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Effects of field-of-view restriction on manoeuvring in a 3-D environment

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Field-of-view (FOV) restrictions are known to affect human behaviour and to degrade performance for a range of different tasks. However, the relationship between human locomotion performance in complex environments and FOV size is currently not fully known. This paper examined the effects of FOV restrictions on the performance of participants manoeuvring through an obstacle course with horizontal and vertical barriers. All FOV restrictions tested (the horizontal FOV was either 30°, 75° or 120°, while the vertical FOV was always 48°) significantly reduced performance compared to the unrestricted condition. Both the time and the number of footsteps needed to traverse the entire obstacle course increased with a decreasing FOV size. The relationship between FOV restriction and manoeuvring performance that was determined can be used to formulate requirements for FOV restricting devices that are deployed to perform time-limited human locomotion tasks in complex structured environments, such as night-vision goggles and head-mounted displays used in training and entertainment systems.

Keywords: Field-of-view; Manoeuvring; Obstacles; Complex environments

1. Introduction

This study addresses the influence of restrictions of the instantaneous horizontal field of view (FOV) on the performance of participants manoeuvring through a course with horizontal and vertical obstacles. Several studies have shown that FOV restrictions degrade human observer performance for a range of different tasks (Dolezal 1982, van Erp and Padmos 2004, Wade *et al*. 2004, Creem-Regehr *et al*. 2005). However, the relationship between manoeuvring performance and FOV size is currently not fully known.

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Head-mounted displays (HMDs) with FOV limited to 40–70° are frequently deployed in virtual environments for training and rehearsing tasks involving human locomotion through complex environments (e.g. first responder actions, military operations in urban terrain), for the evaluation of designs (e.g. buildings, ships, factories), and for entertainment purposes (gaming). Dismounted soldiers performing night-time operations in urban terrain frequently deploy night-vision goggles (NVG), with FOV that are typically limited to 30–40° (RCTA Inc. 2001). In all these applications, the FOV is considerably smaller than the unrestricted FOV, which has an average horizontal angle of approximately 200° and an average vertical angle of about 135° (Werner 1991). Restricting the human visual field results in a predominant activation of the ventral cortical stream relative to the dorsal stream, which may compromise an observer's ability to control heading or process spatial information (Patterson *et al.* 2006). It has been observed that restrictions of the instantaneous FOV influence distance estimates (Watt *et al.* 2000). For FOV sizes in the order of 40–50°, this effect is not found when head movements are allowed (Knapp and Loomis 2004, Creem-Regehr *et al.* 2005). Even with smaller FOV sizes, observers can still accurately judge absolute distances by scanning the environment from near to far, but not in the reverse direction (Wu *et al.* 2004). Hence, it appears that the effects of instantaneous FOV restrictions can be compensated to some degree through the construction of an 'effective FOV', which can be obtained by sweeping the instantaneous FOV over a larger region of space (i.e. through head movements; Knapp and Loomis 2004). However, peripheral vision, much more than foveal vision, is important in maintenance of postural equilibrium (Amblard and Carblanc 1980, Turano *et al.* 1993). 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 task performance. Increasing the amount of peripheral information by extending the FOV of HMDs and NVG is very costly, reduces their resolution or makes them heavier and therefore less comfortable to wear (Latham 1999). Moreover, in virtual environment applications, wider FOV yield greater sensations of motion sickness (Pausch *et al.* 1992, Psotka and Lewis 1995). To determine a trade-off between human performance, cost and ergonomic aspects, it was necessary to find out how FOV restrictions affect human locomotion through complex structured environments.

The purpose of this study is to investigate the relationship between FOV restriction and human locomotion performance in complex environments. Thereto, the performance of participants manoeuvring through a course containing horizontal and vertical obstacles was studied. To perform this task, the participants needed to make both horizontal (turning) and vertical (ducking and stepping) movements to avoid contact with any of the obstacles. Three different performance measurements were registered per trial: the time to complete the course; the number of errors made; and the number of footsteps needed to traverse the course. While the first two of these dependent variables are clearly direct measures of performance, the third one is an indirect performance measure. In pilot experiments it was observed that participants tend to make larger steps when they feel confident about the placement of their legs.

The hypothesis is that a FOV restriction will decrease human performance in a manoeuvring task through a complex 3-D structured environment. This performance degradation will become manifest as an increase in: (1) the time to complete the course; (2) the number of errors made; (3) the number of footsteps needed to traverse the course.

2. Methods

2.1. *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.

2.2. *Apparatus*

2.2.1. Goggles. To restrict the FOV, two pairs of plastic safety goggles were used, from which the lenses had been removed (figure 1). Horizontal angular FOV sizes 30° and 75° were achieved by fitting opaque cardboard templates with rectangular apertures of different sizes to the first pair of goggles (figure 1a). The second pair of goggles was modified, such that it provided a fixed horizontal angular FOV size of 120° (figure 1b). By design, both pairs of goggles restricted the vertical extent of the FOV to 48°. Monocular conditions were created by placing a blinder in front of one of the eyes.

The (horizontal and vertical) physical aperture size of the templates were determined from the geometry of the environment in which a participant wearing the goggles is standing in front of a vertical office wall, to which two (horizontally or vertically separated) markers are attached, such that the (horizontal or vertical) spatial interval defined by the markers just fits in their FOV.

2.2.2. Obstacle course. The obstacle course was a walled enclosure, consisting of a corridor with four turns (figure 2a). 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 110 cm above the ground, extending across the entire width of the corridor. Participants had to duck underneath the

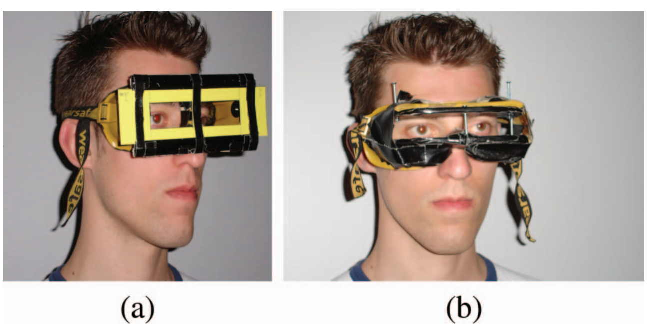

Figure 1. (a) Participant wearing the pair of goggles equipped with field-of-view (FOV)-limiting aperture templates providing horizontal angular FOV sizes of respectively 30° or 75°; (b) participant wearing the modified pair of goggles providing a horizontal angular FOV size of 120°.

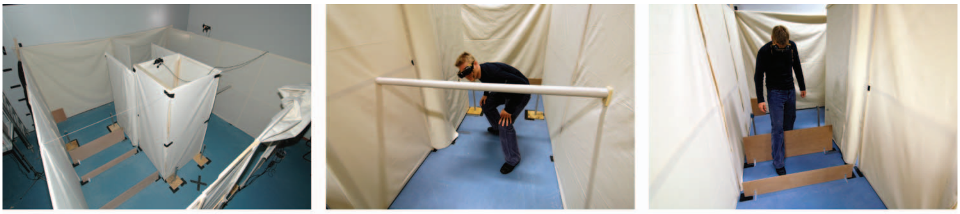
(a) (b) (c)

Figure 2. The test environment. (a) Top view; (b) participant ducking to avoid collision with the hanging obstacle bar; (c) participant stepping over the obstacles on the ground.

bar to avoid bumping into it (figure 2b). 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 (120 cm wide) interval defined by the left sides of the first and the last dividing walls (when passing this obstacle in the clockwise direction: see figure 3). To traverse this segment of the course, participants had to follow an S-curved trajectory through the 60 cm wide passage between each two walls in order to avoid bumping into them.

The third obstacle consisted of three thin wooden boards, with heights of 30, 20 and 40 cm, which were placed in an upright position on the ground, perpendicular to the walls, stretching across the entire width of the corridor (figure 2c). They were designed to tip over if contacted, reducing the possibility of a fall. The board with a height of 20 cm 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.

A future study is planned, in which the present study will be replicated in a virtual environment. The visual structure of the obstacle course was therefore intentionally kept simple and the view of the outside world was blocked by enclosing the course. These measures serve to make it easier to model the whole experimental environment at a later stage in virtual reality.

2.2.3. Time registration. To register the time that the participants needed to traverse each segment of the course, four pairs of poles equipped with infrared 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 infrared 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 these time registrations, both the time needed to traverse each segment of the course and the time needed to traverse the entire course could be computed.

2.2.4. Video registration. All trials were video-taped, using three surveillance cameras (equipped with fish-eye lenses) that were mounted on the ceiling, right above the set-up, looking straight down. The video tapes were used to count the number of steps and the number of errors made by participants.

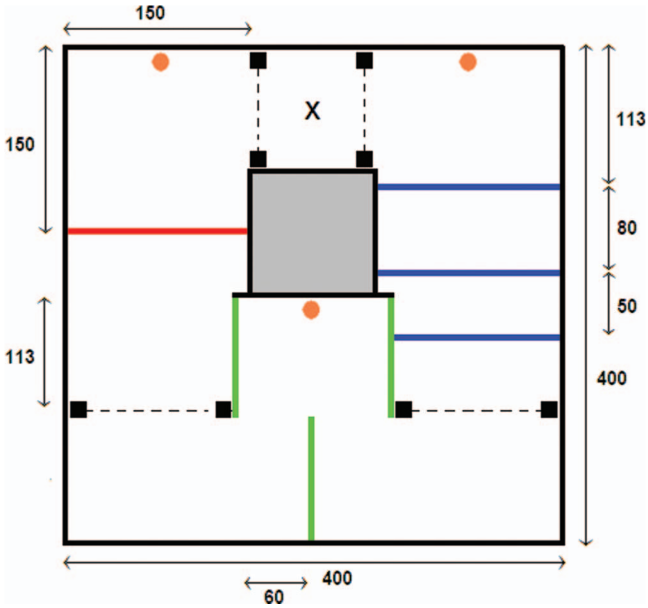

Figure 3. Layout of the environment through which the participants performed the locomotion task. The cross represents the starting point. Square black dots connected by dotted lines represent the detection gateways, which were used to register the time at which the participants passed that particular location. The (orange) circular dots represent the observation cameras that were installed above the set-up. The (red) line segment on the left side of this figure indicates the position of the obstacle bar that was mounted at 110 cm above the ground. The vertical (green) line segments in the lower part of this figure represent three solid walls, consisting of three office room dividing walls. The horizontal (blue) line segments on the right side of this figure represent three parallel and vertically oriented obstacles, consisting of wooden boards that were standing upright on the floor.

2.3. *Design*

A 4 (30°, 75°, 120° and unrestricted FOV) × 2 (monocular and binocular viewing) × 2 (clockwise and counter-clockwise direction of movement) × 3 (repetitions) within-participants design was used. The first two variables were randomized 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.

2.4. *Variables*

Participants' performance in each trial was characterised by three primary measures. First, the average time it took to traverse the entire course was registered, as well as the time required to cross the three segments of the course. Second, using the video tapes, the number of errors made during the traversal of the entire course was counted. The following actions were registered as an error: stumbling and any distinct physical contact of a body part with the environment. Third, again using the video tapes, the number of footsteps needed to complete the entire track was counted.

2.5. *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. This instruction served to keep the error count at a low level.

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, both with one and with two eyes. 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 memorize the entire structure of the environment and needed their attention to perform their task.

2.6. *Data analysis*

Six ANOVA were performed (using STATISTICA 7.0; www.statsoft.com) to compare the FOV (one for each dependent variable; four for time measurements (three course segments and entire course), one for number of errors and one for number of footsteps. All six had the following design: 4 (FOV) $\times$ 2 (clockwise-counter-clockwise) $\times$ 2 (monocular-binocular). Whenever significant effects were found Tukey's HSD post-hoc analysis was used to reveal pairwise differences. For both analyses α was set to 5% (two-tailed).

3. Results

This section will mainly report the significant effects found in the present study.

3.1. *Time to traverse the entire course*

Figure 4 shows the time needed to traverse the entire course as a function of the FOV width. The value plotted at 200° FOV represents the performance with an unrestricted FOV. This value can be adopted as a baseline (represented by the dashed line).

With the smallest FOV size (30°) participants needed significantly more time to traverse the entire course ($p < 0.001$) than with larger FOV sizes. No significant difference was found between FOV sizes of 75° and 120° ($p = 0.998$).

The performance with the unrestricted FOV was significantly better than performance with any of the FOV restrictions tested ($p < 0.001$). Furthermore, manoeuvring through the course in the counter-clockwise direction was faster than manoeuvring in the clockwise direction ($p = 0.026$). No significant difference was found between male and female participants ($p < 0.16$).

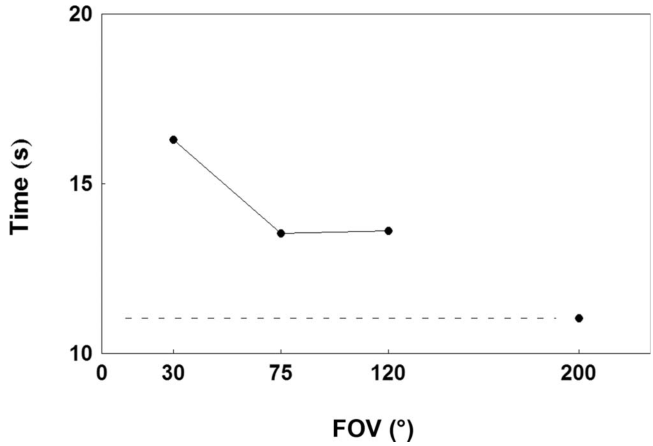

Figure 4. The time needed to traverse the entire course as a function of the field of view (FOV) width. The value plotted at 200° FOV represents the performance with an unrestricted FOV, which can be adopted as a baseline (represented by the dashed line).

3.2. *Time to traverse the 'stepping over' segment*

The effects of FOV restrictions on the time needed to traverse the 'stepping over' segment were significant ($p < 0.001$) and similar to the effects on the time needed to traverse the entire course.

In addition, a significant three-way interaction was found between direction of movement, FOV and mono-/binocular viewing ($p = 0.049$). When manoeuvring with a monocular FOV of 30°, performance decreased substantially more when going clockwise (as compared to counter-clockwise) than with each of the other FOV conditions.

3.3. *Time to traverse the 'avoiding walls' segment*

The effects of FOV restrictions on the time needed to traverse the 'avoiding walls' segment were significant ($p < 0.001$) and similar to the effects on the time needed to traverse the entire course. Also for this segment, manoeuvring with binocular view was faster than manoeuvring with monocular view ($p < 0.001$).

3.4. *Time to traverse the 'ducking' segment*

The effects of FOV restrictions on the time needed to traverse the 'ducking' segment were significant ($p < 0.001$) and similar to the effects on the time needed to traverse the entire course. Also, manoeuvring with binocular view was faster than manoeuvring with monocular view ($p < 0.001$). Manoeuvring through the course in the counter-clockwise direction was faster then manoeuvring in the clockwise direction ($p < 0.001$).

3.5. *Number of footsteps needed to traverse the entire course*

Figure 5 shows the number of footsteps needed to traverse the entire course as a function of the FOV width. The value plotted at 200° FOV represents the performance with an unrestricted FOV. This value can be adopted as a baseline (represented by the dashed line).

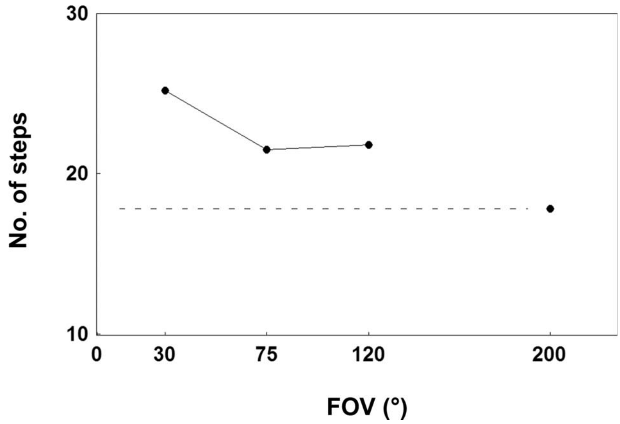

Figure 5. The number of footsteps needed to traverse the entire course as a function of the field of view (FOV) width. The value plotted at 200° FOV represents the performance with an unrestricted FOV, which can be adopted as a baseline (represented by the dashed line).

With the smallest FOV size (30°), participants needed significantly more footsteps to traverse the entire course ($p < 0.001$). Also, participants made significantly less footsteps when manoeuvring with binocular view as compared to manoeuvring with monocular view ($p < 0.001$).

3.6. *Number of errors made in entire course*

No significant effects on error measurement are found for the different viewing conditions.

4. Discussion and conclusions

It was hypothesized that participants manoeuvring with FOV restrictions through an obstacle course would need more time (move at reduced speed), take more footsteps to complete the course and make more errors (such as stumbling over or bumping into obstacles) compared to participants manoeuvring the same course with unrestricted FOV. The results show that FOV restrictions indeed caused participants to move slower on each of the three segments of the obstacle course and take more steps. The FOV of HMDs and NVG that are nowadays commonly used are in the order of the smallest FOV sizes used in the present study (typically not much larger than 40°). Therefore, the present results indicate that the use of these devices may decrease manoeuvring speed in complex environments.

No significant increase in the number of errors for smaller FOV is found. Both the time and the number of footsteps needed to traverse the entire obstacle course are significantly larger compared to the unrestricted FOV condition.

A candidate cause for the observed performance degradation for conditions in which the FOV is restricted may be the fact that loss of peripheral information degrades the maintenance of postural equilibrium (Amblard and Carblanc 1980, Turano *et al.* 1993), which results in a decreased confidence, which may in turn manifest itself in a reduced manoeuvring speed and more footsteps. The current finding that the time needed to traverse the obstacle course increases with decreasing FOV extent agrees with the linear decrease in postural stability, which has been observed with decreasing FOV size (Turano *et al*. 1993).

The finding that FOV 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 (horizontal or vertical).

Visual exteroception (information about the environmental characteristics, e.g. the height of an obstacle) and exproprioception (direct visual information of the body's position relative to the environment) are both important for obstacle avoidance. Visual exproprioceptive information is used to estimate self-position and to fine tune the lower lead limb trajectory during obstacle avoidance (Patla 1998, Mohagheghi *et al*. 2004, Patla and Greig 2006, Rietdyk and Rhea 2006), while visual exteroceptive information is used in a feed forward manner to control the swing limb (Patla *et al*. 1996, Patla 1998, Mohagheghi *et al*. 2004, Patla and Greig 2006). Successful performance in the obstacle-crossing task in this experiment requires correct distance judgements (to keep clear of the walls and the bar and to step over the boards). The environment that was used in this study provided no additional head-obstacle exproprioception cues that could be used to compensate for the obstruction of visual exproprioperception of the lower limbs and the obstacles. 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 and to control their foot placement (Knapp and Loomis 2004, Wu *et al*. 2004, Creem-Regehr *et al*. 2005). However, this study did not explicitly investigate the effect of FOV restrictions on head movements.

Manoeuvring through the obstacle course in the counter-clockwise direction was faster than manoeuvring in the clockwise direction. Analysis of the results for the individual segments of the course shows that this was a result of the extra time needed to traverse the 'stepping over' segment in the course. When manoeuvring through the course in the clockwise direction, the 'stepping over' segment was the first obstacle the participants had to cross, whereas it was the last obstacle they met when going in the counter-clockwise direction. In contrast to the other obstacles, the 'stepping over' segment required careful positioning of the lower limbs. As argued above, in conditions with FOV restrictions this required compensatory head movements to gather sufficient position information. When moving in the counter-clockwise direction, participants probably had more time to adjust to the FOV restrictions and become proficient in making compensatory head movements. When moving in the clockwise direction they were immediately confronted with the 'stepping over' segment and had no time to get adjusted to their FOV limitations.

From an applied perspective, the present findings imply that a FOV restriction will increase the amount of time one needs to move through a complex structured environment. This result can be used to determine a trade-off between human performance and the cost and ergonomic aspects of FOV-restricting devices that are deployed to perform time-limited human locomotion tasks in complex structured environments, such as NVG and HMDs used in training and entertainment systems.

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