2 for a schematic representation of the setup). Participants had to manoeuvre between the ends of the outer two parallel wall segments, while avoiding the end of the middle wall segment, thus making an s-curved movement. They then had to retrace their steps, walking strictly backwards, while maintaining their forward-looking orientation. In that condition, they were allowed to turn their heads as much as they needed to look over their shoulder in the direction of movement.

The edges of the three wall segments were placed at a mutual distance d of respectively $600mm$, $800mm$ or $1000mm$, resulting in three different levels of width of the resulting s-shaped corridor. The entire setup was surrounded by light coloured curtains (extending all the way to the ceiling of the room) to simplify the visual structure of the experimental environment. This was done to eliminate the possibility that participants could use visual cues in the outside world to perform their task (e.g., by judging their distance and heading relative to objects outside the course).

Motion-tracking. The displacement of participants was registered with a motion-tracking device (Flock of Birds, see: `http://www.ascension-tech.com/docs/Flock_of_Birds.pdf`). A sensor was positioned on the participant's lower back. Using an electromagnetic field, the three position coordinates x, y and z of the sensor were measured relative to the position of the field emitter, with an accuracy of approximately 2 mm.

Video registration. All trials were video-taped, using an observation camera that was mounted on the ceiling, right above the setup, oriented straight down, and equipped with a fish-eye lens. This was done to register each participant's style of manoeuvring and other behaviour that may cause variance in the measurements in addition to that caused by the independent variables. Also, suspected collisions with a wall segment were confirmed by inspecting the video-tape of a specific trial.

Design and variables

The set-up was a 5 (field-of-view) x 3 (wall-to-wall distances) x 2 (forwards-backwards) x 3 (monocular: right and left; and binocular) x 5 (repetitions) within-participants design. The first two variables were randomised across trials using a Latin square design (Wagenaar, 1969). The dependent variables were the *average speed* and the *accuracy of movement.* The average speed of

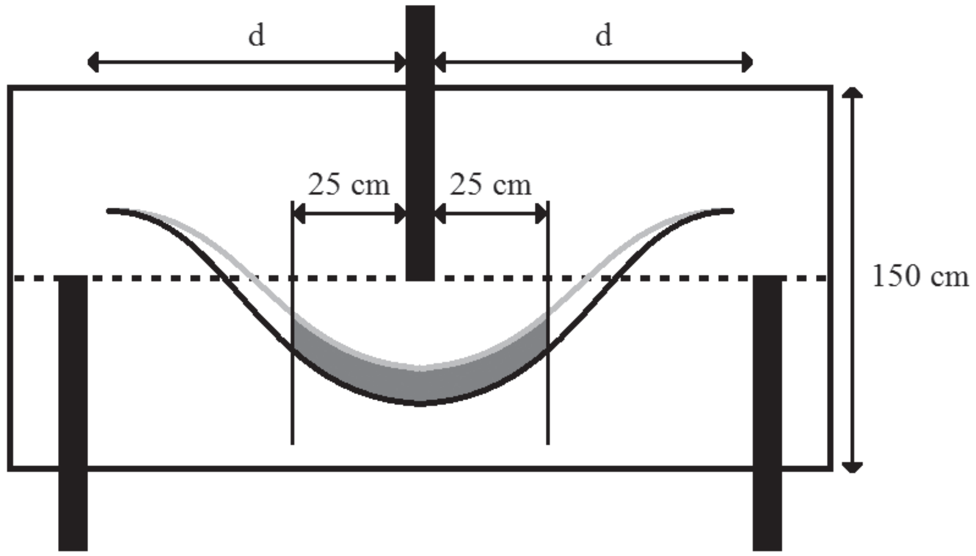


Figure 2.2: Schematic representation of the top-view of the setup. The three thick parallel line segments represent the position of the equidistant wall segments, which were spaced at a distance d of respectively 600, 800 and 1000 mm. The light-grey curved line segment indicates the path traversed by an observer manoeuvring without any field-of-view restrictions. The black curved line segment represents the path taken by the same observer in identical conditions, but with a restriction of the field-of-view.

movement was defined as the ratio of the separation between the first and the third wall segments (in centimetres) and the temporal interval (in seconds) that elapsed between the moments the lower-back sensor passed each of these wall segments. This was then divided by each participant's mean speed when traversing the course unrestricted in the forward direction, thus normalising to the preferred speed.

For each participant we defined the ideal manoeuvring line as the path traversed by the participant (i.e., the transverse displacement of the sensor attached to the participant's lower back) in the unrestricted field-of-view condition. The accuracy of movement was then computed as the area (in cm^2) between the plots of the ideal trajectory and the trajectory traversed with a restriction of the field-of-view, and calculated over a range of 25 cm on both sides of the second wall (Figure 2.2). The ideal line was determined for each participant individually per condition (wall-to-wall distance, monocular-binocular and forward-backward). We intentionally calculated the accuracy over a small section surrounding the middle obstacle to minimise variation due to differences in overall walking strategies.

Procedures

The purpose of the experiment was explained to the participants beforehand, after which they signed an informed consent form. The participants were then instructed to walk as fast as possible along the course without colliding with any of the wall segments. For each condition the track had to be traversed five times, both in the forward and backward directions. The experimenter followed the participant while holding the cords that were attached to the sensor, to prevent the participant from tripping over them. The cords were held very loosely by the experimenter to prevent any haptic cues.

Three separate sessions were carried out, one for every wall to wall distance. Within each session all field-of-view conditions were tested in one binocular and two monocular (left and right eye) viewing conditions. In each condition at least three practice trials were performed to ensure that participants reached a constant level of performance, and to exclude any learning effects. Also, trials in which participants collided with a wall segment (as confirmed from the inspection of the corresponding video recordings) were discarded. In practice, this happened only a few times during initial practice trials. Participants were given a few minutes rest between sessions.

Data analysis

A 4 (restricted viewing angle) x 3 (wall-to-wall distances) x 2 (forwards-backwards) x 3 (monocular: right and left; and binocular) repeated-measures ANOVA was performed for *mean speed* and *accuracy of movement*. Bonferroni's post-hoc analysis was performed to investigate pair wise differences. Whenever Mauchley's test indicated a violation of the sphericity assumption, a Greenhouse-Geisser correction was performed on the variance analysis. All analyses were performed with STATISTICA 8.0 (StatSoft, 2000) and significance levels for each were set to 5%.

2.2.2 Results

Speed

Figure 2.3 shows the mean speed as a function of the horizontal field-of-view size (in degrees). Field-of-view had a main effect on average speed: a wider field-of-view yielded an increase in average speed, $F(3,33) = 6.70, p < .01$. Post-hoc analysis showed significant differences between the 75° condition and the two most restricted conditions (30° and 45°), for both, $p < .01$. Furthermore, increasing the wall to wall distance resulted in increased speed of movement, $F(2,22) = 88.91, p < .001$. Forward locomotion was faster than backwards locomotion, $F(1,11) = 224.11, p < .001$. No difference was found between the monocular and binocular conditions.

Accuracy

Accuracy of movement, as defined by the deviation from the ideal path, is affected by horizontal field-of-view size, $F(3,33) = 4.12, p = .01$. A horizontal view of 75° yields less deviation than a 30° or 60° view (for both, $p < .05$) but no significant difference was found compared to the 45° condition ($p = .12$). See Figure 2.4. Furthermore, walking backwards increases the deviation compared with forwards locomotion, $F(1,11) = 18.53, p < .01$. No difference was found between the monocular and binocular conditions.

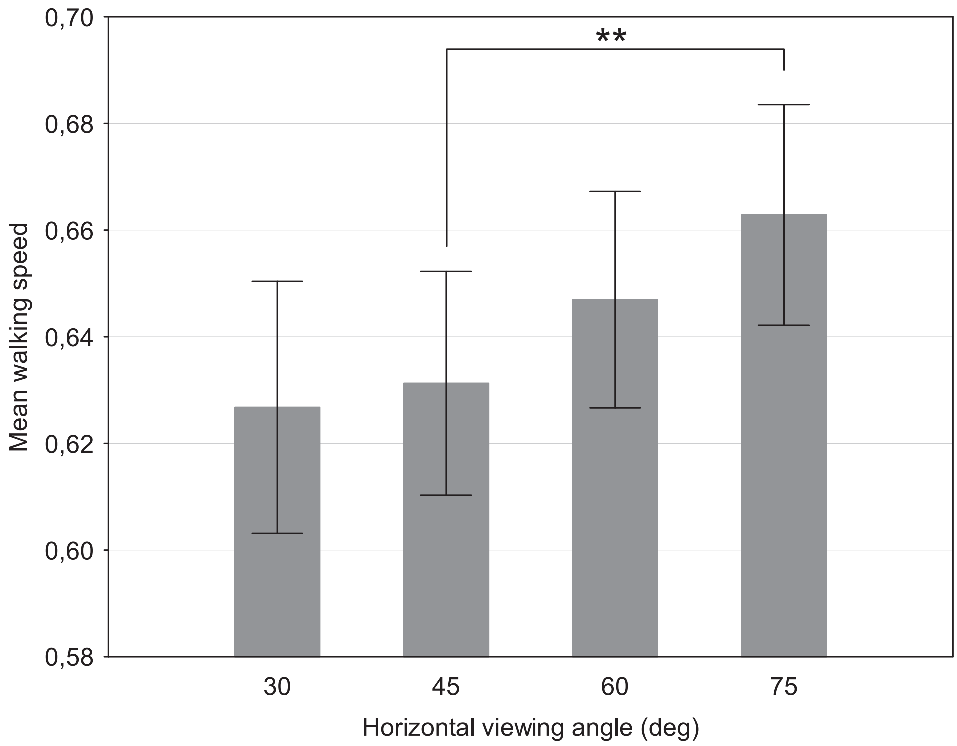


Figure 2.3: Normalised mean speed as a function of horizontal field-of-view extent (in degrees), where the unrestricted view is set at 1. The closest neighbouring significantly different pairs are indicated by * ($p < .05$), ** ($p < .01$) and *** ($p < .001$). Error bars represent standard error.

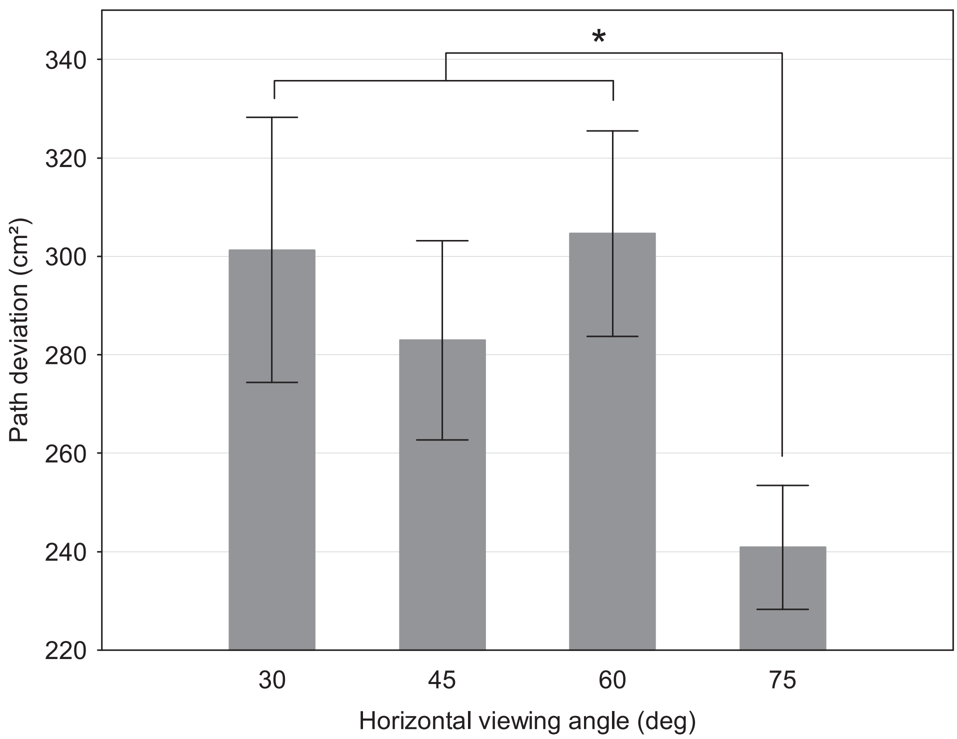


Figure 2.4: Deviation from the preferred path as a function of horizontal field-of-view extent. The closest neighbouring significantly different pairs are indicated by * ($p < .05$), ** ($p < .01$) and *** ($p < .001$). Error bars represent standard error.

2.3 Experiment 2

2.3.1 Methods

Participants

The procedures of this study were approved by the TNO Human Factors internal review board on experiments with human participants. Ten paid participants (five male, five female, all between 19 and 25 years of age) participated with informed consent. All participants were free from any known neurological or orthopaedic disorders or any impediments to normal locomotion, as verified by self-report. All participants had normal (20/20) or corrected-to-normal vision.

Apparatus

Goggles. To restrict the FoV, two pairs of plastic safety goggles were used. Horizontal angular FoV sizes 30° and 75° were achieved with the same pair of goggles used in experiment 1 (see Figure 2.1). A second pair of goggles was modified, such that it provided a fixed horizontal angular FoV size of 120° and a vertical angle of 48° (Figure 2.5).

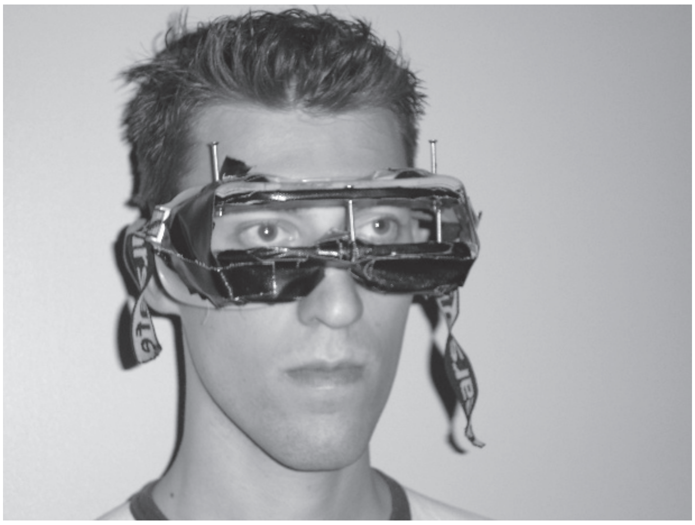


Figure 2.5: Participant wearing the modified pair of goggles providing a horizontal angular FoV size of 120°.

Obstacle course. The obstacle course was a walled enclosure, consisting of a corridor with four turns. See Figure 2.6 for a schematical representation as well as two photographs. The walls were constructed from wooden frames covered with light-coloured linen sheets. At three different locations in the course, evenly spaced over the length of the course, obstacles were positioned. Each of these obstacles required the performance of different bodily movements in order to cross them.

The first obstacle was a horizontal bar, mounted at 110cm above the ground, extending across the entire width of the corridor. Participants had to duck underneath the bar to avoid bumping into it. The bar was made from soft material (polyethylene foam, typically used for pipe work insulation) to prevent participants from hurting themselves in case they collided with this obstacle.

The second obstacle consisted of three room-dividing walls, placed parallel to each other, one behind the other, thus creating an S-shaped trajectory. The right side of the middle wall was located at the midpoint of the (120cm wide) interval defined by the left sides of the first and the last dividing walls. To traverse this segment of the course, participants had to follow an S-curved trajectory through the 60cm wide passages in order to avoid bumping into them.

The third obstacle consisted of three thin wooden boards, with heights of 20, 30 and 40cm, which were placed in an upright position on the ground, perpendicular to the walls, stretching across the entire width of the corridor. They were designed to tip over if contacted, reducing the possibility of a fall. The board with a height of 20cm was located between the other two boards, at a distance of 80 cm from the first board, with a height 30 cm, and at a distance of 50 cm from the last board, with a height of 40 cm.

Time registration. To register the time that the participants needed to traverse each segment of the course, four pairs of poles equipped with infra-red light-emitting diodes, photoelectric beam sensors and retro reflectors (type Velleman PEM5D; www.velleman.de) were used. One of each pair of poles emitted and registered the return of an infra-red light beam, which was reflected by a little mirror on its companion (opposite) pole. Whenever a participant interrupted a beam, the moment of interruption was registered. A pair of poles was placed at the beginning and at the end of each of the three segments of the course. From this, the time needed to traverse each section could be computed.

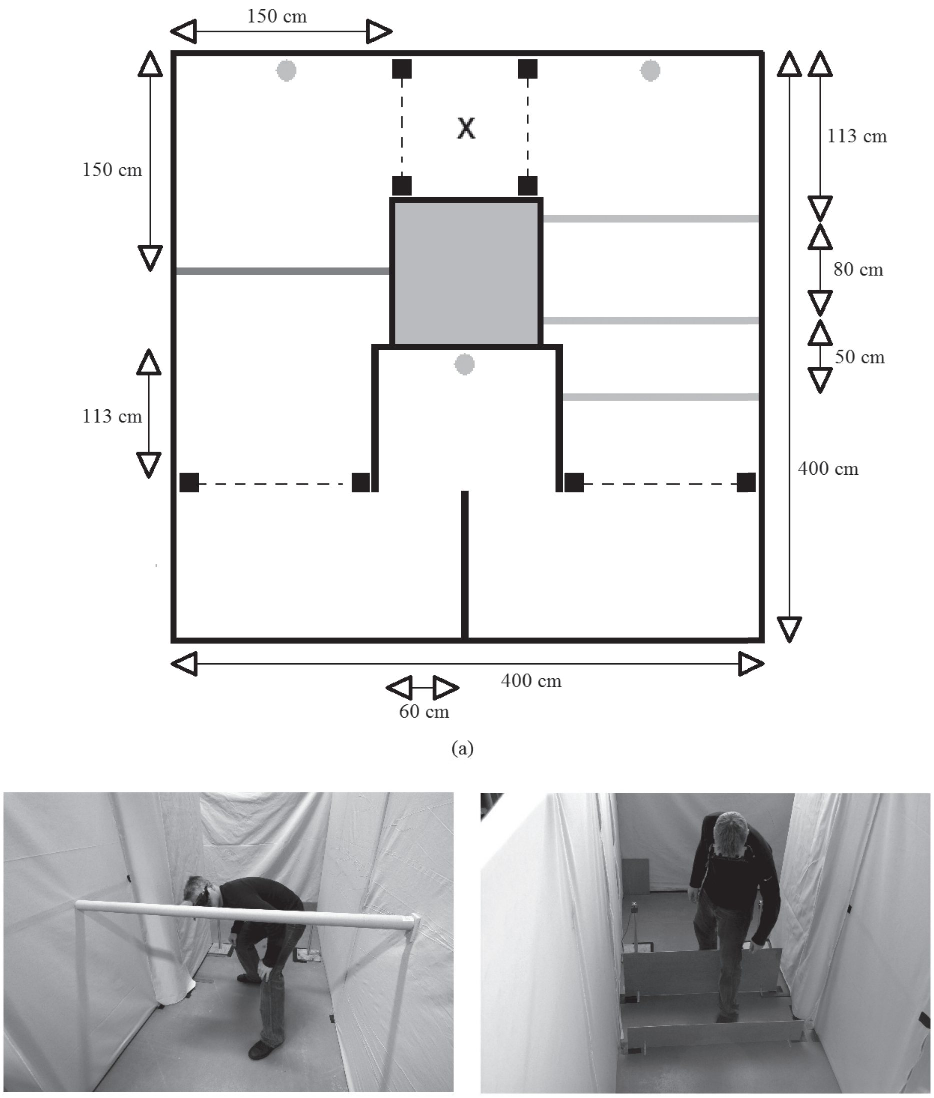


Figure 2.6: The obstacle environment. (a) Top view of the setup. Three *grey lines* indicate thin wooden boards. Three *black lines* represent walls. Single *grey line* indicates low hanging bar. Furthermore, *dashed lines* and *grey circles* represent time registration positions and camera's respectively; (b) participant ducking to avoid collision with the hanging obstacle bar; (c) participant stepping over the obstacles on the ground.

Design and variables

A 4 (30°, 75°, 120° and unrestricted FoV) x 2 (clockwise and counter-clockwise direction of movement) x 3 (repetitions) within participants design was used. The first two variables were randomised across trials using a Latin square design (Wagenaar, 1969), since these were assumed to influence the data collection. The direction of movement (clockwise and counter-clockwise) was balanced over trials to reduce possible learning effects. For each trial, it was analysed how long it took to traverse each of the three segments.

Procedures

After filling out the informed consent form, participants were instructed to traverse the course. They were told that it was extremely important not to touch any of the objects constituting the course, thus simulating a potentially dangerous environment. First, participants were instructed to stand on a cross marked on the ground near the entrance of the course. Then they were asked to traverse the course as quickly as possible, either in the clockwise or the counter-clockwise direction. The time that elapsed between the moment a participant left the starting point and the moment at which he/she returned to this point was recorded. The recordings were stopped when they returned to the cross. All four viewing conditions were tested, both in the clockwise and in the counter-clockwise direction.

Each specific combination of conditions was repeated three times (of which only the last two were recorded). When half of the conditions had been tested, the positions of two of the step-over obstacles (the highest and lowest) were switched. This was done to ensure that participants could not memorise the entire structure of the environment and needed to pay attention to perform their task.

Statistical analyses

Three ANOVA's were performed using STATISTICA (StatSoft, 2000). One for each of the segments. All had the following design: 4 (FoV) x 2 (clockwise-counter-clockwise). Whenever significant effects were found, Tukey's HSD post-hoc analysis was used to reveal pairwise differences. Significance level was set to 5% (two-tailed).

2.3.2 Results

Figure 2.7 shows time needed to complete each segment of the course as a function of the horizontal viewing angle. A decrease in viewing angle yields an increase in time for *obstacle crossing* $F(3, 27) = 40.583, p < .001$, *circumvention* $F(3, 27) = 49.348, p < .001$, and *ducking* $F(3, 27) = 52.667, p < .001$. Time needed to traverse each of the three segments increased similarly as a function of horizontal viewing restriction. An increase was observed between each pair of viewing conditions except between 75° and 120° viewing angles (post-hoc analyses showed $p < .001$ for all other pairs).

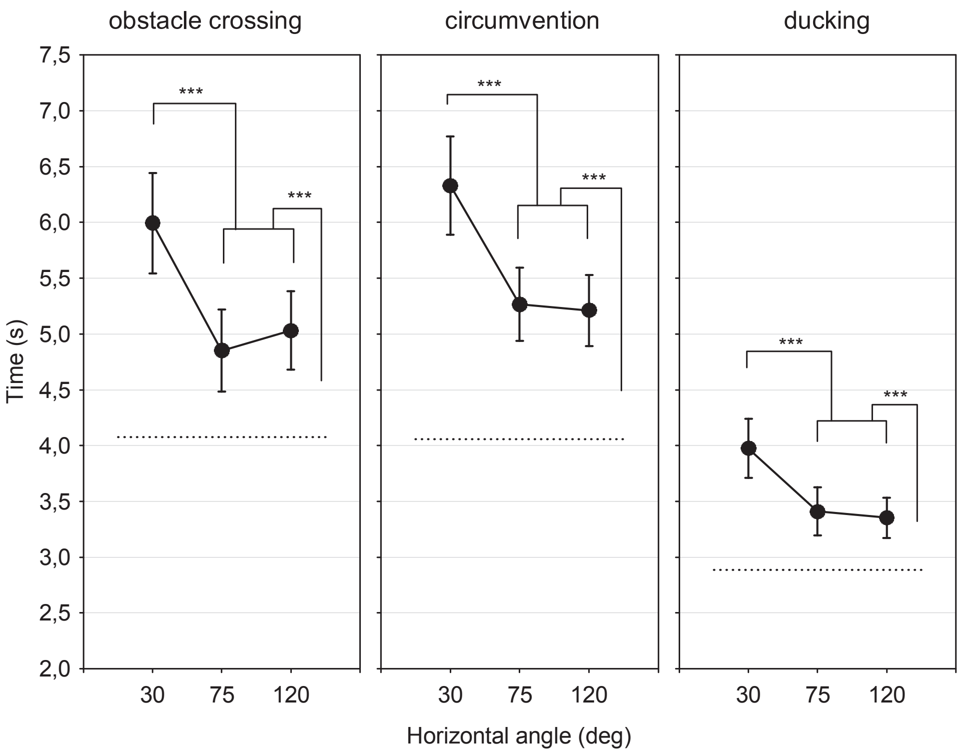


Figure 2.7: Time to complete each segment as a function of horizontal field-of-view extent (in degrees). Dashed lines indicate the full view condition. The closest neighbouring significantly different pairs are indicated by * ($p < .05$), ** ($p < .01$) and *** ($p < .001$). Error bars represent standard error.

2.4 Discussion

This chapter discusses two experiments, both concerned with the influence of horizontal viewing restriction on obstacle avoidance behaviour. In the first experiment, it was investigated how limitation of a participant's horizontal viewing angle influences both speed and accuracy of movement while manoeuvring through a 3-wall setup. We found that speed of movement decreases as the horizontal viewing angle decreases. Specifically, the two smallest angles tested here (i.e., 30° and 45°) caused participants to decrease their walking speed compared to a larger view of 75°. Furthermore, we found that limitation of the horizontal viewing angle decreases the accuracy of this movement. The accuracy was defined by the deviation from the ideal manoeuvring path, which is the path traversed under the same conditions (wall-to-wall distance and direction of movement), but with full view. Traversing the course with a viewing angle of 75° yields higher accuracy (less deviation) than with each of the other viewing conditions, with the unanticipated exception of 45°.

Both the task and the environment in this first experiment were rather simple. Therefore, it was decided to conduct an additional study. This second experiment required participants to traverse a complex course consisting of three segments, each requiring a different obstacle avoidance task. These were: ducking underneath a low hanging bar, stepping over three obstacles on the floor, and a slaloming task, similar to the one in the first experiment.

In addition to this change in task, a viewing condition of 120° was added. Based on the results of the previous experiment, it was hypothesised that limitation of the horizontal viewing angle would reduce walking speed during all three obstacle avoidance tasks. Furthermore, we expected that the wide view of 120° would substantially improve performance compared to the 75° condition.

The results of this second experiment show that the extent of the horizontal viewing angle indeed affects walking speed for all three segments of the obstacle course. Interestingly, there was no difference between the 75° and 120° conditions. Moreover, for all segments, all restricted conditions differed from the full-view condition.

The finding that visual field restriction causes a similar performance degradation for each of the three segments of the obstacle course suggests that the effect is robust and not dependent on the nature of the actual movements required. In order to successfully execute all of these obstacle avoidance tasks, there is a need for both exteroception (information about the environmental characteristics, such as the height of an obstacle) and exproprioception (information of the body's position relative to the environment). Visual exproprioceptive information is used to estimate self-position and to fine tune movement during obstacle avoidance, while visual exteroceptive information is used in a feed forward manner to plan a manoeuvre (Patla, 1998; Mohagheghi, Moraes, & Patla, 2004; Patla & Greig, 2006; Rietdyk & Rhea, 2006a).

The environment that was used in this study provided no additional visual cues that could be used to compensate for the reduction of visual exproprioception of the body with respect to the environment. But since the participants could freely make compensatory head movements, it is likely that they gathered sufficient exteroception and exproprioception visual information to correctly judge the location of the obstacles as well as fine tune their movements while avoiding them (Knapp & Loomis, 2004; Wu et al., 2004; Creem-Regehr et al., 2005). However, the additional time needed to perform these compensatory head movements might be the cause of the observed reduction in speed. In the present study, we did not investigate the effect of visual field limitation on head movements, which is something that is preferable in future work.

Another candidate cause for the observed performance degradation as a result of visual field limitation may be the fact that loss of peripheral information degrades the maintenance of postural equilibrium (Amblard & Carblanc, 1980; Turano et al., 1993), resulting in a decreased confidence, which may in turn manifest itself in a reduced manoeuvring speed.

From an applied perspective, the findings from both experiments imply that a restriction of the horizontal visual field will increase the amount of time one needs to move through a complex structured environment. Even with the rather large visual field of 120° x 48°, a significant reduction in speed of movement was observed. This suggests that the vertical angle may be more important during such tasks than previously thought. The vertical angle tested here complies with most commercially available HMDs. Therefore, we suggest that future work should dissect the influence of the horizontal and vertical angle on obstacle avoidance behaviour.

Chapter 3

The role of the vertical and horizontal viewing angle

This chapter is based on the following publication:

Jansen S.E.M., Toet A., Delleman N.J., (2010) Restricting the Vertical and Horizontal Extent of the Field-of-View: Effects on Manoeuvring Performance. *The Ergonomics Open Journal, 3*, 19-24

This chapter addresses the influence of the vertical angular extent of the FoV on obstacle avoidance behaviour. While the previous chapter focussed on the horizontal viewing angle, the present chapter describes an experiment investigating how limitation of the vertical and horizontal angle affect obstacle avoidance behaviour separately.

3.1 Introduction

It has been shown that under full cue conditions, people can accurately judge the distances of targets resting on the ground up to 25 meters (Loomis, Fujita, Da Silva, & Fukusima, 1992). However, when the FoV is restricted, this causes underestimation of target distance, both in real (Watt et al., 2000; Willemsen, Colton, Creem-Regehr, & Thompson, 2009) and virtual environments (Fortenbaugh et al., 2007; Arthur, 2000). Next to impaired distance estimation, the loss of input from the peripheral visual field also causes a decrease in the maintenance of postural equilibrium (Turano et al., 1993) and the ability to control heading (Patterson et al., 2006). When manoeuvring through complex structured environments, all of these tasks (estimating distance, maintaining balance, controlling heading) are important. Therefore, it is useful to understand how manoeuvring behaviour through such environments is affected by FoV-restriction.

Previous work (Toet, Jansen, & Delleman, 2007, 2008) showed that both speed and accuracy of moving through a complex environment increased as the horizontal angle of the visual field was enlarged to 75°. Surprisingly, further enlargement (to 120°) did not yield any performance improvement. This interesting finding gave rise to the idea that the restricted vertical angle (which was set at 48°) might play an important role in the impairment of performance for such manoeuvring tasks.

Although considerable research has been devoted to the horizontal angular extent of the visual field, rather less attention has been paid to the vertical angle. However, a few studies explored the effects of loss of sight of one's lower limbs on task performance. Wu and colleagues (2004) for instance, observed impaired performance on a distance estimation task with a vertical FoV restriction, and found restored values when participants were allowed to make head movements.

In addition, Rietdyk and Rhea (2006a) studied the effects of expproprioceptive (sight of own limbs) and exteroceptive (cues in the environment) information on obstacle crossing. They conclude that information about obstacle position and size is used in advance to plan a manoeuvre, while information about the body relative to the obstacle is used to control and update movement during the execution (Rhea & Rietdyk, 2007). A recent preliminary study showed that enlarging the vertical angle from 18° to 48° yields a greater performance increase on a complex locomotion task than enlarging the horizontal angle from 75° to 180° (Toet, Van Der Hoeven, Kahrimanović, & Delleman, 2008).

Patla and Vickers (2003b) identified two dominant gaze behaviours during adaptive locomotion: landing target fixation and travel gaze fixation. They argue that the latter is more dominant and consists of the eyes being directed at the ground ahead and not to a specific location. Furthermore, Marigold and Patla (2008) reported increased head pitch angle as a result of a blocked lower visual field. Taken together, these findings show the importance of the lower visual field in adaptive locomotion.

The present study aims to investigate this relationship systematically by fully combining five vertical with four horizontal angles resulting in 20 combinations ranging from a very small to a fully unrestricted FoV. We will explore three different questions. First, we examine the effects of both horizontal and vertical FoV-restriction on manoeuvring performance within a complex structured course. To complete this course, three different types of obstacles need to be overcome. Each of these will require different bodily movements in order to cross them. Performance will be measured as the time needed to traverse the course as well as the number of errors made. It is expected that both horizontal and vertical FoV-restriction will decrease human performance during a manoeuvring task and that this will become manifest as an increase of both the time to complete the course and the number of errors made.

Second, a head-tracker will be used to investigate the influence of FoV-restriction on head movement during locomotion. It is expected that participants will increase the number and extent of head movements to compensate for loss of peripheral vision. Specifically, we expect increased pitch rotation for vertical FoV restrictions and increased yaw rotation for horizontal restrictions.

Third, we will investigate if the orientation of the visual field has an effect on obstacle performance. We therefore examine how an upward, centred and downward oriented view affect time to complete the course. Potential performance differences may suggest an alternative way to optimise performance with visual field limiting devices that does not increase size, weight and cost.

3.2 Methods

3.2.1 Participants

The procedures of this study were approved by the TNO Human Factors internal review board on experiments with human participants. Seventeen paid participants (8 male) with an average age of 23.6 ($SD = 8.7$) gave informed consent to take part in the experiment. All were free of any known neurological or orthopaedic disorders, or any impediments to normal locomotion and had normal (20/20) or corrected-to-normal vision, as verified by self report.

3.2.2 Apparatus

Goggles. For each combination of a horizontal (40°, 80°, 115° and 200°) and a vertical (25°, 40°, 60°, 90° and 135°) angle, a separate pair of safety goggles was used (type Bollé Targa; `www.bolle-safety.com`). To restrict the view to a certain extent of the visual field, part of the lens was covered with duct tape (see Fig 3.1 for a number of examples). Also, four extra pairs of goggles (two upward and two downward oriented) were prepared to investigate the effects of visual field orientation on task performance. This was done for the 80° x 90° and 115° x 60° conditions (H x V). A total of 24 pairs of goggles were used in this study (4 x 5 viewing angles and 2 x 2 orientations).

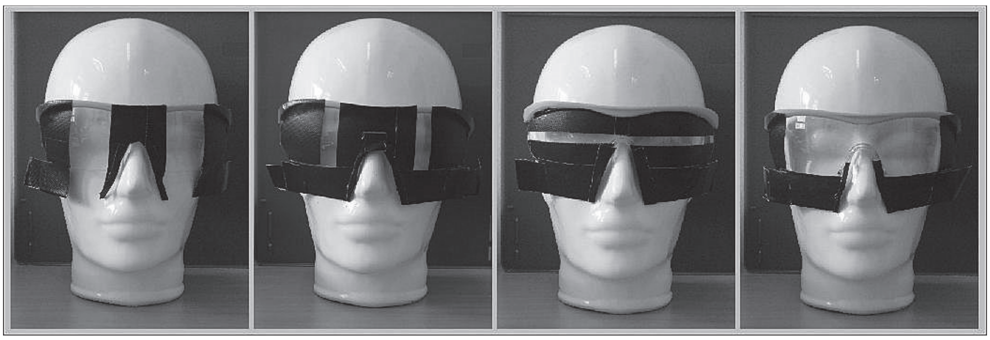


Figure 3.1: Four examples of FoV limiting goggles.

Environment. The obstacle course was a straight pathway (length 850cm, width 140cm), flanked by wooden frames covered with light-coloured linen sheets. Three obstacles were evenly spaced over the length of the course. Each of them required the performance of different bodily movements in order to cross them. The first obstacle consisted of three thin wooden boards, with heights of 20, 30 and 40cm, placed upright on the ground across the entire width of the course.

The second obstacle consisted of three room-dividing walls, placed parallel to each other. To traverse this segment of the course, participants had to follow an S-curved trajectory through a 60cm wide passage between each two walls. The third obstacle was a low hanging bar (at 110cm above the ground) extending across the entire width of the course. Participants needed to duck to get underneath it. The bar was made from soft material (polyethylene foam) to prevent injury in case of collision. The visual structure of the obstacle course was intentionally kept simple and the view of the outside world was blocked by enclosing the course. See Fig 3.2 for a schematic representation with photos.

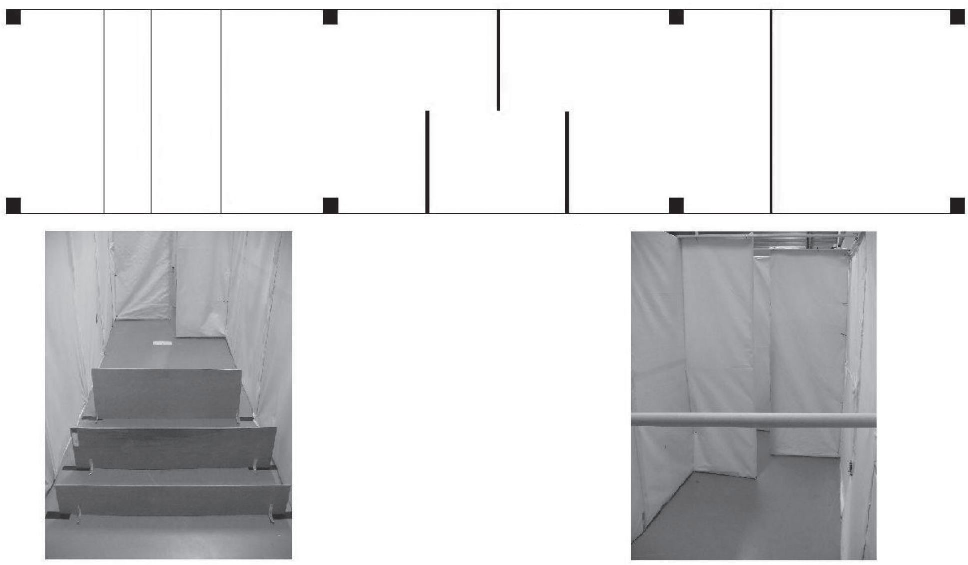


Figure 3.2: A top view schematic representation of the experimental setup. From left to right, lines represent thin wooden boards, walls and lowing hanging bar. Furthermore, black squares represent the time measurement poles. Left photograph: The three thin wooden boards obstacle. Right photograph: The room-dividing walls obstacle in the background and the suspended bar obstacle in the foreground.

Time registration. To register the time that participants needed to traverse the course, four pairs of poles equipped with infra-red light–emitting diodes and photoelectric beam sensors were used (type Velleman PEM5D; `www.velleman.de`). The black squares in Fig 3.2 indicate their position within the course. One pole emits and registers the return of an infra-red light beam, which is reflected by a mirror on its companion (opposite) pole. The moment of interruption of the beam by a participant was registered. From this, the time needed to traverse the course could be computed.

Video registration. Four surveillance cameras recorded all trials. Three of these registered different parts of the course, while the fourth filmed an overview of the entire track by using a fish-eye lens. The videos were used to count the number of errors made by participants as well as to observe certain qualitative aspects of the manoeuvring behaviour.

Head tracking. To register the head movements made by participants during the traversal of the course, a movement registration system was used that measured the orthogonal linear acceleration and the angular velocity of the roll, pitch and yaw rotation of the head. The system consists of a sensory device housing six Murata Gyrostar sensors, which was connected to a data logger using a sampling rate of $50Hz$. Every trial was registered as a separate data file. The sensory device was attached to a headband worn by the participants. The data logger was placed in a bag worn around the waist. The intermediate time registrations were used to investigate the extent of head rotation for each of the segments.

3.2.3 Design and procedures

A four (horizontal angle) x five (vertical angle) within–participants design was used, with an unrestricted (without goggles) condition both at the beginning and end of the experiment. Both variables were randomised across trials using a Latin square design (Wagenaar, 1969), since these were assumed to influence the data collection. In addition, the four extra conditions (orientation) were distributed randomly within each participant's trial-set resulting in a total of 26 different viewing conditions (i.e., 4 horizontal angles x 5 vertical angles, 2 unrestricted and 4 orientation conditions).

After filling out the informed consent form, participants were instructed to traverse the course for each of the conditions. For each trial, three separate measurements were investigated: First, the time that was needed to traverse the entire course. Second, the angular extent of head movement for all three axes (pitch, roll and yaw). Third, the number of errors for each trial. Participants were told that it was important not to touch any of the objects constituting the course, thus simulating a potentially dangerous environment. This instruction served to keep the error count at a low level. A small break was held after half of the trials had been recorded.

3.2.4 Data analysis

Mauchley's sphericity test was performed for each ANOVA. Whenever this revealed a violation of the sphericity assumption, the Greenhouse-Geisser correction was applied. Also in such a case, Bonferroni's post hoc procedure was used instead of Fisher's LSD to compare pairwise means (Field, 2009). All analyses were performed with STATISTICA 8.0 and significance levels were set to 5%.

3.3 Results

3.3.1 Field of view

Time. Because of the high degree of variability in speed between the participants, the time measurement used in this experiment was defined as the percentual increase compared to each participant's unrestricted condition (when not wearing goggles). Fig 3.3 shows the time increase as a function of horizontal and vertical viewing angle. The horizontal angular extent had a main effect on time, $F(3, 36) = 8.532, p < .01$ with pair wise differences showing significance only between the smallest angle (i.e., 40°) and each of the other angles (for all, $p < .001$). Furthermore, the extent of the vertical angle had a main effect on time as well, $F(4, 48) = 9.941, p < .01$. Significant pair wise differences exist between the 25° condition and each of the other angles (for all, $p < .01$).

Error count. Error count was not affected by FoV. However, there was a significant difference in error count between the three tasks: 57% of all errors were made during the stepping over task, compared to 23% during the avoiding walls segment and 20% during ducking.

Head movement. Decreasing the horizontal viewing angle had no significant effect on total yaw rotation, $F(3, 33) = .978, p < .35$. On the other hand,

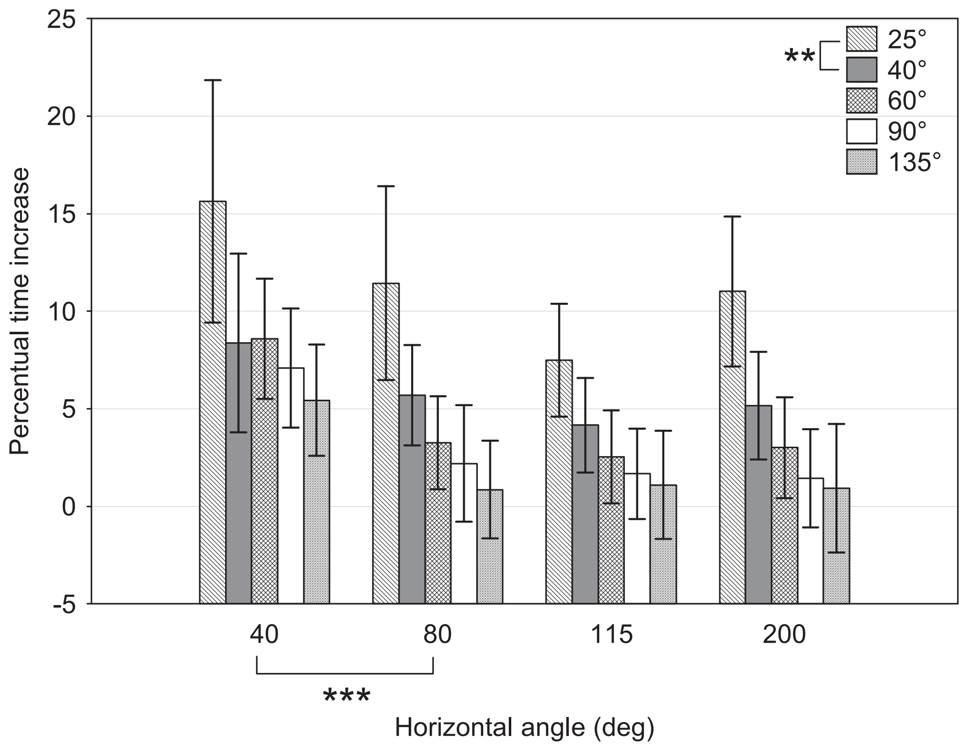


Figure 3.3: Percentual increase of time (compared to each participant's unrestricted condition) as a function of horizontal and vertical viewing angle (bar type). This percentage is normalised to leg length. The closest neighbouring significantly different pairs are indicated by *($p < .05$), **($p < .01$) and ***($p < .001$) and. Error bars represent standard error.

decreasing the vertical angle did cause an increase in pitch rotation, $F(4,44) = 10.763, p < .001$. The interaction between vertical angle and task was also significant, $F(8,88) = 3.727, p < .001$. Pitch rotation during the avoiding walls and stepping over tasks were influenced by the limitation of the angle, while the pitch rotation during the ducking task was not affected (see Fig 3.4).

3.3.2 Orientation

Time to complete the course was affected by viewing orientation, $F(2,30) = 5.253, p = .011$ (see Fig 3.5). Pairwise comparison revealed a time increase for the upward oriented viewing condition compared to the centred view ($p = .01$).

3.4 Discussion

The present study investigated a number of research questions, which will be discussed here independently. First we hypothesised that FoV-restriction would cause performance degrading effects on manoeuvring tasks through a structured environment. According to Rieser and colleagues (1992), a large visual field is required to create and maintain an accurate representation of the world. Limitation of this field by reducing either the horizontal or vertical viewing angle produces an impairment of this representation, which results in impaired perceptuomotor performance.

We expected that a reduction of either the horizontal or the vertical viewing angle would become manifest as an increase in elapsed time and error count in our experimental paradigm. Indeed, the results indicate that both a limitation of the horizontal and the vertical viewing angle caused participants to move slower through the course. However, it can not be concluded from this study that this causes increased error rate.

When looking at the main effect of the horizontal viewing angle on elapsed time, it can be observed that a reduction of the horizontal extent of the visual field yields an increase in time needed to complete the course. An interesting exception to this was the unanticipated high elapsed time of the specific FoV of 200° x 25° (HxV). A possible explanation for this finding could be that the ratio between the horizontal and vertical angle is very unnatural (a very narrow slit), which results in slower movement. Apart from this specific condition, the overall findings are consistent with previous studies, which showed impaired performance caused by horizontal FoV-restriction on manoeuvring tasks (Toet et al., 2007, 2008), distance estimation (Watt et al., 2000; Fortenbaugh et al., 2007) and postural equilibrium (Turano et al., 1993). In these cases the vertical

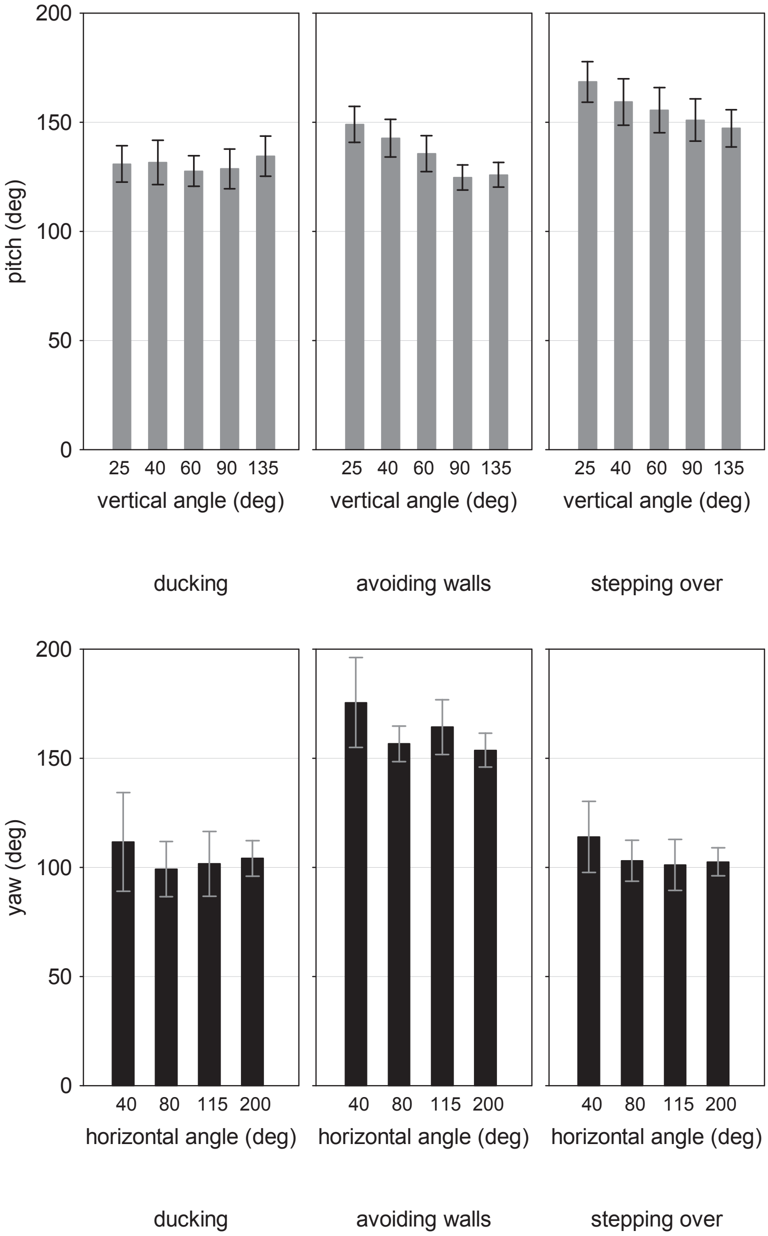


Figure 3.4: Top: Total pitch rotation of the head as a function of vertical angular extent and task. Bottom: Total yaw rotation of the head as a function of horizontal angular extent and task. Error bars represent standard error.

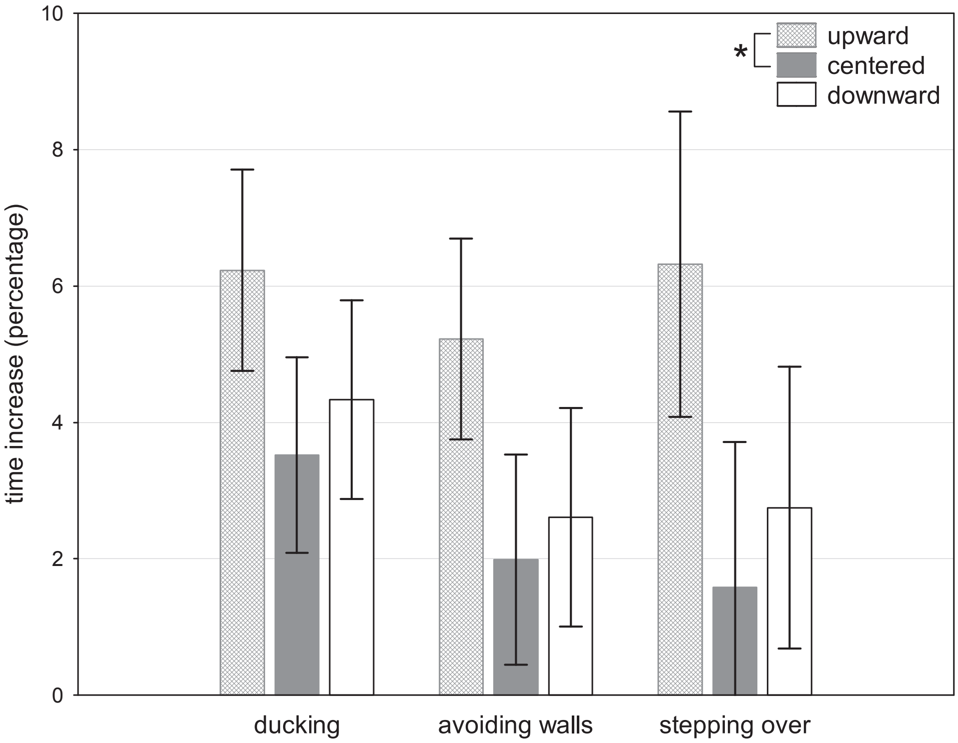


Figure 3.5: Percentual increase of time (compared to each participant's unrestricted condition) as a function of task and aperture orientation. Error bars represent standard error.

angle was kept constant, usually at an extent commonly found in current FoV-restricting devices (i.e., 30–50°).

In addition to the replication of these findings, the present study also investigated the effects of a reduction of the vertical angular extent. It was observed that decreasing the vertical angle results in increased time needed to complete the course. Specifically, performance with a small vertical angle (25°) differs from that with larger ones. These results were similar for all three tasks (i.e. stepping over, avoiding walls, and ducking), suggesting that the effects are robust and do not depend on the nature of the actual bodily movements needed for each manoeuvring task.

Furthermore, it is interesting to look at the interaction between horizontal and vertical angle restriction. For instance, enlarging a FoV of 80° x 40° (HxV) can be done by increasing either the horizontal or vertical extent of the visual field. When enlarging to 115° x 40° by increasing the horizontal angle, performance improves by 1.34%. On the other hand, when enlarging the vertical component to create a FoV of 80° x 60° , the performance improves by 2.84%. This confirms previous findings, which showed that an enlargement of the vertical angle from 18° to 48° results in greater performance improvement than an enlargement of the horizontal angle from 75° to 180° (Toet et al., 2008). The results presented here should encourage further investigation of the effects of vertical FoV-restriction.

The second hypothesis concerned the influence of FoV restriction on head movements. It was expected that participants would compensate for the loss of peripheral visual information by making extensive head movements. More specifically, it was expected that a decrease of the horizontal angle would cause an increase of the extent of yaw rotation of the head, while reduction of the vertical angle would result in increased pitch rotation. The results show that a horizontal restriction does not have an effect on head movement, but a vertical restriction does. During the avoiding walls and stepping over tasks especially, pitch rotation is increased with vertical restriction. These tasks required participants to estimate distances between obstacles, which is facilitated by integrating ground surfaces (Wu et al., 2004). Therefore, a decrease of the vertical angular extent requires increased pitch rotation of the head.

It was observed that the ducking task is least influenced by FoV restriction. A possible explanation for this could be that the manoeuvre needed to avoid this obstacle did not require a view of the obstacle during the actual ducking. Instead, it seems that participants planned this manoeuvre beforehand and could then perform the actual movement without visual feedback. The other two tasks (stepping over and avoiding walls) demanded visual information during the execution to control heading and foot placement in order to avoid collision. Therefore, visual field restriction did cause increased head movement for these tasks.

Besides the influence of FoV restriction, we explored the effect of visual field orientation on task performance and head movement. From the results it can be concluded that an upward oriented view yields impaired performance as compared to a centred view. This became manifest as an increase in elapsed time. This is in line with work by Mon-Williams and colleagues (1999), who state that high gaze angles quickly cause visual fatigue, which may account for the performance decrements found here. Another cause could be the disturbance of the vestibular system that is caused by the altered head orientation, which is needed to compensate for the change in visual field orientation. Furthermore, the data suggest that a centred view has a slight advantage over a downward oriented view but this could not be confirmed by statistical analysis. This was done to explore the possibility of display orientation instead of display enlargement as a means to improve task performance in virtual environments. At this point, the results do not suggest that an alternative orientation would increase performance during a manoeuvring task, but a more elaborate investigation is preferable.

Chapter 4

Obstacle crossing behaviour

This chapter is based on the following publication:

Jansen S.E.M., Toet A., Werkhoven P.J., (2011) Obstacle Crossing With Lower Visual Field Restriction: Shifts in Strategy *The Journal of Motor Behaviour, Vol. 43, No. 1*, 55-62

This chapter addresses the influence of lower visual field obstruction on performance during an obstacle crossing task. Using full-body motion capture techniques, kinematics of this specific task are analysed and used to infer strategy changes accompanied by such limitation.

4.1 Introduction

A common, everyday activity for humans is to walk through an environment while avoiding collisions with obstacles. One way to achieve such collision-free locomotion is to step over an obstacle situated in the pathway. To ensure safe and efficient locomotion, this obstacle crossing requires visual guidance both before and during the execution of the manoeuvre.

From an information-processing point of view, this task can be divided into the following subtasks: first, the dimensions of the obstacle have to be estimated to decide whether it is feasible (i.e., safe, comfortable, and efficient) to step over the obstacle or some other avoidance strategy is necessary (e.g., circumvention); second, a strategy must be devised to decide how the action will be executed. Depending on the distance from the obstacle, a change in speed or step length may be required during the approach; third, during the execution of the manoeuvre, the movement needs to be updated in order to deal with perturbations in the limb trajectory caused by any initial misperception of the obstacle dimensions and position as well as by any balancing problems.

Several studies have investigated lower limb kinematics during obstacle crossing (Chou & Draganich, 1997, 1998; McFadyen & Winter, 1991). Specifically, Patla and Rietdyk (1993) revealed that limb trajectory is substantially modulated for height changes but minimally for the width of an obstacle. They proposed three strategies that minimize the danger of tripping. First, adequate toe clearance is critical. Second, reduced forward velocity of the toe permits minimal stability threats in case of contact with the obstacle. Third, by positioning the centre of mass further back (close to the stance limb) during obstacle crossing, balance is increased, which is beneficial in case of a trip. They reported increased toe clearance with obstacle height. This is in accordance with results of Chen and colleagues (1991), who further reported that older participants exhibited a more conservative strategy by slowing down and shortening their step length in comparison with younger participants. However, they did not find a difference in toe clearance between the age groups.

During obstacle crossing under naturalistic viewing conditions (i.e., without restrictions), some of the visual information needed for the task is gathered by fixating on the object during the approach. This (exteroceptive) information is used in a feed-forward manner and can be used to judge the position and size of the obstacle. However, information concerned with the body relative to the environment can be perceived through the peripheral visual system and is used to update movement during obstacle crossing (Patla & Vickers, 1997). When unrestricted, the human field of view (FoV) has an average horizontal angle of 200° and an average vertical angle of 135° (Werner, 1991). However, FoV can be restricted for several reasons, such as eye disease (e.g., retinitis pigmentosa, glaucoma) or when wearing FoV-limiting devices such as head-mounted displays (HMDs) or night vision goggles (NVGs). Even an everyday activity such as carrying a tray or other large object causes occlusion of part of the lower visual field.

Early studies have shown that restriction of FoV impairs everyday functioning (Alfano & Michel, 1990; Dolezal, 1982). Specifically, the distance to targets on the ground is underestimated when the visual field is restricted (Watt et al., 2000; Willemsen et al., 2009). Furthermore, FoV restriction has been shown to disturb the maintenance of postural equilibrium (Amblard & Carblanc, 1980; Paulus et al., 1984; Turano et al., 1993) as well as the ability to control heading (Patterson et al., 2006). Also, observers tend to compensate for the reduction in their instantaneous visual field by making extensive head movements (Kasper, Haworth, Szoboszlay, King, & Halmos, 1997; Wells & Venturino, 1990). According to Rieser and colleagues (1992), early experience with a large visual field is required to create and maintain an accurate representation of the world, which is assumed by some to be used during perceptuomotor tasks. It has been proposed that optic flow is used to guide this behaviour (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). In contrast, it is argued that visual guidance of locomotion is achieved not by optic flow, but by keeping targets and obstacles at fixed angles, or eccentricity, relative to the body (Rushton, Harris, Lloyd, & Wann, 1998; Rushton, Wen, & Allison, 2002).

Moreover, much of the research concerning FoV restriction has focused either on the horizontal angle of the visual field or on circular restriction. However, in the last decade there have been studies investigating the effects of the vertical extent of the visual field on perceptuomotor tasks. Wu, Ooi, and He (2004) observed impaired performance of distance estimation when the lower visual field was blocked, and found that values returned to normal when participants were allowed to make head movements. Additionally, a number of researchers investigated the influence of the lower visual field on obstacle crossing behaviour (Mohagheghi et al., 2004; Patla, Davies, & Niechwiej, 2004; Patla, 1998). Specifically, Patla reported an experiment in which participants stepped over obstacles without information from the lower visual field. He found increased toe clearance as a consequence of this visual impairment and concluded that this is caused by the lack of visual information needed to fine-tune the lower limb trajectory. Following this, Rietdyk and Rhea (2006b; 2007) studied the effects of expproprioceptive (sight of own limbs) and exteroceptive (cues in the environment) information on obstacle crossing. Similarly to Patla (1998), they concluded that information about obstacle position and size is used in advance to plan a manoeuvre, whereas information about the body relative to the obstacle is used to control and update movement during the execution.

In addition to lower body kinematics, several researchers have investigated gaze behaviour during obstacle crossing: Patla and Vickers (1997, 2003a) identified two dominant gaze behaviours during adaptive locomotion: landing target fixation and travel gaze fixation. They argued that the latter is more dominant and consists of the eyes being directed at the ground ahead and not to a specific location. Marigold and colleagues (2008; 2007) examined the lower body kinematics and gaze behaviour of participants when stepping over obstacles that suddenly appeared in the pathway. Downward-directed saccades were rarely made and when present were directed to the landing area and not the obstacle. The conclusion was that peripheral visual information is sufficient for safe obstacle negotiation. They further reported an increased head pitch angle as well as an altered gait speed and step length when 30–40° of the lower visual field was blocked. Moreover, in a recent review article, Marigold (2008) stressed the importance of the lower visual field for online visual guidance of locomotion. In a similar manner, recent studies conducted by Graci, Elliott, and Buckley (2009, 2010) investigated the effects of peripheral visual field restriction on overground locomotion and on stepping over an obstacle. They found increased toe clearance and stride length for a lower visual field occlusion as well as for a circumferential occlusion when stepping over low obstacles (4.8cm high).

Although some work has been done to investigate the influence of the lower visual field on obstacle avoidance and locomotion, studies examining the effects of different levels of viewing restriction are sparse. Previous work investigating this showed that a decrease of both the horizontal (Toet et al., 2007, 2008) and vertical viewing angle (Jansen, Toet, & Delleman, 2010; Toet et al., 2008) affects manoeuvring performance while traversing an obstacle course consisting of multiple obstacles. It is argued that the vertical angular extent is more dominant for local obstacle avoidance tasks. For example, a visual field of 80° x 40° can be enlarged by increasing either the horizontal or vertical extent. It was shown that an enlargement of the vertical angle by 20° constitutes a greater performance increase (of traversing an obstacle course) when compared to an enlargement of 35° of the horizontal angle.

In the present experiment, we investigate how obstacle crossing behaviour is affected by (partial) occlusion of the lower visual field. It is expected that a reduced vertical viewing angle causes an increase in step length and toe clearance during obstacle crossing. The same is expected for maximum head pitch during the approach phase. Furthermore, we expect a decrease in overall speed of movement.

Additionally, it will be investigated how trail limb clearance is modulated as a result of a restricted vertical view. This is interesting because the trail limb is always occluded during obstacle crossing. Therefore, modulation as a result of this viewing manipulation may be interpreted as a holistic behavioural shift to emphasise safety. A full-body motion capture system was used to gather kinematic data during the crossing of obstacles of different dimensions. By interpreting the kinematic measures, it is possible to shed some light on the behavioural strategies that are employed.

4.2 Methods

4.2.1 Participants

The procedures of this study were approved by the TNO Human Factors internal review board on experiments with human participants. Twelve participants (6 men) ranging in age from 19 to 39 years ($M = 25.2, SD = 4.9$) took part in the experiment and gave informed consent. All were free of any known neurological or orthopaedic disorders, or any impediments to normal locomotion. Furthermore, all participants had normal or corrected-to-normal vision as verified by self-report.

4.2.2 Apparatus

Goggles. For each viewing condition, an unrestricted horizontal angular extent was combined with each of four vertical viewing angles. This set of vertical visual angles was chosen to incorporate a small condition (25°) as well as a commonly used angle in HMDs (40°), a large angle (90°), and an unrestricted condition (135°). A separate pair of safety goggles was used for each of these conditions (of the type Bollé Targa; http://www.bolle-safety.com; see Figure 4.1). Part of the lens was covered with duct tape in such a way that a restriction of the vertical angular extent was induced without altering the horizontal angle. Because of variation in bone structure, the exact visual angle varied slightly per participant. However, because we used a within-subjects design, this did not alter any possible conclusions drawn from the data.

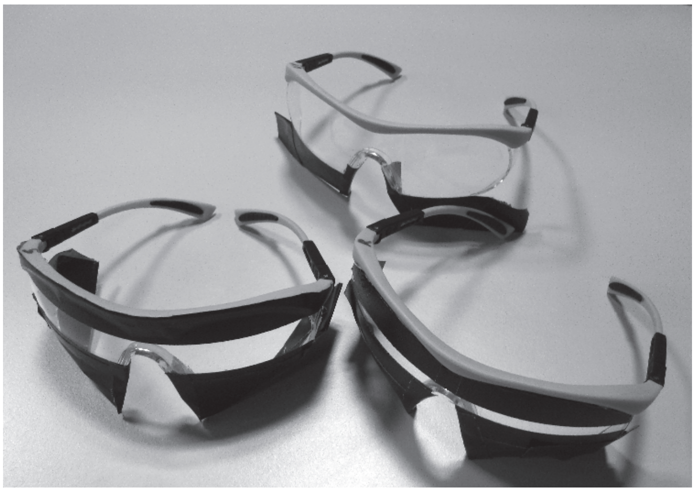


Figure 4.1: Goggles used to restrict the vertical viewing angle while leaving the horizontal extent unrestricted.

Motion capture. Full-body motion was registered using the MVN motion capture system by XSens (http://www.xsens.com, Enschede, the Netherlands). Participants wore a Lycra suit equipped with 17 sensory modules, containing three-dimensional gyroscopes, accelerometers, and magnetometers. Using the Xsens software, a participant's full-body motion was recorded for each trial with an update rate of $100Hz$. A sensor fusion scheme calculated the position, velocity, acceleration, orientation, angular velocity, and angular acceleration of each body segment, with respect to an Earth-fixed reference coordinate system. For a more extensive description of this system, see Roetenberg, Luinge, and Slycke (2009).

Obstacle. During each trial, participants stepped over a single obstacle placed exactly halfway between the start and end positions, which were indicated by markings on the floor. Two separate obstacles were used, each in two different configurations, resulting in a total of four obstacle conditions. Height and depth dimensions were $280x140mm$ for the larger obstacle and $210x70mm$ for the smaller obstacle. A schematic illustration of the setup is in Figure 4.2.

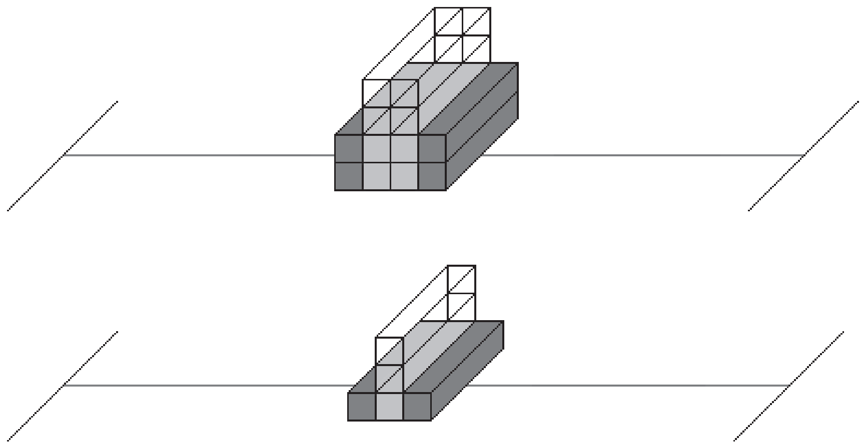


Figure 4.2: The four obstacle configurations situated in the pathway. Black lines indicate the start and end position for each trial. Both the large and small obstacles are shown in upright (transparent) and recumbent (grey) orientations.

4.2.3 Design and Procedure

A 4 (Vertical Angular Extent) x 4 (Obstacle Size) full factorial design was used, resulting in 16 conditions. Using a Latin square (Wagenaar, 1969), conditions were randomised across trials and performed three times each. In total, each participant performed 48 trials. After filling out the informed consent form, participants put on the Lycra suit containing the sensors. Before starting the experimental session, a calibration procedure was performed in which the sensor to body alignment and body dimensions were determined. First, body height and foot size were measured. Using regression equations based on anthropometric models, other dimensions were obtained as well. Second, a calibration procedure was performed. The rotation from sensor to body segment was then determined by matching the orientation of the sensor in the global frame with the known orientation of each segment in a specific pose. For further reading about this process, see Roetenberg et al (2009).

During the experimental session, participants were instructed to walk at a comfortable, self-preferred pace from the start to end positions while avoiding contact with the obstacle. After the third trial of each condition was performed, the experimenter changed the obstacle arrangement and viewing condition in accordance with the next condition. All conditions were performed consecutively without interruption. During the entire experimental session, full-body motion was recorded at a sampling rate of $100Hz$. This rate is in accordance with recent work involving foot placement (Rietdyk & Drifmeyer, 2009).

4.2.4 Dependent Variables

The MVN motion-capture system outputs three-dimensional position of 23 body segments using a biomechanical model (Roetenberg et al., 2009). With the use of Matlab (Guide, 1998), several dependent measures were extracted for each trial. First, step length was calculated as the Euclidean distance between the lead-limb toe and the trail-limb toe at the moment the lead limb touches the floor. Second, max lead and trail-limb clearance were defined as the maximum height of the toe during obstacle crossing for the lead and trail limbs, respectively. Obstacle height was subtracted from this to remove the systematic increase. Third, the maximum head pitch was calculated as the maximum angular offset from looking straight ahead. Finally, average speed was calculated over a $4s$ interval centred around the moment of contact between lead-limb toe and floor. By taking the Euclidean distance between the position of the chest at the start and end of this interval, the average speed was calculated. Figure 4.3 gives a schematic representation of the spatial variables.

4.2.5 Statistical Analysis

Although each condition was tested three times, only the final two trials were analysed. This was done to counter possible learning effects. In order to be clear, these two trials are referred to by their initial numbers (i.e., two and three). Overall, this resulted in a 4 (Vertical Angular Extent) x 4 (Obstacle Size) x 2 repeated measures analysis of variance (ANOVA) for each of the dependent measures (i.e., step length, lead and trail clearance, maximum head pitch, and average speed). Whenever Mauchley's test indicated a violation

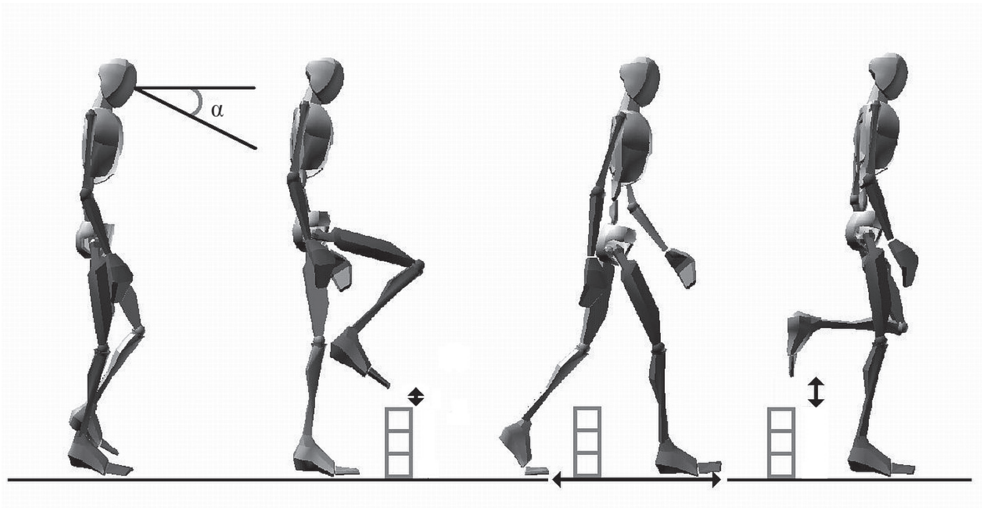


Figure 4.3: The spatial variables analysed in this study. From left to right: maximum head pitch angle, lead limb clearance, step length, and trail limb clearance.

of the sphericity assumption, a Greenhouse–Geisser correction was applied to the variance analysis as well as a Bonferroni adjustment on the pairwise comparisons (Field, 2009). All analyses were performed with STATISTICA 8.0 (StatSoft, 2000) and significance levels for each were set to 5%.

4.3 Results

4.3.1 Step length

There is an effect of vertical viewing angle on step length while stepping over an obstacle, $F(3, 33) = 21.299, p < .001$. A decrease in viewing angle led to an increase in step length (Figure 4.4). Pairwise analysis shows significant differences between each of the viewing conditions except between 40° and 90° ($p = .12$), for all others $p < .001$. Step length was not affected by obstacle type. Furthermore, the analysis shows no difference between the two trials. Moreover, no interaction effects were found.

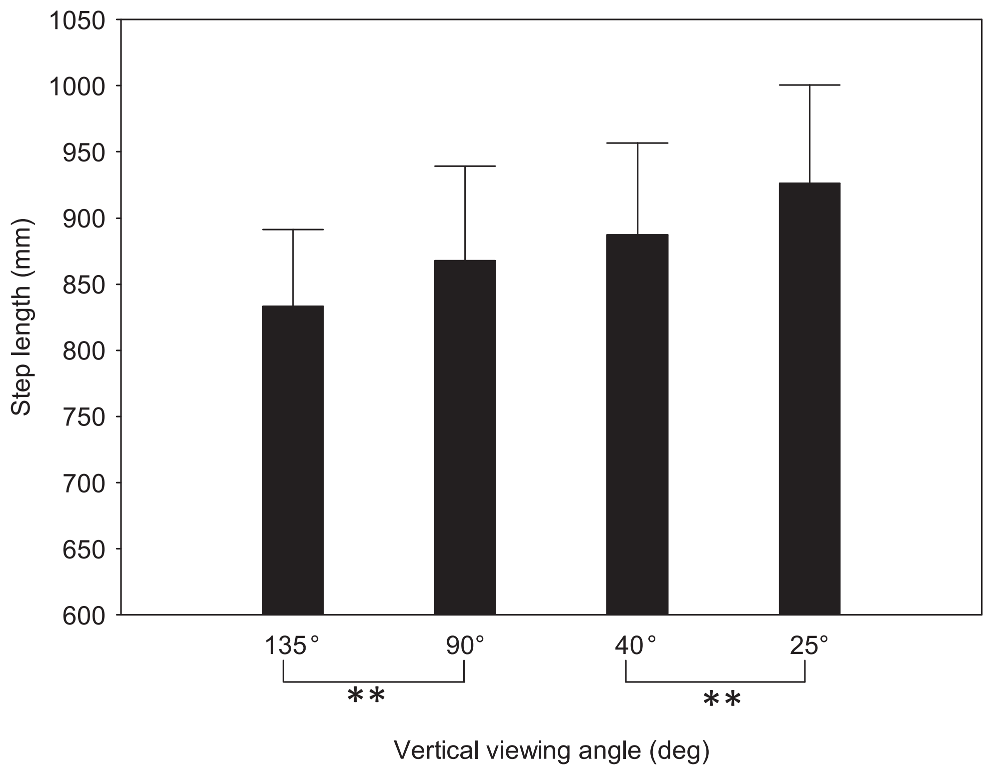


Figure 4.4: Step length as a function of vertical viewing angle. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$), and ***($p < .001$). Error bars represent standard error.

4.3.2 Toe clearance

Lead limb. The extent of the vertical viewing angle affects lead limb clearance, $F(3, 33) = 18.313, p < .001$. A decrease in viewing angle yielded an increase in lead limb clearance. Pairwise comparison shows significant differences between each of the viewing conditions except between 40° and 90° ($p = .12$), for all others $p < .05$. Furthermore, there was an effect of obstacle type on lead limb clearance, $F(3, 33) = 16.781, p < .001$. Pairwise analysis showed that toe clearance was smaller for the shortest obstacle (i.e., $70x210mm$) compared to the other types (for all $p < .001$). No difference was found between the two trials, and there were no interaction effects. See the left-hand graph in Figure 4.5 for the data.

Trail limb. Trail limb clearance was affected, in a similar manner as that of the lead limb, by the extent of the vertical viewing angle, $F(3, 33) = 5.726, p < .01$. A pairwise comparison revealed significant differences between the smallest visual angle (25°) and the 135° ($p < .001$) and 90° ($p = .03$) conditions as well as between 40° and 135° ($p = .03$). Additionally, there was an effect of obstacle type on trail limb clearance, $F(3, 33) = 21.642, p < .001$. Trail limb clearance differed for all obstacle types, except between the $210x70mm$ and the $280x140mm$ configurations ($p = .11$, for all other comparisons $p < .01$). Furthermore, no interaction effects were found between viewing condition and obstacle type, and there was no difference between the two trials. See the right-hand graph in Figure 4.5.

4.3.3 Maximum head pitch

The extent of the vertical viewing angle affected the maximum head pitch angle during the approach to the obstacle, $F(3, 33) = 4.740, p < .01$. Pairwise comparison shows increased pitch for the 25° viewing angle compared to the 135° ($p = .02$) and 90° ($p = .01$) conditions. Furthermore, obstacle type affects maximum head pitch angle, $F(3, 33) = 14.771, p < .001$. Downward pitch increased for the tallest obstacle ($280x140mm$) compared to all others ($p < .01$). Also, the $210x70mm$ configuration caused increased pitch compared to the shortest ($70x210mm$) one ($p < .01$), see Figure 4.6. Additionally, head pitch angle increased during the third trial of a condition as compared to the second, $F(1, 11) = 8.286, p = .02$. No interaction effects were observed.

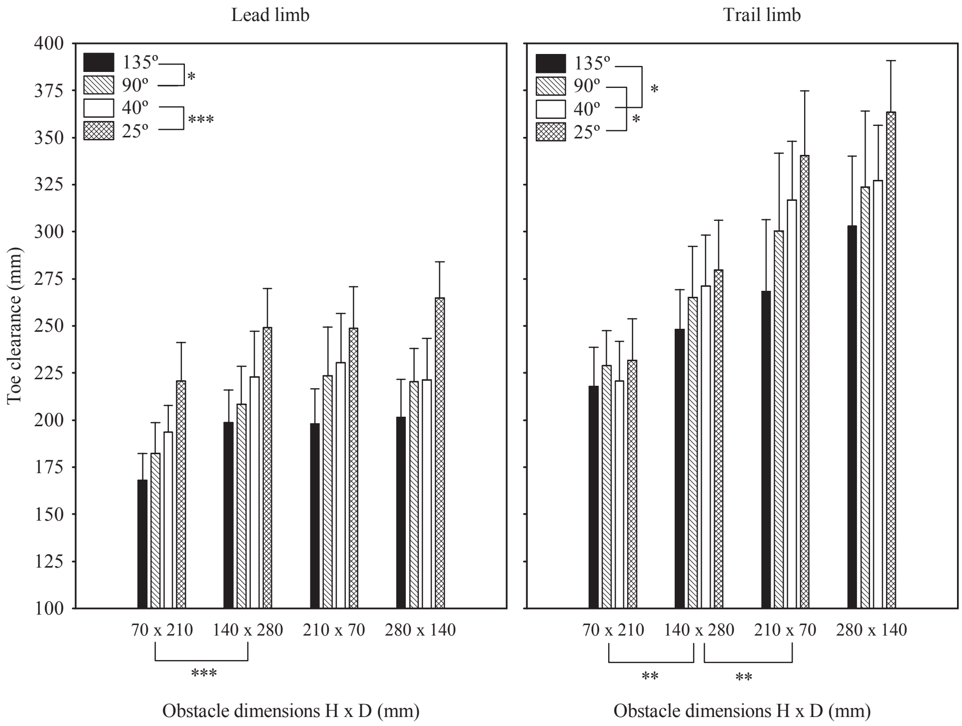


Figure 4.5: Toe clearance as a function of viewing condition and obstacle type. Lead and trail limb clearance are shown in the left and right panels respectively. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$), and ***($p < .001$). Error bars represent standard error.

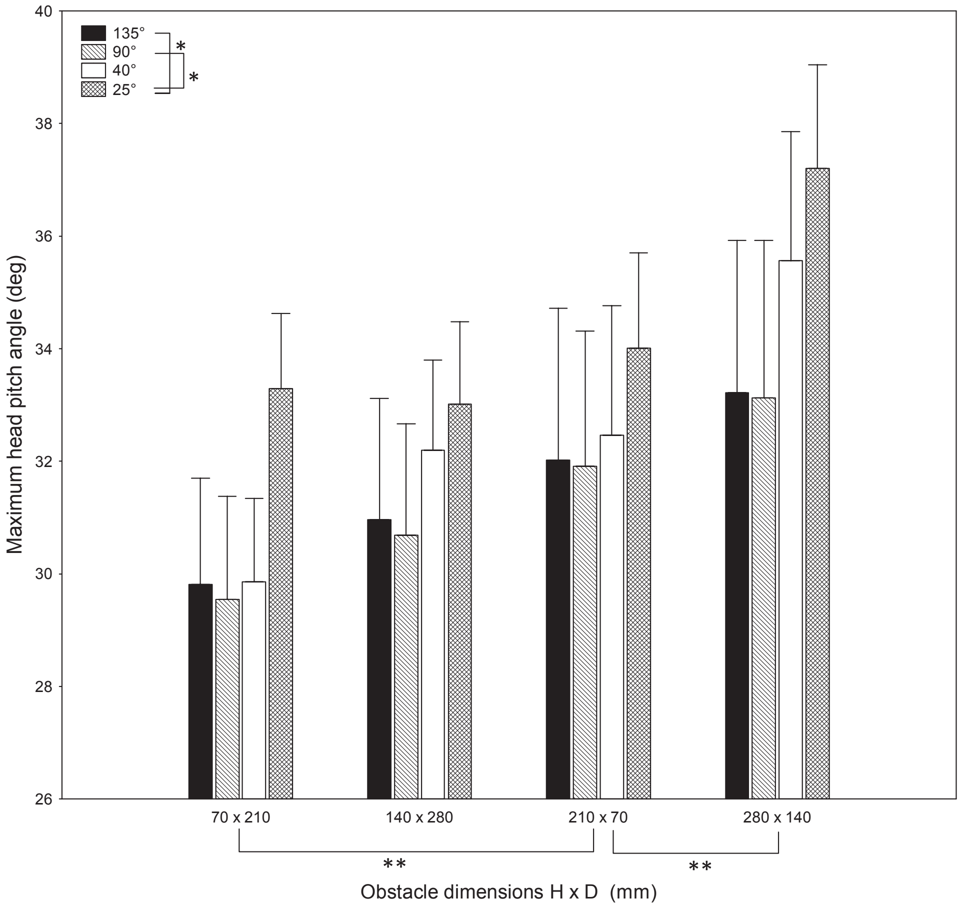


Figure 4.6: Maximum head pitch angle as a function of viewing condition and obstacle type. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$), and ***($p < .001$). Error bars represent standard error.

4.3.4 Average speed

Decreasing the vertical viewing angle resulted in a decrease in average speed, $F(3,33) = 5.934, p < .01$. Specifically, the smallest angle (i.e., 25°) caused slower movement than any of the other conditions ($p < .01$). Additionally, there was an effect of obstacle type on speed, $F(3,33) = 42.643, p < .001$. All conditions differed from each other except the $70x210mm$ and $140x280mm$ configurations ($p = .15$, for all others $p < .01$). Figure 4.7 shows the data. Overall, speed was decreased for the third trial as compared to the second, $F(1,11) = 10.505, p < .01$. Moreover, an interaction effect was found between viewing condition and trial number, $F(3,33) = 4.440, p < .001$. For viewing angles 135°, 40°, and 25°, the third trial was slower than the second one. However, for the 90° condition the opposite was true. Furthermore, no interaction effect between viewing condition and obstacle type was found.

4.4 Discussion

The results of this study indicate that restriction of the vertical viewing angle affected lower body kinematics during obstacle crossing. Specifically, decreasing the vertical viewing angle affected step length and lead limb clearance in a similar manner. Unrestricted (i.e., with a 135° view), participants crossed the obstacle at a preferred speed while employing the lower limb kinematics that they favoured. When confronted with an intermediate (40°–90°) view, step length and lead limb clearance increased. Likewise, with a 25° view, the smallest visual angle tested here, step length and lead limb clearance increased even more. Investigation of the average speed during obstacle crossing revealed that only the smallest visual angle resulted in a decreased speed. This finding is in accordance with previous work (Jansen et al., 2010) showing that a vertical viewing angle of 25° yielded decreased speed during traversal of an obstacle course as compared with larger angles.

With an unrestricted view, there is a minimal risk of tripping. Therefore, it is likely that priority is given to minimize energy expenditure and maximise time efficiency. Applying such a strategy resulted in small lead limb clearance and step length while moving at a preferred speed. When performing the obstacle-crossing task with an intermediate vertical angle (40°–90°), the decrease in visual information from the lower visual field caused the lead limb and obstacle to be invisible during the actual crossing of the obstacle. This may pose a threat to safety because possible perturbations in the limb trajectory (caused by misperception of obstacle dimensions and position as well as

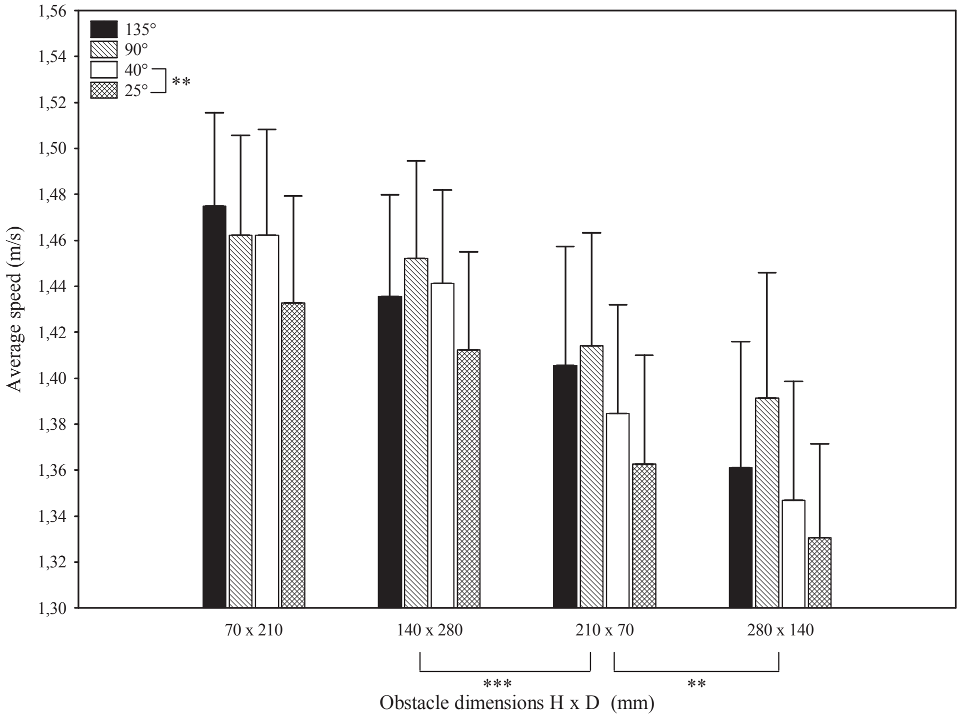


Figure 4.7: Maximum head pitch angle as a function of viewing condition and obstacle type. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$), and ***($p < .001$). Error bars represent standard error.

balancing problems) cannot be perceived and therefore acted on. As a result, it seems the strategy was altered to give priority to the prevention of tripping instead of the minimisation of energy and time. As a consequence, step length and toe clearance increased.

Surprisingly, under these viewing conditions the average speed remained unaltered. Moreover, when confronted with the smallest visual angle (i.e., 25°), safety became even more compromised. This resulted in further increases in step length and lead limb clearance. In this case, however, the average speed was also altered. This can be explained as the increased priority of safety at the cost of energy and time considerations. Judging from the results, it seems that for a simple obstacle-crossing task, walking with the preferred speed has priority over energy conservation. This is concluded from the observation that the latter was sacrificed first as a consequence of compromised safety and a decrease in speed was only observed after additional reduction of the vertical viewing angle.

As a result of vertical viewing restriction, trail limb clearance increased in a similar manner to that of the lead limb. This is in accordance with previous findings, which show a correlation between the elevation of both limbs when there is no online visual information available (Patla et al., 2004). However, under full cue conditions, lead and trail limb have been shown to be independently controlled (Patla, Rietdyk, Martin, & Prentice, 1996). The fact that viewing restriction modulates trail limb clearance is interesting because the trail limb is never visible during obstacle crossing. Therefore, the increased clearance cannot be the result of impaired vision of the limb during execution of the manoeuvre. Instead, it seems that the overall strategy to prioritise safety over energy conservation and time efficiency is a holistic approach.

When looking at the maximum head pitch angle, we saw an increase in pitch as a result of vertical viewing restriction. But significant differences were only found between the smallest viewing angle (i.e., 25°) and both 90° and 135°. This indicated that a vertical angle of 40° was sufficient to update information regarding the body relative to the obstacle position, and there was no need for extensive head pitch movement in the approach phase. Only when the angle is very small is there a need for increased downward pitch movement during the approach phase. Furthermore, during none of the restricted viewing angles was the lead limb visible during obstacle crossing. The increase in downward pitch seen with smaller angles did not change this. Instead, we argue that the increase in toe clearance and step length is a way of ensuring safety when there is no visual information concerning the obstacle and the lead limb during obstacle crossing.

Surprisingly, we found that average speed and maximum head pitch angle differed between the two trials analysed for each condition. The later trial yielded slower movement and increased pitch compared with the earlier one. We do not have a good explanation for these sequence effects. Also, we did not find similar results for the other dependent variables. Future studies should examine if this sequence effect is caused by something like fatigue, which is in itself an interesting manipulation to investigate in light of strategy changes.

When discussing the influence of obstacle type, it should be noted that the dimensions were not manipulated independently (height covaries with depth); therefore, it is not possible to draw inferences concerning either height or depth. Nevertheless, it seems that larger obstacles (in the sense of volume) cause increased toe clearance of both the lead and trail limbs compared to smaller obstacles. Conversely, we found no difference in step length as a result of obstacle type. This is in accordance with previous findings (Chen et al., 1991; Patla & Rietdyk, 1993). Furthermore, it seems that larger obstacles yielded increased head pitch angle and decreased speed compared to smaller obstacles.

In conclusion, our results agree with several studies reporting increased toe clearance and step length combined with decreased speed as a consequence of lower visual field occlusion (Graci et al., 2009, 2010; Marigold & Patla, 2008; Mohagheghi et al., 2004). The important difference is that we investigated several levels of visual field restriction, which enables the observation of shifts in strategy as viewing conditions deteriorate.

It should be noted that the strategy shifts observed here hold only for this specific task and (experimental) conditions. We cannot conclude that other environmental circumstances yield the same strategy shifts. For instance, when the consequence of tripping becomes more severe (e.g., when running), it may very well be that time efficiency is sacrificed immediately as a result of an increased risk of tripping.

Future studies should investigate if the strategy shift found here also holds for other manoeuvring tasks and under other suboptimal conditions. An example of this is the effect of impaired lighting conditions on obstacle avoidance behaviour. Furthermore, it would be useful to investigate if the existence of the 40–90° plateau that we found here can be replicated in other situations. Finally, it would be interesting to investigate how certain predispositions in people or specific instructions alter the strategies used during obstacle avoidance.

Chapter 5

Steering through a multi-obstacle environment

This chapter is based on the following publication:

Jansen S.E.M., Toet A., Werkhoven P.J., (2011) Human locomotion through a multiple obstacle environment: strategy changes as a result of visual field limitation *Experimental Brain Research, Vol. 212, No. 3*, 449-456

This chapter addresses the influence of visual field size on obstacle avoidance behaviour during a steering task. Full-body motion was captured to analyse the kinematics during locomotion through a multiple obstacle environment.

5.1 Introduction

Humans need to walk through structured environments without colliding with any obstacles or parts of that environment. In order to achieve this, there is a constant need for information concerning the surrounding space. Specifically, it is important to know the spatial relations between different parts of an environment (exteroception) to ensure that safe passage is possible. Furthermore, it is essential to have information concerning the position of the body in that environment (exproprioception). Both types of information need to be monitored during locomotion toward a goal. It is possible that distances between parts of the environment are misperceived initially and need to be corrected along the way. Moreover, the positioning of the body in the environment needs constant updating in order to predict and act upon potential future collisions.

Previous research has shown that obstacle size and position can be judged from a distance, while information concerning the position of the body in the environment is updated continuously during adaptive locomotion (Patla & Vickers, 1997). In addition, Mohagheghi and colleagues (Mohagheghi et al., 2004) showed that dynamic sampling (by means of head movement) prior to locomotion was sufficient to ensure safe obstacle crossing in the absence of vision in the approach phase. However, despite succeeding at the task, participants increased their safety margin around the obstacle. Walking through a structured environment requires both steering of the body in a new travel direction and circumvention of obstacles situated in the travel path. Although related, these tasks are not the same. Circumvention requires a transient change in the centre of mass (COM) while maintaining the underlying travel direction. Alternatively, during steering, the COM is guided in a new travel direction (Vallis & McFadyen, 2003). Several studies on steering behaviour reported a systematic sequence of body re-orientations which is initiated by head yaw rotation (Patla, Adkin, & Ballard, 1999; Hollands et al., 2001).

Next to visual cues, both vestibular and proprioceptive information (concerning the orientation of the head with respect to the torso) are important during navigational tasks (Courtine & Schieppati, 2003; Prévost, Yuri, Renato, & Alain, 2003). It is argued that the alignment of the head with the future direction of travel provides the CNS with an allocentric frame of reference (Hollands, Patla, & Vickers, 2002). One important aspect of human locomotion is the need for energy conservation (Saunders et al., 1953; Inman, 1966; Zarrugh, Todd, & Ralston, 1974). Specifically, Donelan and colleagues (2004) propose that the metabolic cost of walking is largely determined by the work performed to redirect the COM and the accompanying mediolateral foot placements that provide stabilisation. They argue that humans prefer a step width that minimises this cost. In addition, Bauby and Kuo (2000) proposed that during unobstructed walking straight ahead, this results in a step width of $0.12L$ (where L is leg length). Moreover, the increase in step width has been associated with postural instability (Gabell & Nayak, 1984). Furthermore, Patla and colleagues (1999) show that when participants are confronted with an undesirable landing area, the dominant choice for an alternative position is the one that requires least adjustment, thereby conserving energy.

In addition to minimising energy expenditure, there is also the concern of safety when negotiating obstacles. Much of the research done on safety during obstacle avoidance involves elderly people. It has been shown that compared with young adults, older subjects exhibit a more conservative gait pattern, characterised by reduced velocity and shorter step length (Menz, Lord, & Fitzpatrick, 2003; Paquette, Fuller, Adkin, & Vallis, 2008). Also, they employ a hip strategy during obstacle circumvention, as opposed to the foot placement strategy shown by younger adults (Paquette & Vallis, 2010). Furthermore, Chapman and Hollands (2007) propose that older adults prone to falling prioritise the planning of future steps over the accurate execution of ongoing movement, which may actually cause accidents instead of preventing them. Because elderly people are confronted with a multitude of risk factors influencing steering behaviour (i.e., impaired vision, deficits to the musculoskeletal system, and impairment of the proprioceptive and vestibular systems), it is difficult to investigate the relation between a single impairing factor and the resulting steering behaviour. Therefore, in this study, we focus solely on the influence of visual field limitation on locomotion through a multi-obstacle environment.

In order to successfully steer through a structured environment, several subtasks (maintaining balance, distance estimation, and heading control) need to be performed correctly. Recently, a comprehensive review was written on the role of peripheral visual cues in the online guidance of locomotion (Marigold, 2008). In previous work, we showed that restriction of the visual field causes impairment on various obstacle avoidance tasks such as circumvention, ducking and crossing (Toet et al., 2008). Specifically, for local obstacle avoidance tasks, we observed that restriction of the vertical viewing angle causes greater performance degradation than that of the horizontal angle (Jansen et al., 2010). Subsequently, in a recent study, we investigated the effects of lower visual field restriction on obstacle crossing behaviour (Jansen, Toet, & Werkhoven, 2011). It seems that compared with an unrestricted viewing condition, an intermediate vertical viewing angle (40°-90°) causes participants to enlarge their safety margin when stepping over an obstacle by increasing toe clearance and step length. However, no change in speed was found. When confronted with a smaller viewing angle (i.e., 25°), perceived safety became even more compromised, resulting in a further enlargement of clearance as well as a decrease in speed. Consequently, it seems that for such an obstacle avoidance task, the size of the visual field has important consequences for the priority of behavioural strategies.

With the present study, we want to investigate whether visual field restriction affects steering in a similar manner as it does obstacle crossing. Using full-body motion capture, we examine the influence of four different visual field sizes on steering behaviour when walking through an environment consisting of multiple obstacles. The results are discussed in terms of changes in priority between several optimisation strategies. Specifically, we want to know whether speed preference has priority over energy conservation considerations as was found during the recently reported obstacle crossing task (Jansen et al., 2011). Furthermore, we are interested in the role of postural balance in this strategy shift. By investigating how step width is affected by visual field size, we gain insight into the postural instability that results from peripheral field loss. In addition, we want to know how head movement is altered as a consequence of visual field limitation. Previous work suggests that a decrease in visual field size causes an increase in the magnitude of head movement, but a decrease in its speed (Wells & Venturino, 1990). This requires additional time which may be provided by a reduction in overall speed of movement. Finally, it is interesting to see if the performance plateau for medium to large visual field sizes found in previous studies (Toet et al., 2008; Jansen et al., 2011), can be replicated here.

5.2 Methods

5.2.1 Participants

The procedures of this study were approved by the TNO internal review board. Twelve paid participants gave informed consent and took part in the experiment. Three of them were excluded from analyses because of incomplete data sets (due to technical problems during the experiment). Eventually, nine participants were included in the analyses (four male) ranging in age from 21 to 59 years ($M = 33.6; SD = 15.3$). All were free of any known neurological or orthopaedic disorders, or any impediments to normal locomotion. As verified by self-report, all participants had normal or corrected-to-normal vision (by use of contact lenses).

5.2.2 Experimental materials

Goggles. Four separate pairs of safety goggles (type Bollé Targa; www.bolle-safety.com) were used to create each of the visual conditions: small (S: 40° x 25°), medium (M: 80° x 60°), large (L: 115° x 90°), and unrestricted visual field (U). Part of the plastic lens was covered with duct tape in such a way that only light from the specified visual field was permitted to enter the eye. Because of variations in facial bone structure, the exact viewing angles differed slightly per participant. However, the within-subjects design of the study ensures correct inference about the relation between visual field size and the performance measures. See the left panel of Fig. 5.1 for an example of the visual field restricting goggles.

Motion capture. Full-body motion was captured using the MVN inertial motion capture system by XSens (Roetenberg et al., 2009). Participants wore a Lycra suit equipped with 17 sensory modules, containing 3d gyroscopes, accelerometers, and magnetometers (see the right panel of Fig. 5.1 for a graphical representation). Furthermore, they wore their own comfortable walking shoes. Using the Xsens software, full-body motion was recorded for each trial (update rate of $100Hz$). A sensor fusion scheme calculated the position, velocity, acceleration, orientation, angular velocity, and angular acceleration of each body segment,with respect to an earth-fixed reference co-ordinate system. The reader is referred to a paper by Roetenberg and colleagues (2009) for a more extensive description of this system. Because of its inertial nature, the MVN system suffers from drift in absolute positioning. Therefore, an optical tracking system was employed as well (WorldViz, 2005). This system returns

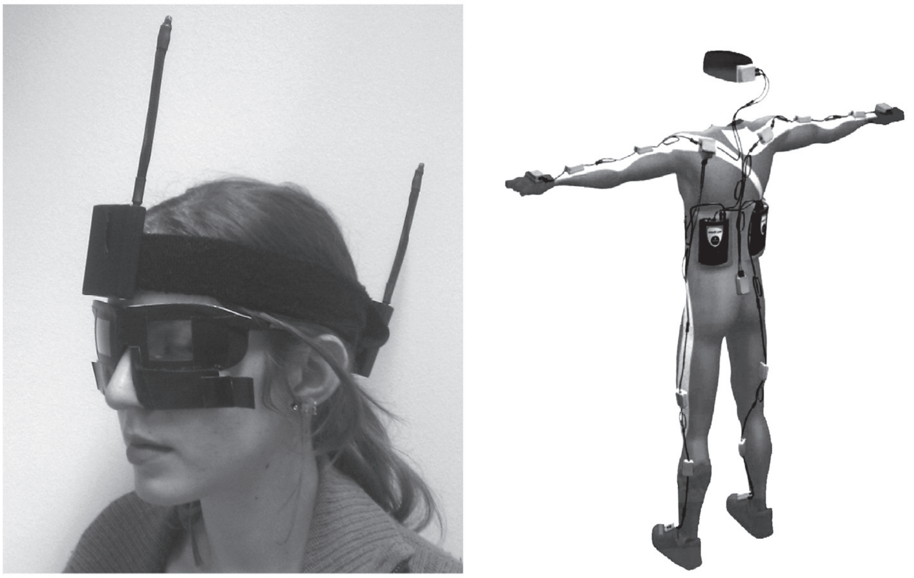


Figure 5.1: Left image showing one of the visual field restricting goggles as well as the optical markers placed on a headband. Right: MVN suit containing inertial sensory modules layout.

the participant's exact position within a global world co-ordinate system by tracking optical markers (update rate of $60Hz$). Participants wore a headband on which two markers were placed, one on the front and one on the back of the head. See the left panel of Fig. 5.1 for a photograph of the optical markers attached to the headband.

The following steps were undertaken to eliminate the absolute drift from the data: First, the inertial data were down-sampled to $60Hz$ to match the optical data. Then, for each trial, we calculated the initial offset between the position of the head as given by MVN and the frontal optical marker. Second, for each frame, yaw and pitch orientation of the head was calculated from the 3d positions of both optical markers. Third, from these orientations and offset, a new head position could be generated. Finally, for each body segment in each frame, a new position was generated by taking the offset between that particular MVN segment and the original MVN head position for that frame and applying it to the new MVN head position.

Environment. The obstacle environment consisted of five open square wooden frames (2000 mm (H) x 2000 mm (W) x 15 mm (D)) placed one behind the other such that participants had to slalom from the start to goal positions in order to avoid collision with the obstacles. Distance between consecutive walls was $1m$. See Fig. 5.2 for a schematic representation of the obstacle environment. The use of open wooden frames prevents occlusion of the markers, thereby enabling optical tracking.

5.2.3 Design and procedures

The four visual field conditions were randomised and performed four times each, resulting in 16 trials per participant. For each condition, the first trial was used to familiarise with each specific condition; only the last three trials were analysed. Prior to execution of the experiment, participants gave informed consent and put on the Lycra sensor suit as well as the optical markers. After this, a calibration procedure was performed, in which the sensor to body alignment and body dimensions were determined for the inertial system. First, body height and foot size were measured. The other dimensions were obtained from regression equations based on anthropometric models (provided by Xsens). Second, matching took place between the orientation of a sensor in the global frame and the known orientation of each segment in the neutral (N) pose. This pose is characterised by standing upright and facing forward with the shoulders above hip, hip above knees, and knees above feet. The feet

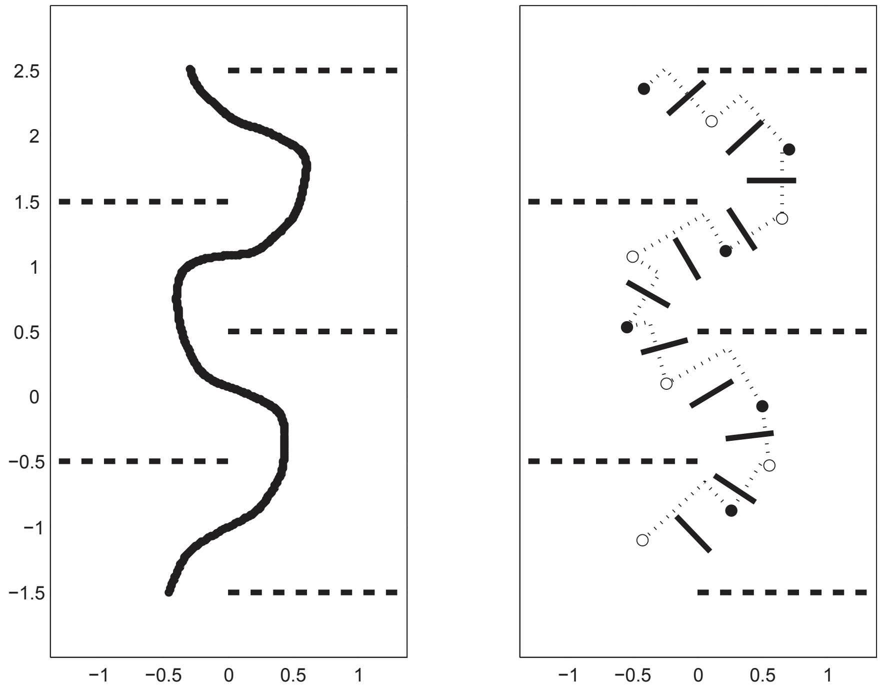


Figure 5.2: Dependent measures for a representative trial with *dashed lines* indicating walls. Left: *bold line* represents the hip trajectory in the transverse plane. From this, pathlength and mean speed were derived. Right: *black and white circles* indicate right and left foot positions, respectively. *Black line segments* represent trunk orientation at each heel strike. *Dotted lines* indicate step length and width based on this orientation.

were placed parallel, one foot width apart. Arms extended besides the body (vertically) with thumbs forward. During each trial, participants wore one of the pairs of goggles and were instructed to walk at a comfortable, self preferred pace from the start to end position while avoiding contact with the walls. All 16 trials were performed consecutively without interruption.

5.2.4 Dependent measures

Matlab (Guide, 1998) was used to analyse the 3D positional data of 23 body segments produced by the inertial motion capture system. The data were filtered using a low-pass second-order Butterworth filter with a cut-off frequency of $6Hz$. For each trial, several kinematic measures were extracted. First, pathlength was defined as the displacement of the pelvis (in mm) in the transverse plane between passing the first and last walls.

Second, mean speed was defined as the length of the path divided by the temporal interval that elapsed between these two moments of passing. In order to deal with differences in preferred speed, this was then normalised to leg length L, defined as the vertical displacement of the hip during upright stance (as given by the MVN system).

Third, proportional step width was defined as the component of the step that is perpendicular to the direction of movement at the moment of heel strike. This was divided by leg length L. Furthermore, the orientation of the trunk at the moment of heel strike was used to define the direction of movement. Mean step width was then calculated per trial as the average proportional step width over all steps within the aforementioned interval. See Fig. 5.2 for a graphical representation of the dependent measures.

Finally, the total magnitude of head rotation and its mean angular velocity were analysed using the position of both optical markers. This was done separately for both the transverse (yaw) and the sagittal planes (pitch). The temporal interval over which these parameters were calculated was defined by the moments of passing the first and fourth walls. We decided on this interval to exclude the downward pitch typically observed at the end of each trial (done to see the 'finish line' taped down on the floor).

5.2.5 Statistical analysis

A four (visual field size) x three (repeated measures) ANOVA was performed for mean speed, pathlength and mean step width. Additionally, a two (rotational direction) x four (visual field size) x three (repeated measures) ANOVA was performed for total magnitude of head rotation and head mean angular speed. Whenever Mauchley's test indicated a violation of the sphericity assumption, a Greenhouse-Geisser correction was applied to the variance analysis as well as a Bonferroni adjustment (instead of Tukey HSD) on the pairwise comparisons (Field, 2009). All analyses were performed with STATISTICA 8.0 (Weiß, 2007), and significance levels for each were set to 5%.

5.3 Results

5.3.1 Pathlength

Visual field size affects pathlength, $F(3, 15) = 56.650, p < .001$. A decrease in size yields an increase in pathlength. Pairwise comparison shows significant differences between all visual field conditions except medium and large (see top panel of Fig. 5.3).

5.3.2 Mean speed

Mean speed of movement is affected by visual field size, $F(3, 15) = 38.405, p < .001$. A decrease in size leads to a decrease in mean speed. Pairwise comparison shows significant differences between the smallest visual field and all others (see bottom panel of Fig. 5.3).

5.3.3 Mean step width

A decrease of visual field size yields an increase in step width, $\mathrm{F}(3, 15) = 3.955, p = .029$. Pairwise comparison shows a significant difference between the smallest and unrestricted visual fields (see Fig. 5.4).

5.3.4 Head movement

Total magnitude of head rotation was greater for yaw than pitch rotation, $F(1, 8) = 62.950, p < .001$. However, this did not vary as a function of visual field size, $F(3, 24) = 0.227, p = .88$. Yaw mean angular speed was higher than pitch mean angular speed $F(1, 8) = 89.379, p < .001$. Also, a significant interaction effect was found for visual field size x rotational direction, $F(3, 24) = 4.299; p = .014$. The size of the field affects head mean angular speed in the yaw, but not in the pitch direction. Pairwise comparison shows a significant difference in yaw rotation between the smallest and both the large and unrestricted field sizes (see Fig. 5.5).

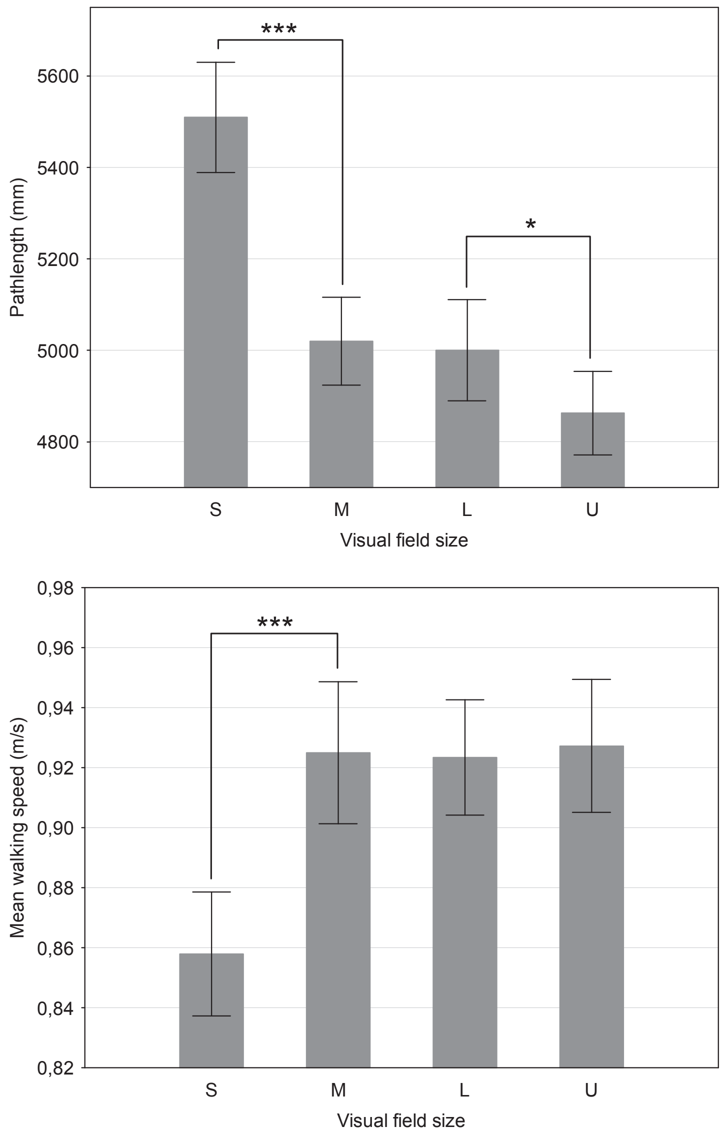


Figure 5.3: Pathlength as traversed by the hip (top) and mean walking speed (bottom) over the interval between passing the first and last walls as a function of visual field size: Small (S: 40° x 25°), Medium (M: 80° x 60°), Large (L: 115° x 90°), and Unrestricted (U). The closest neighbouring significantly different pairs are indicated by *($p < .05$), **($p < .01$) and ***($p < .001$). Error bars represent standard error.

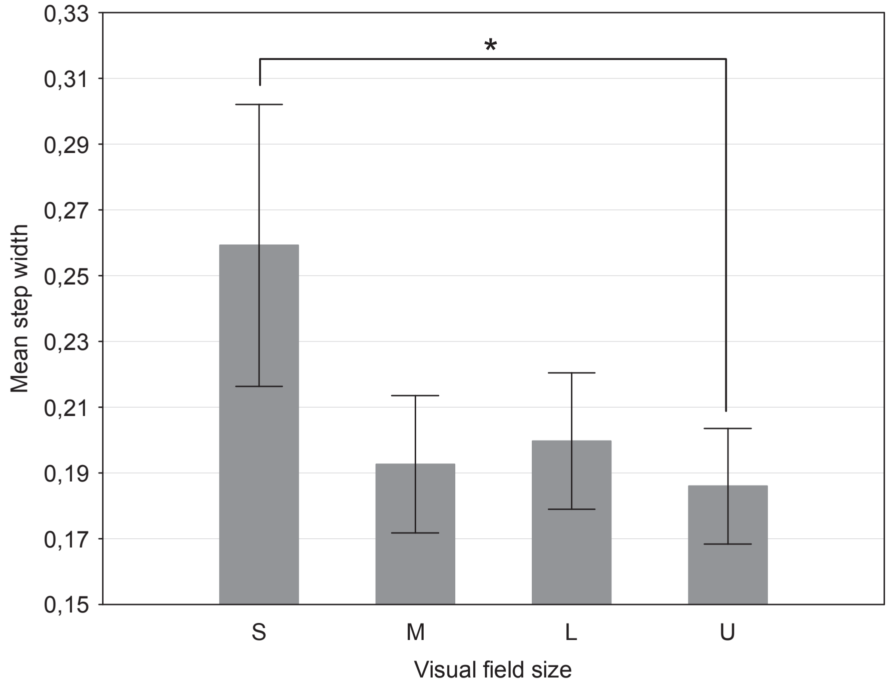


Figure 5.4: Mean step width (proportional to leg length L) as a function of visual field size: Small (S: 40° x 25°), Medium (M: 80° x 60°), Large (L: 115° x 90°), and Unrestricted (U). The closest neighbouring significantly different pairs are indicated by *($p < .05$), **($p < .01$) and ***($p < .001$). Error bars represent standard error.

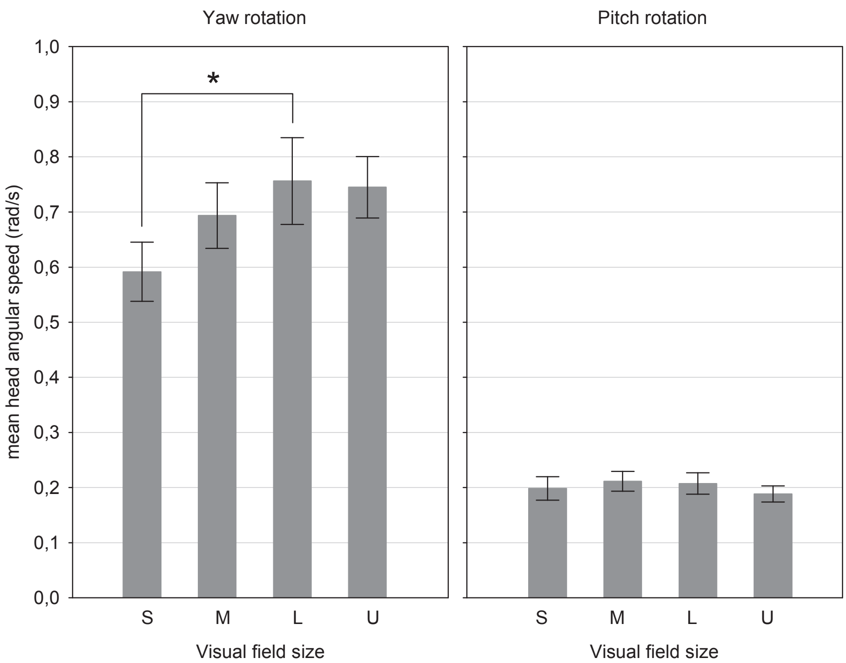


Figure 5.5: Head mean angular speed in the yaw (left panel) and pitch (right panel) direction as a function of visual field size: Small (S: 40° x 25°), Medium (M: 80° x 60°), Large (L: 115° x 90°), and Unrestricted (U). The closest neighbouring significantly different pairs are indicated by *($p < .05$), **($p < .01$) and ***($p < .001$). Error bars represent standard error.

5.4 Discussion

The current study investigated the influence of visual field size on a steering task involving multiple obstacles. The results indicate that restriction of the visual field affects performance. When we take the mean speed and pathlength in the unrestricted condition as a baseline, it is observed that participants move at their desired speed over a path providing them with clearance to the obstacles that permits only small deviation from the planned path. It seems that under these conditions, the perceived threat to safety is minimal and therefore behaviour is governed by energy conservative and time efficient strategies. Next, when the visual field is restricted to a medium–large field size (i.e., 80° x 60° and 115° x 90°), we observed that participants enlarged their safety margin by taking a path that increased their clearance around the obstacles. However, they did not slow down. Finally, when confronted with the smallest visual field (i.e., 40° x 25°), participants did slow down, next to an additional increase in the pathlength.

These observations are in accordance with findings from a recent obstacle crossing study (Jansen et al., 2011), in which we report increased toe clearance when stepping over an obstacle with an intermediate vertical viewing angle (i.e., 40°–90°). With a small angle of 25°, we observed a further increase in clearance as well as decreased speed of movement. As a consequence of the perceived threat to safety, induced by visual field restriction, all participants chose to optimise safety (collision avoidance) at the cost of spending more energy.

We hypothesised that the reduction in speed of movement observed as a consequence of a small visual field may be the result of additional time needed to execute larger but slower head movements. In order to investigate whether this may be the case here, we analysed the total magnitude of head rotation as well as the mean angular speed of the head. The results indicate no effect of visual field size on the total magnitude of head rotation. However, we did observe a decrease in yaw rotation speed for the smallest visual field condition. This decrease in mean rotational speed of the head as a function of reduced visual field is in line with previous work (Wells & Venturino, 1990).

When combining these results with the observed effect of visual field size on walking speed, it seems plausible that participants reduce their walking speed in the S condition in order to execute the slower head movements that are required by such a small field. An alternative explanation for this reduced speed of movement may be that it increases the amount of time to prepare for and execute the bodily movement required to avoid the obstacle. Also, in case of a collision, the impact would be minimised.

An important consequence of visual field restriction is the impairment of balance maintenance (Paulus et al., 1984; Turano et al., 1993), which has been shown to affect step width (Gabell & Nayak, 1984). The present results show that the average step width increased from approximately $0.19L$ in the M, L, and U conditions to $0.26L$ in the S condition, indicating balancing problems. The difference between the mean step width found in the unrestricted condition here and the $0.12L$ reported by Bauby and Kuo (2000) is likely to be explained by the difference between both tasks. They investigated step width during unobstructed walking in a straight line, whereas the task in the present study was to steer through a multiple obstacle environment. The latter requires a constant change in COM direction, which is accompanied by foot placements that enable this redirection. This inevitably enlarges the average step width.

By increasing the width of a step, the base of support becomes wider, preventing increased postural sway to result in a fall. However, this will result in additional energy expenditure (Maxwell Donelan, Kram, Arthur, et al., 2001). Based on the results, we propose that only for the smallest visual field were balance problems substantial enough to warrant this extra cost. Additionally, it seems that the increased length of the travel path as observed in both the M and L conditions cannot be accounted for by balancing problems. Finally, no differences were found between the M and L conditions for each of the dependent variables. This similarity in performance is in accordance with previous studies on obstacle avoidance behaviour under restricted viewing conditions, which reported a similar performance plateau (Toet et al., 2008; Jansen et al., 2011).

It should be noted that the walls used in this experiment do not simulate a closed indoor environment, since they were constructed as open frames to permit tracking of the optical markers. This means that participants could always see the remaining obstacles as well as the goal position. In addition, it should be mentioned that the obstacles were evenly spaced throughout the environment, which does not simulate any specific real world situation. It would be interesting to see if similar behavioural patterns emerge when using opaque walls placed at varying distances.

To summarise the results: we investigated how visual field size affects steering behaviour through a multiple obstacle environment. The results suggest that compared to an unrestricted visual field, an intermediate field size causes participants to select a wider path around the obstacles without slowing down or altering step width. Alternatively, when confronted with a small visual field (i.e., 40° x 25°), participants did slow down and increased their step width in addition to further enlarging their obstacle clearance. Therefore, we conclude that for all visual field limitations, participants chose to optimise safety (collision avoidance) at the cost of spending more energy. However, it seems that only for the smallest viewing condition, safety concerns were substantial enough to warrant the additional metabolic cost associated with increased step width. This precaution may be taken in order to deal with the balance impairment caused by the extensive lack of input from the peripheral visual field. Moreover, we suggest that this change in locomotion characteristics may well be the result of a transition from an energy conservative and time efficient strategy to one that emphasises safety. In addition, it may be that the reduction in speed of movement observed as a consequence of a small visual field is the result of additional time needed to execute a similar magnitude of head rotation, but at a lower speed.

Chapter 6

General Discussion

The first section of this chapter discusses the results from the previous chapters in relation to each other. Following this, the research questions as stated in section 1.5 will be addresses based on these results. In the final section, I will discuss the relevance of this work for several application areas and give some recommendations for future research.

6.1 Discussion of results

6.1.1 Visual field size

Chapter 2 investigated how limitation of the horizontal visual field affects speed and accuracy of locomotion while avoiding collision with obstacles. Two separate experiments were presented in this chapter. Following this, chapter 3 presented a study investigating the role of the vertical visual angle on different obstacle avoidance tasks. All three studies will be discussed here successively.

The first experiment presented in chapter 2 investigated how limitation of the horizontal viewing angle affects speed and accuracy while manoeuvring through a 3-wall setup. Wall-to-wall distance ranged from 60–120 cm and participants were instructed to traverse an S-curved path in order to avoid collision with each of the walls. Task performance was compared for four horizontal viewing angles: 30°, 45°, 60°, and 75°. All were combined with a vertical angle of approximately 48°. These angles were chosen to simulate field sizes typically found in commercially available Head-Mounted Displays (HMDs) and Night Vision Goggles (NVGs).

It was observed that a decrease in horizontal viewing angle caused a decrease in speed of movement. Specifically, the two smallest conditions tested here (i.e., 30° and 45°) caused participants to decrease their walking speed compared to a larger view of 75°. Furthermore, the results indicated that accuracy of movement also decreased as a function of horizontal viewing angle. Accuracy was defined by the deviation from the ideal manoeuvring path, which is the path traversed under the same conditions (wall-to–wall distance and direction of movement), but with full view.

The second experiment of chapter 2 was setup to extend upon the first one. An obstacle course was created presenting participants with both a ducking and a crossing task in addition to the 3-wall setup. This was done to examine the robustness of the findings from the previous study. Furthermore, a wide visual field of 120° x 48° (H x V) was added to the viewing conditions to investigate how this compared to a full view condition.

As expected, it was observed that the extent of the horizontal viewing angle affected speed of movement on the 3-wall manoeuvring task. In addition to this replication, the results showed that time needed to complete the other tasks was affected in a similar manner. Surprisingly, for all three tasks, participants walked with the same speed during the 120° condition as with the 75°viewing angle. However, both yielded a substantial speed decrease compared to the full view condition and an increase relative to the smallest viewing angle (30°).

The finding that the size of the visual field causes similar performance degradation for each of the tasks suggests that the effect is robust and not dependent on the nature of the actual movements required to complete the task. In order to successfully complete all of these tasks, one needs to gather information regarding the environment such as the dimensions of the obstacle and its allocentric position (exteroception). In addition, there is a need for constant updating of information concerning the body in relation to the environment (expproprioception). A number of previous studies argued that visual exteroceptive information is used in a feed forward manner to plan a manoeuvre while visual expproprioceptive information is used to fine tune movement during the execution (Patla, 1998; Mohagheghi et al., 2004; Patla & Greig, 2006; Rietdyk & Rhea, 2006a).

To establish the nature of an obstacle (e.g., piece of wood or a dog?) as well as its dimensions and relative position in the environment, a high spatial resolution is necessary. Also, for detection of obstacles that are non–voluminous in nature, such as tripwire, this high level of detail is required. This can only be obtained within the central portion of the visual field. Gaze re–direction during approach is sufficient to sample the environment. Therefore, such exteroceptive information gathering is not much affected by loss of peripheral information. (Knapp & Loomis, 2004; Wu et al., 2004; Creem-Regehr et al., 2005).

On the other hand, the visual expproprioceptive information gathering is affected more severely by limitation of the visual field. After all, small viewing angles prevent capturing the body and obstacle in a single gaze. Dependent on the severity of the limitation, extensive head movements are necessary to make sure there is sufficient clearance between the body and the obstacle. These compensatory head movements require additional time resulting in the observed decrease in speed as a function of horizontal viewing angle. An additional advantage of decreasing the speed of movement is that in case of a collision, impact is reduced.

The unexpected lack in performance improvement for the wide viewing condition of 120° x 48° (H x V) compared to 75° condition justifies a systematic inquiry of the vertical viewing angle and its effect on obstacle avoidance behaviour. In addition, it would be interesting to test the hypothesis concerning extensive head movements as a cause for speed reduction. Chapter 3 described the experiment performed to address these issues.

By employing a full factorial design with four horizontal angles and five vertical ones, it was possible to investigate how both affected obstacle avoidance behaviour independently. The tasks adopted in this experiment were similar to the ones described in the second experiment of chapter 2. The results show that both the horizontal and vertical angles affect speed of movement during obstacle avoidance tasks. However, increase of the vertical angle results in greater performance improvement than increase of the horizontal angle. Specifically, with an unlimited vertical angle, full view performance is reached when it is combined with a horizontal angle of 80°. Widening the visual field beyond that does not improve performance. On the other hand, it seems that enlargement of the vertical angle continues to increase walking speed, meaning that a larger vertical angle is always better than a smaller one. This last claim is not proven statistically, but the data do suggest this to be the case. Further investigation is needed to confirm this.

A second hypothesis stated that participants would compensate for the limitation of their visual field by making extensive head movements. More specifically, it was expected that a decrease of the horizontal angle would cause an increase of the extent of yaw rotation of the head, while reduction of the vertical angle would result in increased pitch rotation. The results indicate that a horizontal restriction does not affect head movement, but a vertical restriction does. During the 3-wall task and the obstacle crossing task, total pitch rotation increased as the vertical viewing angle decreased. Both these tasks require correct egocentric distance estimation. This can be obtained by utilising what is called the ground surface integration theory, which states that visually scanning the ground surface between an observer and object yields accurate distance estimation (Wu et al., 2004).

When relating these results to the findings from the experiments presented in chapter 2, it does not seem plausible that the speed decreases observed as a consequence of narrowing the visual field were caused by extensive head movements. Other known effects of visual field limitation such as balance impairment (Turano et al., 1993) and reduced magnitude of optic flow (Warren et al., 2001) need to be investigated. Furthermore, it would be interesting to investigate how body kinematics, such as step length and toe clearance, are affected as a function of visual field size. Full-body motion capture would be very interesting in that respect.

6.1.2 Strategy changes

Chapters 4 and 5 describe experiments that investigate how visual field limitation affects an obstacle crossing and steering task respectively. Using full body motion capture, body kinematics were analysed. The results will be discussed here in terms of higher order strategy changes, such as efficiency and safety.

The results of chapter 4 indicate that the extent of the vertical viewing angle affects lower body kinematics and speed of movement during obstacle crossing. Specifically, decreasing the vertical viewing angle affected step length and toe clearance (both lead and trail limb) in a similar manner. Compared to the full view condition, participants increased step length and toe clearance when confronted with intermediate vertical angles of 40°–90°. Furthermore, limitation to 25° yielded even further enlargement of each of these clearance measures. In addition, it was observed that such a narrow view resulted in reduced speed of movement. Such a reduction was not observed for the intermediate angles.

Under full view conditions, it seems that behaviour is governed by an energy efficiency strategy. Participants walk at their preferred speed and maintain a relative small safety clearance around the obstacle. With a fairly large angle of 90°, already part of the lower visual field is occluded. This impairs visual feedback of the lower limbs and the obstacle and it is suggested that this threat to safety causes participants to increase clearance. However, this does not affect the speed of movement. When confronted with a narrow view of 25°, safety became even more threatened resulting in further increases in step length and lead limb clearance. In addition, speed of movement decreased.

As a result of vertical viewing restriction, trail limb clearance increased in a similar manner to that of the lead limb. This is in accordance with previous findings, which show a correlation between the elevation of both limbs when there is no online visual information available (Patla et al., 2004). However, under full cue conditions, lead and trail limb have been shown to be independently controlled (Patla et al., 1996). It is interesting to observe that trail limb clearance is modulated by viewing limitation, because the trail limb is never visible during obstacle crossing and feedback relies solely on proprioceptive information from the muscles and joints. Therefore, impaired vision of the limb does not seem to be the direct cause of the observed increase in clearance. Instead, it seems that the overall strategy to prioritize safety over energy conservation and time efficiency is a holistic approach.

These results agree with previous studies on visual field limitation and obstacle crossing (Graci et al., 2009, 2010; Marigold & Patla, 2008; Mohagheghi et al., 2004). This study investigated several levels of lower visual field occlusion, which enables the observation of shifts in strategy as viewing conditions deteriorate. It would be very interesting to see if similar results can be obtained with different avoidance tasks.

The results of chapter 5 suggest that compared with an unrestricted visual field, intermediate field sizes (i.e., 80° x 60° and 115° x 90°) cause participants to select a wider path to increase clearance around the obstacles without slowing down. Alternatively, when confronted with a small visual field (i.e., 40° x 25°), a decrease in speed was observed in addition to further enlargement of the obstacle clearance.

From the results discussed in chapter 3, it was concluded that only vertical angle limitation led to increased magnitude of head rotation and horizontal limitation did not. This time, not only the magnitude of head movements was analysed, but also the rotational speed. The results indicate no effect of visual field size on the total magnitude of head rotation. However, the speed of yaw rotation decreased for the smallest visual field condition. This decrease in mean rotational speed of the head as a function of reduced visual field is in line with previous work (Wells & Venturino, 1990). When combining these results with the observed effect of visual field size on walking speed, it seems plausible that participants reduce their speed when walking with a small visual field in order to execute the slower head movements that are required to process all the small bits of visual information sampled from the environment.

Previous studies have reported that visual field restriction impairs balance maintenance (Paulus et al., 1984; Turano et al., 1993), which has been reported to affect step width (Gabell & Nayak, 1984). By increasing the width of a step, the base of support becomes wider, preventing increased postural sway to result in a fall. However, this will result in additional energy expenditure (Maxwell Donelan et al., 2001). The results of the present study indicate an increase in step width for the smallest visual field size compared to all others. Therefore, it seems that only for the smallest visual field balance problems were substantial enough to warrant this extra cost.

Even though the tasks described in chapter 4 and 5 are quite different, the results are very similar. Both studies showed behavioural changes as a function of severity of visual field limitation. Under full view conditions, there is a minimal threat to safety and therefore it is observed that participants move at their preferred speed while maintaining a small clearance from the obstacle. This was the case for both the crossing and the steering task. It seems that this behaviour is governed mostly by an energy conservative strategy.

When confronted with an intermediate viewing condition, participants in both studies increased their obstacle clearance while maintaining their preferred speed. In the crossing experiment this became evident from the increased toe clearance and step length. During the steering task, a widening of the path around the obstacles was observed. Finally, under very limited viewing conditions, obstacle clearance increased even more. In addition, there was a decrease in speed of movement for both these tasks. It seems there exists a great deal of similarity between these obstacle avoidance tasks concerning the shift in strategy as a result of visual field limitation. The energy conserving strategy is replaced by one based on safety where increased clearance is employed before decreased speed. See Figure 6.1 for an overview of these results.

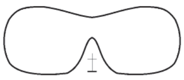
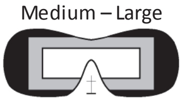
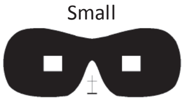
Visual field size	***Strategies***	***Observed behaviour***
Unrestricted 	Energy conservation	• Small clearance • Preferred speed • Preferred step width
Medium – Large 	Safety & Energy conservation	• large clearance • Preferred speed • Preferred step width
Small 	Safety	• Very large clearance • Decreased speed • Increased step width

Figure 6.1: Overview of the effect of visual field limitation on obstacle avoidance behaviour.

6.2 Summary of results

In summary, in this thesis I have presented research concerning visual field limitation and obstacle avoidance behaviour. I will now address the research questions stated in section 1.5 based on these results.

1. *How do limitations of the horizontal and vertical viewing angles affect obstacle avoidance behaviour?*

   First, decreasing the size of the visual field causes impairment of performance on several obstacle avoidance tasks. The finding that the size of the visual field causes similar performance degradation for each of the tasks suggests that the effect is robust and not dependent on the nature of the actual movements required to complete the task.

   Second, there seems to be a performance plateau between a width of 75° and 120°. Even though this is a considerable widening of the visual field, for all obstacles avoidance tasks it was observed that speed of movement did not change between these values. With a more narrow field, speed decreased. With an unlimited view, speed increased.

   Third, by manipulating the horizontal and vertical viewing angle independently, it was possible to examine how each affected performance. It was observed that an enlargement of the vertical angle yields a greater increase in speed compared to a similar enlargement of the horizontal angle.

2. *How does vertical viewing limitation affect body kinematics and strategy changes during an obstacle crossing task?*

   As the viewing angle decreases, participants prefer to maintain speed but enlarge obstacle clearance by increasing toe clearance and step length. However, further decrease of the vertical viewing angle does cause them to slow down in addition to further enlarging clearance.

For all viewing limitations, participants choose to optimise safety at the cost of spending more energy. Furthermore, it seems that walking with the preferred speed has priority over minimising clearance since the latter was sacrificed first as a consequence of compromised safety and a decrease in speed was only observed after further reduction of the vertical viewing angle.

Moreover, modulation of trail limb clearance as a result of visual field limitation is similar to that of the lead limb. Under full-view conditions it has been shown that these are controlled independently. These two observations support the idea of a higher level strategy that affects both limbs similarly.

3. *Can similar strategy changes be found during a steering task and how are head movement and balancing affected by visual field limitation?*

   During the steering task similar strategy changes were observed. As viewing conditions deteriorate, safety becomes increasingly threatened causing participants to first enlarge their clearance before decreasing their speed.

   Furthermore, speed of head movement decreases as the visual field decreases while magnitude of head rotation remains unaltered. It seems that the spatiotemporal integration of small pieces of visual information requires additional processing time compared to larger pieces.

   Also, the increased step width that was observed with a small visual field indicates the presence of balancing problems. Widening the base of support prevents increased postural sway to result in a fall.

6.3 Application areas and future research

The results presented in this thesis contribute to the understanding of human adaptive locomotion under restricted viewing conditions. Several application areas may benefit from such insight. These will be discussed in this section.

One cause for limitation of the visual field can be eye diseases such as retinitis pigmentosa and glaucoma. Although very different in their origin, both can cause progressive peripheral visual field loss. People suffering from these diseases could benefit from such knowledge by learning to explicitly adjust their behaviour so they can move around as safe and efficient as possible. In addition, it is very useful to understand which situations and tasks cause severe problems. They may lead to recommendations concerning the adjustment of the layout of houses and workplaces. For example, based on the results of the current experiments, it seems preferable to increase the distance between different parts of furniture to enable wider passage around each.

An important factor which is not tested explicitly in this thesis, is the effect of habituation and training on adaptive locomotion. Often, in people who suffer from these diseases, the loss of vision occurs gradually over a long period of time. This enables them to prepare for and train to adjust to this. It would be very interesting to investigate how they learn to cope with the limitation at different stages of visual field loss. This could then be used to devise a specific training for people who need to work with hardware that restricts their visual field temporarily.

In addition to involuntary causes such as eye disease, visual field size can also be limited by the use of optical devices. For example, dismounted soldiers performing night-time operations in urban terrain frequently deploy night-vision goggles (NVGs), the visual angle of which is typically 30°–40° (Inc, 2001).

Head Mounted Displays (HMDs) are another example of hardware that severely reduces the visual field. Such devices are used to present an immersive virtual environment to a user. For both of these types of hardware (i.e., NVGs and HMDs) it is very important to know how they affect obstacle avoidance behaviour. This can help to make an informed decision when buying or developing such devices. Based on the present results, it seems preferable to focus mainly on the size of the vertical angle where larger is better. Enlarging the horizontal angle does not improve performance much after 80°. However, note that this is based on tasks performed in indoor structured environments, which may not generalize to open field situations.

The results presented in this thesis may also be of interest outside the community of people (in)voluntarily confronted with a limitation of their visual field. By investigating the (changes in) strategies associated with obstacle avoidance under restricted viewing conditions, this work also contributes to the comprehension of human adaptive locomotion in general. The approach discussed in this thesis may be useful in understanding the changes in human motor strategies during other suboptimal conditions. Examples of these could be environmental aspects such as lighting conditions or surface type, but also factors such as agility and emotional states of the individual performing the task.

One area that could greatly benefit from such insight into human motor behaviour is computer animation. Modern day games and especially the so-called serious games are increasingly dependent on realistic character movement. As a result, visually compelling and natural looking avoidance behaviour has become a necessity in these applications. One way to achieve this is by using motion capture techniques to record human motion and applying this to fully articulated virtual characters (Moeslund & Granum, 2001). This does result in 'natural' moving characters but such an approach is very time consuming and costly. An alternative to this can be to create computational models to drive these movements. In order to create these models there is a need for a thorough understanding of human adaptive locomotion.

Finally, the elderly are another group of people for whom such knowledge can be of great use. Injuries resulting from falls in elderly people are a major public-health concern, representing one of the main causes of longstanding pain, functional impairment, disability, and death in this population (Kannus, Sievänen, Palvanen, Järvinen, & Parkkari, 2005). A better understanding of the risk factors involved in perceptuomotor behaviour could help identify who is at an increased risk of falling. Based on the results in this thesis it may be very useful to include visual field limitation when assessing this. Furthermore, this knowledge could give rise to adequate training to help them locomote more safely. Such training could include skills such as risk assessment of certain manoeuvres and employing strategic gaze behaviour.

References

Alfano, P. L., & Michel, G. F. (1990). Restricting the field of view: Perceptual and performance effects. *Perceptual and Motor Skills*.

Amblard, B., & Carblanc, A. (1980). Role of foveal and peripheral visual information in maintenance of postural equilibrium in man. *Percept Mot Skills*, *51*(3 Pt 1), 903–12.

Anderson, F. C., & Pandy, M. G. (2001). Dynamic optimization of human walking. *Journal of Biomechanical Engineering*, *123*, 381.

Arthur, K. (1996). Effects of field of view on task performance with head-mounted displays. In *Conference companion on human factors in computing systems: common ground* (pp. 29–30).

Arthur, K. W. (2000). *Effects of Field of View on Performance with Head-Mounted Displays.* Unpublished doctoral dissertation, University of North Carolina.

Bauby, C. E., & Kuo, A. D. (2000). Active control of lateral balance in human walking. *Journal of Biomechanics*, *33*(11), 1433–1440.

Black, A. a., Wood, J. M., & Lovie-Kitchin, J. E. (2011). Inferior field loss increases rate of falls in older adults with glaucoma. *Optometry and vision science : official publication of the American Academy of Optometry*, *88*(11), 1275–82.

Chapman, G. J., & Hollands, M. A. (2007). Evidence that older adult fallers prioritise the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & posture*, *26*(1), 59–67.

Chen, H. C., Ashton-Miller, J. A., Alexander, N. B., & Schultz, A. B. (1991). Stepping over obstacles: gait patterns of healthy young and old adults. *Journal of Gerontology*, *46*(6), M196.

Chou, L. S., & Draganich, L. F. (1997). Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. *Journal of biomechanics*, *30*(4), 331–337.

Chou, L. S., & Draganich, L. F. (1998). Placing the trailing foot closer to an obstacle reduces flexion of the hip, knee, and ankle to increase the risk of tripping. *Journal of biomechanics*, *31*(8), 685–691.

Courtine, G., & Schieppati, M. (2003). Human walking along a curved path. i. body trajectory, segment orientation and the effect of vision. *European Journal of Neuroscience*, *18*(1), 177–190.

Creem-Regehr, S. H., Willemsen, P., Gooch, A. A., & Thompson, W. B. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual environments. *Perception*, *34*(2), 191–204.

Dolezal, H. (1982). *Living in a world transformed: Perceptual and performatory adaptation to visual distortion.* Academic Press.

Donelan, J. M., Shipman, D. W., Kram, R., & Kuo, A. D. (2004). Mechanical and metabolic requirements for active lateral stabilization in human walking. *Journal of Biomechanics*, *37*(6), 827–835.

Downton, J. H., & Andrews, K. (1991). Prevalence, characteristics and factors associated with falls among the elderly living at home. *Aging (Milan, Italy)*, *3*(3), 219.

Field, A. (2009). *Discovering statistics using SPSS.* Sage Publications Ltd.

Fortenbaugh, F. C., Hicks, J. C., Hao, L., & Turano, K. A. (2006). High-speed navigators: Using more than what meets the eye. *Journal of Vision*, *6*(5).

Fortenbaugh, F. C., Hicks, J. C., Hao, L., & Turano, K. A. (2007). Losing sight of the bigger picture: Peripheral field loss compresses representations of space. *Vision Research*, *47*(19), 2506–2520.

Gabell, A., & Nayak, U. S. L. (1984). The effect of age on variability in gait. *Journal of Gerontology*, *39*(6), 662.

Gibson, J. J. (1966). The senses considered as perceptual systems.

Graci, V., Elliott, D. B., & Buckley, J. G. (2009). Peripheral visual cues affect minimum-foot-clearance during overground locomotion. *Gait & posture*, *30*(3), 370–374.

Graci, V., Elliott, D. B., & Buckley, J. G. (2010). Utility of peripheral visual cues in planning and controlling adaptive gait. *Optometry & Vision Science*, *87*(1), 21.

Guide, M. U. (1998). The mathworks. *Inc., Natick, MA*, *5*.

He, Z. J., Wu, B., Ooi, T. L., Yarbrough, G., & Wu, J. (2004). Judging egocentric distance on the ground: Occlusion and surface integration. *PERCEPTION-LONDON-*, *33*(7), 789–806.

Henson, D. B. (1993). *Henson (1993) visual fields.* Oxford University Press (Oxford and New York).

Hollands, M., Sorensen, K., & Patla, A. E. (2001). Effects of head immobilization on the coordination and control of head and body reorientation and translation during steering. *Experimental brain research*, *140*(2), 223–233.

Hollands, M. A., Patla, A. E., & Vickers, J. N. (2002). look where youre going!: gaze behaviour associated with maintaining and changing the direction of locomotion. *Experimental Brain Research*, *143*(2), 221–230.

Inc, R. (2001). Minimum operational performance standards for integrated night vision imaging system equipment.

Inman, V. T. (1966). Human locomotion. *Canadian Medical Association Journal*, *94*(20), 1047.

Jansen, S. E. M., Toet, A., & Delleman, N. J. (2010). Restricting the vertical and horizontal extent of the field-of-view: effects on manoeuvring performance. *The Ergonomics Open Journal*, *3*, 19–24.

Jansen, S. E. M., Toet, A., & Werkhoven, P. J. (2011). Obstacle crossing with lower visual field restriction: shifts in strategy. *Journal of motor behavior*, *43*(1), 55.

Kannus, P., Sievänen, H., Palvanen, M., Järvinen, T., & Parkkari, J. (2005). Prevention of falls and consequent injuries in elderly people. *The Lancet*, *366*(9500), 1885–1893.

Kasper, E. F., Haworth, L. A., Szoboszlay, Z. P., King, R. D., & Halmos, Z. L. (1997). Effects of in-flight field-of-view restriction on rotorcraft pilot head movement. *Proceedings of SPIE*, *3058*, 34.

Knapp, J. M., & Loomis, J. M. (2004). Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence: Teleoperators & Virtual Environments*, *13*(5), 572–577.

Latham, R. (1999). Head-mounted display survey. *Real Time Graphics*, *8*(2), 6–13.

Loomis, J. M., Fujita, N., Da Silva, J. A., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance*, *1*(4), 921.

Marigold, D. S. (2008). Role of peripheral visual cues in online visual guidance of locomotion. *Exercise and sport sciences reviews*, *36*(3), 145.

Marigold, D. S., & Patla, A. E. (2008). Visual information from the lower visual field is important for walking across multi-surface terrain. *Experimental Brain Research*, *188*(1), 23–31.

Marigold, D. S., Weerdesteyn, V., Patla, A. E., & Duysens, J. (2007). Keep looking ahead? Re-direction of visual Wxation does not always occur during an unpredictable obstacle avoidance task. *Exp Brain Res*, *176*, 32–42.

Maxwell Donelan, J., Kram, R., Arthur, D., et al.. (2001). Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *268*(1480), 1985.

McFadyen, B. J., & Winter, D. A. (1991). Anticipatory locomotor adjustments during obstructed human walking. *Neurosci Res Commun*, *9*(1), 37–44.

Menz, H. B., Lord, S. R., & Fitzpatrick, R. C. (2003). Age-related differences in walking stability. *Age and Ageing*, *32*(2), 137.

Milner, A. D., & Goodale, M. A. (2006). *The visual brain in action.* Oxford University Press, USA.

Mishkin, M., Ungerleider, L. G., & Macko, K. A. (1983). Object vision and spatial vision: Two cortical pathways. *Trends in neurosciences*, *6*, 414–417.

Moeslund, T. B., & Granum, E. (2001). A survey of computer vision-based human motion capture. *Computer Vision and Image Understanding*, *81*(3), 231–268.

Mohagheghi, A., Moraes, R., & Patla, A. E. (2004). The effects of distant and on-line visual information on the control of approach phase and step over an obstacle during locomotion. *Experimental Brain Research*, *155*(4), 459–468.

Mon-Williams, M., Burgess-Limerick, R., Plooy, A., & Wann, J. (1999). Vertical gaze direction and postural adjustment: An extension of the Heuer model. *Journal of Experimental Psychology, Applied*, *5*, 35–53.

Paquette, M. R., Fuller, J. R., Adkin, A. L., & Vallis, L. A. (2008). Age-related modifications in steering behaviour: effects of base-of-support constraints at the turn point. *Experimental Brain Research*, *190*(1), 1–9.

Paquette, M. R., & Vallis, L. A. (2010). Age-related kinematic changes in late visual-cueing during obstacle circumvention. *Experimental brain research*, *203*(3), 563–574.

Patla, A. E. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & Posture*, *5*(1), 54–69.

Patla, A. E. (1998). How is human gait controlled by vision. *Ecological Psychology*, *10*(3), 287–302.

Patla, A. E., Adkin, A., & Ballard, T. (1999). Online steering: coordination and control of body center of mass, head and body reorientation. *Experimental brain research*, *129*(4), 629–634.

Patla, A. E., Davies, T. C., & Niechwiej, E. (2004). Obstacle avoidance during locomotion using haptic information in normally sighted humans. *Experimental brain research*, *155*(2), 173–185.

Patla, A. E., & Greig, M. (2006). Any way you look at it, successful obstacle negotiation needs visually guided on-line foot placement regulation during the approach phase. *Neuroscience letters*, *397*(1-2), 110–114.

Patla, A. E., Prentice, S. D., Rietdyk, S., Allard, F., & Martin, C. (1999). What guides the selection of alternate foot placement during locomotion in humans. *Experimental brain research*, *128*(4), 441–450.

Patla, A. E., & Rietdyk, S. (1993). Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width. *Gait & Posture*, *1*(1), 45–60.

Patla, A. E., Rietdyk, S., Martin, C., & Prentice, S. (1996). Locomotor patterns of the leading and the trailing limbs as solid and fragile obstacles are stepped over: Some insights into the role of vision during locomotion. *Journal of motor behavior*.

Patla, A. E., & Vickers, J. N. (1997). Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport*, *8*(17), 3661.

Patla, A. E., & Vickers, J. N. (2003a). How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Experimental Brain Research*, *148*(1), 133–138.

Patla, A. E., & Vickers, J. N. (2003b). How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Experimental Brain Research*, *148*(1), 133–138.

Patterson, R., Winterbottom, M. D., & Pierce, B. J. (2006). Perceptual Issues in the Use of Head-Mounted Visual Displays. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *48*(3), 555–573.

Paulus, W. M., Straube, A., & Brandt, T. H. (1984). Visual stabilization of posture. *Brain*, *107*(4), 1143.

Pausch, R., Crea, T., & Conway, M. (1992). A literature survey for virtual environments- military flight simulator visual systems and simulator sickness. *Presence: Teleoperators and Virtual Environments*, *1*(3), 344–363.

Pierrynowski, M. R., Winter, D. A., & Norman, R. W. (1980). Transfers of mechanical energy within the total body and mechanical efficiency during treadmill walking. *Ergonomics*, *23*(2), 147.

Prévost, P., Yuri, I., Renato, G., & Alain, B. (2003). Spatial invariance in anticipatory orienting behaviour during human navigation. *Neuroscience letters*, *339*(3), 243–247.

Psotka, J. (1998). *Effects of field of view on judgements of self-location: Distance estimations using plainview representations as a function of observer eye station points (esp) and geometric field of view (fovg).* (Tech. Rep.). DTIC Document.

Rhea, C. K., & Rietdyk, S. (2007). Visual exteroceptive information provided during obstacle crossing did not modify the lower limb trajectory. *Neuroscience Letters*, *418*(1), 60–65.

Rieser, J. J., Hill, E. W., Talor, C. R., Bradfield, A., & Rosen, S. (1992). Visual experience visual, field size and the development of nonvisual sensitivity to the spatial structure of outdoor neighborhoods explored by walking. *J Exp Psychol Gen*, *121*(2), 210–21.

Rietdyk, S., & Drifmeyer, J. E. (2009). The rough-terrain problem: Accurate foot targeting as a function of visual information regarding target location. *Journal of motor behavior*, *42*(1), 37–48.

Rietdyk, S., & Rhea, C. K. (2006a). Control of adaptive locomotion: effect of visual obstruction and visual cues in the environment. *Experimental brain research*, *169*(2), 272–278.

Rietdyk, S., & Rhea, C. K. (2006b). Control of adaptive locomotion: effect of visual obstruction and visual cues in the environment. *Experimental Brain Research*, *169*(2), 272–278.

Roetenberg, D., Luinge, H., & Slycke, P. (2009). Xsens mvn: Full 6dof human motion tracking using miniature inertial sensors. *Xsens Motion Technologies BV, Tech. Rep.*

Rushton, S., Wen, J., & Allison, R. (2002). Egocentric direction and the visual guidance of robot locomotion background, theory and implementation. In *Biologically motivated computer vision* (pp. 27–36).

Rushton, S. K., Harris, J. M., Lloyd, M. R., & Wann, J. P. (1998). Guidance of locomotion on foot uses perceived target location rather than optic flow. *Current Biology*, *8*(21), 1191–1194.

Sattin, R. W. (1992). Falls among older persons: a public health perspective. *Annual Review of Public Health*, *13*(1), 489–508.

Saunders, J. B., Inman, V. T., & Eberhart, H. D. (1953). The major determinants in normal and pathological gait. *The Journal of bone and joint* *surgery. American volume*, *35*(3), 543.

Spry, P. G. D., et al.. (2001). Senescent changes of the normal visual field: an age-old problem. *Optometry & Vision Science*, *78*(6), 436.

StatSoft, I. (2000). STATISTICA for Windows. *Tulsa, OK*, *1*.

Szoboszlay, Z. P., Haworth, L. A., Reynolds, T. L., Lee, A. G., & Halmos, Z. L. (1995). Effect of field-of-view restriction on rotocraft pilot workload and performance: preliminary results. In *Proceedings of spie* (Vol. 2465, p. 142).

Toet, A., Jansen, S. E. M., & Delleman, N. J. (2007). Effects of field-of-view restrictions on speed and accuracy of manoeuvring. *Percept Mot Skills*, *105*(3 Pt 2), 1245–56.

Toet, A., Jansen, S. E. M., & Delleman, N. J. (2008). Effects of field-of-view restrictions on manoeuvring in a 3-D environment. *Ergonomics*, *51*(3), 385–94.

Toet, A., Van Der Hoeven, M., Kahrimanović, M., & Delleman, N. J. (2008). Effects of field-of-view on human locomotion. *Proceedings of SPIE*, *6955*, 69550H.

Turano, K., Herdman, S., & Dagnelie, G. (1993). Visual stabilization of posture in retinitis pigmentosa and in artificially restricted visual fields. *Invest Ophthalmol Vis Sci*, *34*(10), 3004–10.

Vallis, L. A., & McFadyen, B. J. (2003). Locomotor adjustments for circumvention of an obstacle in the travel path. *Experimental brain research*, *152*(3), 409–414.

Wagenaar, W. A. (1969). Note on the construction of digram-balanced Latin squares. *Psychological Bulletin*, *72*(6), 384–386.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience*, *4*(2), 213.

Waters, R. L., & Mulroy, S. (1999). The energy expenditure of normal and pathologic gait. *Gait & Posture*, *9*(3), 207–231.

Watt, S. J., Bradshaw, M. F., & Rushton, S. K. (2000). Field of view affects reaching, not grasping. *Experimental Brain Research*, *135*(3), 411–416.

Weiß, C. H. (2007). Statsoft, inc., tulsa, ok.: Statistica, version 8. *AStA Advances in Statistical Analysis*, *91*(3), 339–341.

Wells, M. J., & Venturino, M. (1990). Performance and head movements using a helmet-mounted display with different sized fields-of-view. *Optical Engineering*, *29*, 870.

Werner, E. B. (1991). *Manual of Visual Fields.* Churchill Livingstone.

Willemsen, P., Colton, M. B., Creem-Regehr, S. H., & Thompson, W. B. (2009). The effects of head-mounted display mechanical properties and field of view on distance judgments in virtual environments. *ACM Transactions on Applied Perception*, *6*(2).

WorldViz, P. (2005). *3d optical tracker.*

Wu, B., Ooi, T. L., & He, Z. J. (2004). Perceiving distance accurately by a directional process of integrating ground information. *Nature*, *428*(6978), 73–7.

Zarrugh, M. Y., Todd, F. N., & Ralston, H. J. (1974). Optimization of energy expenditure during level walking. *European Journal of Applied Physiology and Occupational Physiology*, *33*(4), 293–306.

Publications

Original publications discussed in this thesis

Jansen S.E.M., Toet, A., Werkhoven, P.J., (2011) Human Locomotion through a Multiple Obstacle Environment: Strategy Changes as a Result of Visual Field Limitation. *Experimental Brain Research, Vol. 212, No. 3*, 449-456

Jansen S.E.M., Toet, A., Werkhoven, P.J., (2011) Obstacle Crossing with Lower Visual Field Restriction: Shifts in Strategy. *Journal of Motor Behavior, 43: 1*, 55-62

Jansen S.E.M., Toet, A., Delleman, N.J., (2010) Restricting the Vertical and Horizontal Extent of the Field-of-View: Effects on Manoeuvring Performance. *The Ergonomics Open Journal, Vol. 3*, 19-24

Toet, A., Jansen S.E.M., Delleman, N.J., (2008) Effects of field-of-view restriction on manoeuvring in a 3-D environment. *Ergonomics, Vol. 51, No. 3, March 2008*, 385-394

Toet, A., Jansen S.E.M., Delleman N.J., (2007) Effects of field-of-view restrictions on speed and accuracy of manoeuvring. *Perceptual and Motor Skills, 2007, 105*, 1245-1256

Original publications not discussed in this thesis

Jansen S.E.M., de Jong, H.J., Toet, A., Werkhoven, P.J., (2011) Walking through Apertures with Visual Field Restriction. *in preparation*

van Basten, B.J.H., Jansen, S.E.M., Karamouzas, I., (2009) Exploiting Motion Capture to Enhance Avoidance Behaviour in Games, in *2nd International Workshop on Motion in Games*, Zeist, The Netherlands, November 21-24, 2009

Jansen, S.E.M. and van Welbergen, H. (2009) Methodologies for the User Evaluation of the Motion of Virtual Humans, in *9th International Conference on Intelligent Virtual Agents*, Amsterdam, the Netherlands, September 10-12, 2009

Samenvatting

Menselijk voortbewegen vindt voor een groot gedeelte plaats in gestructureerde omgevingen. Hierin bevinden zich vaak muren en andere obstakels die ontweken moeten worden. Zowel voor als tijdens het uitvoeren van een ontwijk manoeuvre is er behoefte aan visuele informatie om succesvol een botsing met zo'n obstakel te voorkomen. Op afstand kan door middel van het fixeren van het centrale visuele veld op het obstakel worden vastgesteld om wat voor object het gaat. Hieruit wordt vervolgens ook informatie gewonnen die betrekking heeft op de (mogelijke) beweging van het object. Zo kan een huisdier zich verplaatsen, dit in tegenstelling tot een meubel. Naast het vaststellen van de aard van het obstakel is het van belang om een schatting te maken van zijn dimensies. Deze bepalen in grote mate of het veilig en efficiënt is om er over- dan wel omheen te stappen. Het verkrijgen van deze exteroceptieve informatie vindt zoals gezegd plaats door het centrale visuele veld op het obstakel te richten. Dit gebeurt alvorens een ontwijkmanoeuvre wordt uitgevoerd. Hierbij is dus sprake van feedforward visuele informatieverwerking.

Nadat besloten is hoe een botsing met een obstakel afgewend zal worden, is het van belang om deze manoeuvre zowel veilig als efficiënt uit te voeren. Zodoende is het noodzakelijk om de spatiële relatie tussen het lichaam en het obstakel te monitoren tijdens het uitvoeren van de ontwijkmanoeuvre. Dit maakt het mogelijk om de beweging tijdig aan te passen wanneer de veiligheid in het gedrang komt. Voor deze feedback informatie is het niet noodzakelijk dat het centrale visuele veld gericht is op het obstakel. Het volstaat om de ledematen, grond en het obstakel in het perifere visuele veld waar te nemen.

Echter, er bestaan verschillende oorzaken voor een beperking van het perifere visuele veld. Oogaandoeningen zoals retinitis pigmentosa en glaucoom veroorzaken een graduele afname van het visuele veld. Daarnaast bestaan er apparaten die een gelimiteerd visueel veld aan een gebruiker aanbieden. Voorbeelden van zulke apparaten zijn: Head-Mounted Displays (HMDs) en

Night Vision Goggles (NVGs). Ten slotte zijn er alledaagse situaties die ervoor zorgen dat het gezichtsveld beperkt wordt. Het dragen van een wasmand heeft bijvoorbeeld als effect dat een groot gedeelte van het lagere visuele veld geblokkeerd wordt, waardoor de benen en de grond daar omheen niet zichtbaar zijn. Ook wanneer men een capuchon opheeft zal een gedeelte van het perifere visuele veld geblokkeerd zijn. In dit proefschrift wordt onderzocht wat de invloed is van gezichtsveldbeperking op het ontwijken van obstakels.

In hoofdstuk 2 worden twee experimenten besproken waarbij onderzocht is hoe de grootte van de horizontale kijkhoek invloed heeft op het obstakel ontwijk gedrag tijdens verschillende taken. Experiment 1 toont aan dat tijdens een slalom taak een kleine horizontale hoek (30°–45°) zorgt voor een vermindering van snelheid en accuraatheid van bewegen vergeleken met een hoek van 75°. De verticale hoek was in alle gevallen 45°.

Het daaropvolgende experiment (eveneens beschreven in hoofdstuk 2) toont aan dat bij een verbreding naar 120° de snelheid niet vergroot wordt ten opzichte van de 75° conditie, maar ook niet in de buurt komt van de snelheid onder full-view condities. Naast de slalom taak, is hier gekeken naar het stappen over obstakels op de grond en naar het bukken onder een laaghangende stang door. Het eerder gevonden effect blijkt robuust, aangezien dezelfde relatie tussen horizontale hoek en snelheid van bewegen kan worden aangetoond voor al deze ontwijk taken.

Hoofdstuk 3 beschrijft een studie waarin de invloed van de horizontale en verticale kijkhoek onafhankelijk van elkaar worden geanalyseerd. Het blijkt dat beiden een effect hebben op de snelheid van bewegen tijdens verschillende obstakel-ontwijk taken. Echter, een vergroting van de verticale hoek zorgt voor meer snelheidsverbetering dan eenzelfde vergroting van de horizontale hoek. Daarnaast geeft een ongelimiteerde verticale hoek gecombineerd met een horizontale hoek van 80° een performance die de full-view conditie benadert.

In hoofdstuk 4 wordt een experiment beschreven waarin onderzocht wordt hoe verschillende verticale kijkhoeken (gecombineerd met een ongelimiteerde horizontale kijkhoek) het stappen over obstakels beïnvloeden. Full-body motion capture wordt gebruikt om de stap lengte, toe clearance en snelheid van de beweging te onderzoeken. Het blijkt dat bij een middelgrote kijkhoek (40°–90°) de voeten hoger opgetild en verder van het obstakel geplaatst worden dan in de full-view conditie. Echter, de snelheid waarmee deze manoeuvre wordt uitgevoerd verandert niet bij deze verticale beperking.

Wanneer de verticale hoek verkleind wordt naar 25°, wordt er naast een verdere vergroting van toe clearance en stap lengte wel een snelheidsvermindering waargenomen. In alle gevallen verkiest men veiligheid boven energie efficiëntie. Bij een middelgrote hoek vergroot men de ruimte tussen zichzelf en het obstakel zonder de snelheid aan te passen. Een verder verkleining van de verticale hoek veroorzaakt wel een vermindering in de snelheid, naast een verdere vergroting van de veiligheidsmarge.

Het experiment dat beschreven wordt in hoofdstuk 5 lijkt in opzet erg op dat van hoofdstuk 4. Er wordt gekeken naar de invloed van de grootte van het visuele veld op een aantal kinematische maten tijdens het ontwijken van obstakels. De taak is om door een omgeving te lopen waarin meerdere verticale obstakels staan zonder hiermee in botsing te komen. De resultaten tonen een soortgelijke strategie verandering zoals geobserveerd in het experiment uit hoofdstuk 4: Alleen bij een klein visueel veld wordt de veiligheid dermate bedreigd dat men de snelheid aanpast; bij middelgrote afmetingen van het visuele veld wordt enkel de ruimte tussen het lichaam en de obstakels vergroot.

Om inzicht te krijgen in eventuele balansproblemen als gevolg van gezichtsveldbeperking is er ook gekeken naar de gemiddelde stapbreedte tijdens het uitvoeren van de taak. Hieruit blijkt dat deze enkel toeneemt voor het kleinste visuele veld. Daarnaast heeft de analyse van hoofdbewegingen tijdens deze taak aangetoond dat de bewegingen niet groter zijn, maar wel langzamer worden uitgevoerd. We nemen aan dat de integratie van veel kleine stukjes visuele informatie (als gevolg van een klein visueel veld) meer tijd kost en daardoor een oorzaak zou kunnen zijn voor de geobserveerde snelheidsvermindering tijdens deze conditie.

Het onderzoek dat beschreven wordt in dit proefschrift heeft een aantal mogelijke toepassingsgebieden. Zorg en welzijn is hier één van. Door inzicht in de gevolgen van gezichtsveld beperking op obstakel-ontwijkgedrag kunnen trainingen ontwikkeld en verbeterd worden voor mensen met oogaandoeningen, zodat zij leren zich veilig en efficiënt door gestructureerde omgevingen te bewegen. Ouderen zijn een specifieke groep voor wie het belangrijk is dat vroegtijdig wordt vastgesteld of ze een verhoogd risico lopen om te vallen met alle gevolgen van dien. Kennis van de effecten van gezichtsveld beperking op beweging is daarbij erg belangrijk.

Een ander domein dat zou kunnen profiteren van de opgedane inzichten is dat van virtuele trainingen. De hardware die gebruikt wordt voor dit soort trainingen (HMD) heeft vaak een zeer gelimiteerd visueel veld. De reden hiervoor is optische complexiteit en de daarbij komende gewichts- en kostenverhogingen die gepaard gaan met grotere gezichtsvelden. Het is daarom van groot belang om vast te stellen hoe de grootte van het visuele veld de beweging tijdens een simulatie beïnvloedt. Dit draagt in belangrijke mate bij aan de overdracht van getrainde vaardigheden naar de echte wereld. Met deze kennis is het mogelijk om specifieke hardware te kopen en produceren die voldoet aan de eisen die gesteld worden voor een bepaalde training.

Naast het nut voor deze toepassingsgebieden is het uiterst interessant om meer inzicht te verkrijgen in menselijk bewegingsgedrag in het algemeen. De aanpak zoals die in dit proefschrift is gehanteerd kan nuttig zijn om veranderingen in gedrag tijdens andere suboptimale omstandigheden te analyseren. Voorbeelden hiervan zijn omgevingsfactoren zoals een onregelmatige ondergrond en verminderde licht condities, maar ook persoonlijke factoren zoals behendigheid en emotionele toestand van een individu.

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Curriculum Vitae

Sander Jansen was born in Nieuwegein on the 3rd of September 1983. After finishing high school in 2002 he went on to study at Utrecht University. This resulted in a BSc degree in Psychology in 2005 and a MSc degree in Applied Cognitive Psychology (cum laude) in 2006. His research internship and graduation project took place at TNO Human Factors in Soesterberg. Following his graduation, he spent a year for travel and other relaxing activities. In October 2007, he became a PhD student both at the department of Information and Computing Sciences of Utrecht University, and at TNO Human Factors. Starting November 2011, he works as a postdoctoral researcher in the Physics of Man group of the department of Physics and Astronomy at Utrecht University.