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EFFECTS OF FIELD-OF-VIEW RESTRICTIONS ON SPEED AND ACCURACY OF MANOEUVRING [1, 2, 3]

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Summary.—Effects of field-of-view restrictions on the speed and accuracy of participants performing a real-world manoeuvring task through an obstacled environment were investigated. Although field-of-view restrictions are known to affect human behaviour and to degrade performance for a range of different tasks, the relationship between human manoeuvring performance and field-of-view size is not known. This knowledge is essential to evaluate a trade-off between human performance, cost, and ergonomic aspects of field-of-view limiting devises like head-mounted displays and night vision goggles which are frequently deployed for tasks involving human motion through environments with obstacles. In this study the speed and accuracy of movement were measured in 15 participants (8 men, 7 women, 22.9 ± 2.8 yr. of age) traversing a course formed by three wall segments for different field-of-view restrictions. Analysis showed speed decreased linearly with decreasing field-of-view extent, while accuracy was consistently reduced for all restricted field-of-view conditions. Present results may be used to evaluate cost and performance trade-offs for field-of-view restricting devices deployed to perform time-limited human-locomotion tasks in complex structured environments, such as night-vision goggles and head-mounted displays.

Many studies have shown that restrictions in the field of view lead to perceptual and visuomotor performance decrements, both in real and in virtual environments (Dolezal, 1982; Alfano & Michel, 1990; Arthur, 2000; Nash, Edwards, Thompson, & Barfield, 2000; Delleman, 2004; Creem-Regehr, Willemsen, Gooch, & Thompson, 2005; Patterson, Winterbottom, & Pierce, 2006). 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 control of heading or processing of spatial information (Patterson, *et al.*, 2006). The amount of performance degradation depends on the nature of the task. For tasks that require the analysis of spatial detail, such as targeting and object recognition, a field of view as small as 40° may be sufficient to maintain acceptable accuracy. For tasks requiring the analysis of spatial relations and the control of heading during manoeuvring, any field-of-view size less than the unrestricted one may degrade performance accuracy.

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The field of view of most current head-mounted displays and night-vision devises like night-vision goggles is typically 40° to 60° in diameter. This is considerably smaller than the unrestricted human field of view, which has an average horizontal angle of approximately 200° and an average vertical angle of about 135° (Werner, 1991). Increasing the field of view of devices like the above complicates their optical design and increases cost and weight (Latham, 1999). Moreover, in virtual environment applications, wider fields of view yield greater sensations of motion sickness (Pausch, Crea, & Conway, 1992; Psotka & Lewis, 1995). Therefore, one must assess for a given task the trade-off between human performance, cost, and ergonomic aspects. Thereto, one needs to know both the minimum dimensions of the field of view below which performance degrades to unacceptable levels and the maximum dimensions of the field of view over which there is no significant gain in performance (Chevaldonné, Ballaz, Mérienne, Neveu, Chevassus, Guillaume, & Arbez, 2006).

Dismounted soldiers performing nighttime military operations in urban terrain frequently wear field-of-view limiting night-vision goggles. Currently these devices have a field of view with a diameter of typically 40°. Since these operations involve human manoeuvring through confined spaces or environments with obstacles (narrow alleys, corridors, hallways, etc.), it is essential to know how performance is affected by limitation of the visual field. This information is needed to decide how much effort and money should be spent on the design of night-vision goggles with a wider field of view.

Serious gaming is increasingly deployed to train first responders for urban catastrophes. The military increasingly uses virtual environments for mission rehearsal and training of dismounted soldiers. Special locomotion interfaces have been developed to enable users to move "on foot" through virtual spaces much larger than the real space actually enclosing the virtual environment system (Whitton, Cohn, Feasel, Zimmons, Razzaque, Poulton, McLeod, & Brooks, 2006). Many of these applications involve the use of field-of-view limiting head-mounted displays to simulate manoeuvring in confined environments and those with obstacles (Gamberini, Cottone, Spagnolli, Varotto, & Mantovani, 2003). For transfer of training it may be essential that performance in a virtual environment reflects performance in reality. To assess the extent to which performance observed in a virtual environment simulation reflects the corresponding real-world performance, we need to know the effects of field-of-view limitations on human manoeuvring performance. This knowledge is currently lacking (Delleman, 2004; Patterson, *et al.*, 2006).

In this study the effects of field-of-view restrictions on a real-world manoeuvring task through a structured environment were investigated. The environment required the participants to follow an s-shaped path through a narrow corridor. The field of view of participants was restricted by wearing opaque goggles with rectangular apertures of different sizes. It was hypothesized that loss of peripheral visual field information by field-of-view restrictions would degrade an observer's estimation of distances and control heading, resulting in a reduction of the speed and accuracy of movement. The outcome of this study would provide quantitative information for the design, procurement, and application of field-of-view restricting devices like night-vision goggles and head-mounted displays.

Method

Participants

Procedures were approved by the TNO Human Factors internal review board on experiments with human participants. Fifteen paid participants (8 men, 7 women, 22.9 ± 2.8 yr. of age) gave informed consent and participated. All participants reported normal or corrected-to-normal vision.

Apparatus

Goggles.—To restrict field of view, opaque templates with rectangular apertures of different sizes were attached to plastic safety goggles from which the lenses had been removed (Fig. 1). By design, all apertures restricted the vertical extent of the field of view to 48°. Horizontal angular field-of-view sizes were 30°, 45°, 60°, and 75°, respectively. These dimensions correspond to field-of-view sizes typical for commercially available head-mounted displays and night-vision goggles. The dimensions of the frames of the safety goggles did not allow 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). Because the manoeuvring task used in this study involved only the judgment of horizontal distances, an increase was expected in the vertical extent of the field of view that would not significantly influence participants' speed and accuracy. Both monocular and binocular visual-field restrictions were tested, 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 eye. The horizontal and vertical physical aperture sizes of the templates were estimated from the geometry of the situation in which an observer, wearing the goggles fitted with the windows and with 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 the field of view. The angular aperture sizes so constructed differed less than 4° among subjects tested.

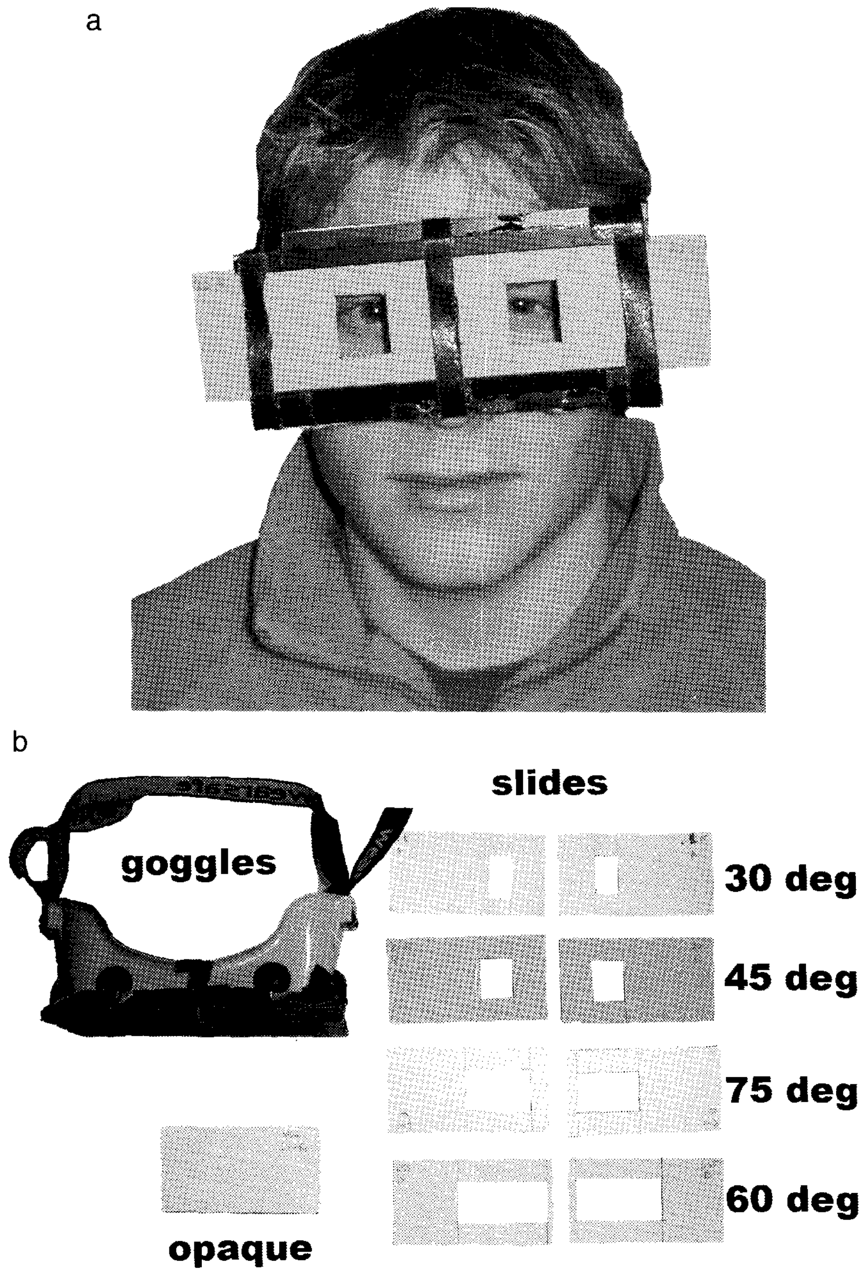

FIG. 1. (a) Participant wearing the goggles equipped with field-of-view limiting aperture templates and (b) top view of the pair of goggles and the set of aperture templates

Task.—The course was constructed with three wall segments for office rooms, placed parallel to one another, 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 Fig. 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 segment, which path required s-curved movement. They then had to retrace their steps, walking strictly backwards, while maintaining the forward-looking orientation. In that condition, they were allowed to turn their heads as much as they needed to look over the shoulder in the direction of their movement. Both forward and backward movement were tested since these conditions are both typical for practical applications. The edges of the three wall segments were placed at a mutual distance of 0.6 m, 0.8 m, or 1.0 m, respectively, resulting in three different widths of the 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 both 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, and to facilitate the simulation of this task in a virtual environment (which will be used in a follow-up study).

Motion-tracking.—A motion-tracking device ("Flock of Birds"[4]) was used to register the displacement of the participants over time. 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 1.8 mm.

Video registration.—All trials were videotaped, using an observation camera 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 which may generate variance in measurements in addition to that related to the independent variables. Also, suspected collisions with a wall segment were confirmed by inspecting the videotape of a specific trial.

Experimental Design and Independent Variables

The setup was a 5 (fields of view) × 3 (wall-to-wall distances) × 2 (forwards-backwards) × 3 (monocular: right, left, and binocular) × 5 (repetitions) within-participants design. The first two variables were randomized across trials using a Latin square design (Wagenaar, 1969).

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[4]http://www.ascension-tech.com/products/flockofbirds.php.

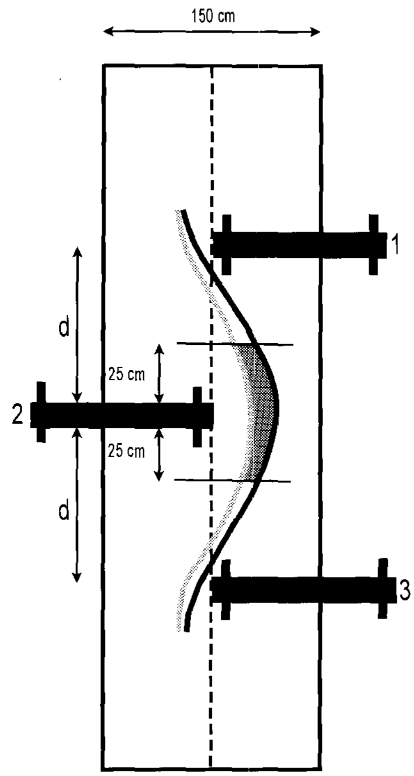

FIG. 2. Schematic representation of the top-view of the setup. The three parallel horizontal line segments (1, 2, and 3) represent the positions of the equidistant wall segments, spaced at a distance d of 60, 80, and 100 cm, respectively. The light-grey curved line segment indicates the path traversed by an observer manoeuvring without field-of-view restrictions and that (black) taken by the same observer in identical conditions but with field-of-view restrictions.

Dependent Variables

The dependent variables were the average speed and the accuracy of movement. The average speed of movement was defined as the ratio of the separation between the first and the third wall segments (in centimeters) and the temporal interval (in sec.) that elapsed between the moments the lower-back sensor passed each of these wall segments. For each participant the ideal manoeuvring line was defined as the path walked by the participant (i.e., traversed by 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 wall 2 (Fig. 2). The ideal line was specified for each participant individually per condition (wall-to-wall distance, monocular-binocular, and forward-backward). Intentionally, the accuracy over a small section surrounding the middle obstacle was calculated to minimise variation due to differences in overall walking strategies.

Procedure

The purpose of the experiment was explained to 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 wall segments. For each condition the track had to be traversed five times, both in the forward and backward directions (i.e., while walking strictly backwards). In each condition the experimenter followed the participant while holding the cords attached to the sensor to prevent the participant from tripping over them. The cords were held very loosely by the experimenter to prevent generating 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 eyes) viewing conditions.

In each condition at least three practice trials were performed before starting the actual data collection. This was done to ensure that participants reached a constant level of performance and to exclude 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 repeated-measures analysis of variance (using STATISTICA 7.0) was performed for speed and accuracy of movement. Whenever significant effects were found, a Tukey *HSD post hoc* analysis was performed to assess pairwise differences. For both analyses, α (two-tailed) was set at 5%. No significant difference was found between the men and women ($p < .16$).

Results

Speed

Field-of-view effects.—Fig. 3 shows the mean speed (in cm/sec.) as a function of the horizontal field-of-view size (in deg). The dashed line in this figure represents a linear fit to the data points (Speed = 0.06 · field-of-view + 53.7; $R^2 = 0.97$). A linear fit to all data points except the unrestricted condition yielded nearly the same result (Speed = 0.07 · field-of-view + 53.0; $R^2 = 0.80$). Field of view had a main effect on average speed: a wider field of view yielded an increase in average speed ($F_{4,32} = 29.43$, $p < .001$). A Tukey *HSD* test showed significant differences between the nonrestricted condition and

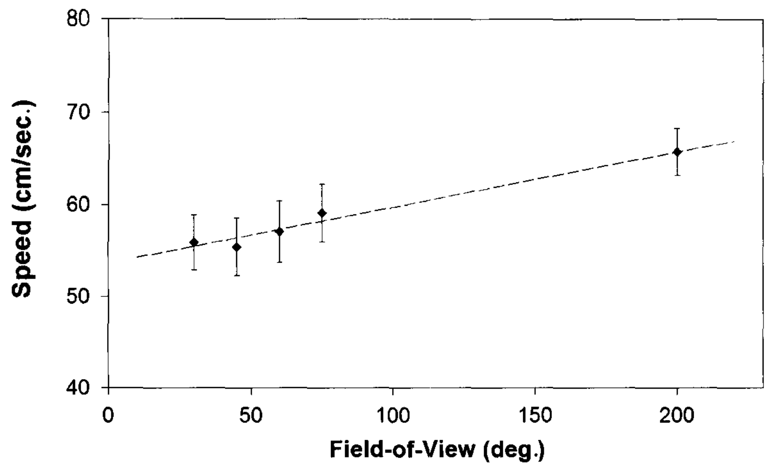

FIG. 3. Mean speed (in cm/sec.) as a function of horizontal field-of-view extent (in degrees) for the unrestricted field-of-view condition using an average horizontal angle of 200° and the linear fit to the data points (– – –)

all restricted conditions as well as significant differences between the least restricted condition (75°) and the two most restricted conditions (30° and 45°; see Table 1). No significant interactions were found between field of view and each of the other variables.

TABLE 1
SIGNIFICANCE OF TUKEY *HSD* TEST COMPARING PAIR-WISE MEANS FOR SPEED AT TWO FIELD-OF-VIEW LEVELS

Field of View		*p*			
Size	*M*	2	3	4	5
1. 30°	55.92	.99	.83	.05	.001
2. 45°	55.43		.56	.02	.001
3. 60°	57.08			.37	.001
4. 75°	59.09				.001
5. Full	65.73				

Wall-to-wall distance.—Wall-to-wall distance had a significant main effect on average speed: a larger wall-segment spacing showed a higher average speed ($F_{2,16}=62.80$, $p<.001$). Table 2 shows the *post hoc* analysis.

Monocular-binocular viewing.—The variable monocular-binocular viewing had a significant main effect on average speed ($F_{2,16}=3.72$, $p=.05$). Table 3 shows the *post hoc* analysis.

Direction.—Forward movement was significantly faster than backward movement, for all conditions tested ($F_{2,8}=79.84$, $p<.001$).

TABLE 2
SIGNIFICANCE OF TUKEY *HSD* TEST COMPARING PAIR-WISE MEANS FOR SPEED IN TWO VIEWING CONDITIONS

Viewing Condition		*p*	
View	*M*	2	3
1. Binocular	59.21	.92	.05
2. Monocular Right	58.98		.11
3. Monocular Left	57.75		

Accuracy

Field-of-view.—The variable field of view had four levels (instead of five when looking at speed) because each restricted condition was compared with the unrestricted condition. Field of view had a main effect on accuracy ($F_{3,33} = 4.12$, $p = .01$). Wider field of view yielded greater accuracy (i.e., less deviation from the non-restricted condition) of movement.

TABLE 3
SIGNIFICANCE OF TUKEY *HSD* TEST COMPARING PAIR-WISE MEANS FOR SPEED AT TWO WALL-TO-WALL DISTANCES

Wall-to-Wall Distance		*p*	
Size	*M*	2	3
1. 60 cm	46.60	.001	.001
2. 80 cm	60.00		.001
3. 100 cm	69.34		

Post hoc analysis indicated significant differences only for the 75° condition versus the 30° and the 60° conditions (see Table 4). No significant interactions were found between field of view and the other variables.

TABLE 4
SIGNIFICANCE OF TUKEY *HSD* TEST COMPARING PAIR-WISE MEANS FOR ACCURACY AT TWO FIELD-OF-VIEW LEVELS

Field of View		*p*		
Size	*M*	2	3	4
1. 30°	301.31	.81	1.00	.03
2. 45°	282.96		.71	.19
3. 60°	304.63			.02
4. 75°	240.88			

Other results.—Wall-to-wall distance had no significant effect on accuracy of movement ($F_{2,22} = 0.57$, $p = .58$). Also, there is no significant effect of monovular vs binocular viewing on accuracy of movement ($F_{2,22} = 2.44$, $p = .11$). However, manoeuvring direction had a significant effect on accuracy: forward movement was more accurate than backward movement ($F_{1,11} = 18.53$, $p < .001$).

Speed vs Accuracy

In the present study, manoeuvring performance is measured as speed and accuracy of movement. When comparing the data sets of both dependent variables a significant correlation was found (Pearson = .19, $p < .001$). The coefficient of determination r^2 was therefore .04. This small but statistically significant correlation indicates that the independent variables affected speed and accuracy in a similar way.

Discussion

Limiting participants' horizontal field of view degraded both speed and accuracy of movement when manoeuvring through an environment with obstacles. Speed of movement appeared to decrease linearly with decreasing field-of-view size. This effect held for several conditions (wall-to-wall distances, monocular viewing, and direction). Participants moved significantly more slowly with field-of-view restriction than without. Accuracy of movement, defined as the deviation from the ideal manoeuvring path (i.e., the path traversed under the same conditions but without field-of-view restriction), was consistently reduced for all restricted field-of-view conditions. A field of view of 75° yielded higher accuracy (less deviation) than the other field-of-view restrictions with the unanticipated exception of 45°. Further research is required to assess the exact nature of the relationship between field-of-view restriction and accuracy.

A likely basis for the observed performance degradation in conditions in which the field of view was restricted was the loss of peripheral visual information, which is important in estimating heading and distances (Patterson, *et al.*, 2006), for the maintenance of postural equilibrium (Amblard & Carblanc, 1980; Dolezal, 1982; Turano, Herdman, & Dagnelie, 1993), and for having correct distance estimates (Watt, Bradshaw, & Rushton, 2000; Fortenbaugh, Hicks, Hao, & Turano, 2007). A large visual field appears essential for construction and maintenance of accurate visual representation of the spatial layout of the environment (Rieser, Hill, Talor, Bradfield, & Rosen, 1992; Fortenbaugh, *et al.*, 2007). It has also been observed that loss of peripheral vision decreases situational awareness, which in turn is associated with decreased confidence (Dolezal, 1982; Alfano & Michel, 1990). Observers tend to compensate for reduction in their instantaneous visual field by making large head movements (Wells & Venturino, 1990; Szoboszlay, Haworth, Reynolds, Lee, & Halmos, 1995; Kasper, Haworth, Szoboszlay, King, & Halmos, 1997; Gallimore, Brannon, & Patterson, 1998). The process of gathering additional visual information about the environment by making compensatory head movements may require additional time, which may in turn be manifest in reduced manoeuvring speed. Inspection of the video recordings of these experiments showed participants made more and larger head movements in conditions with field-of-view restrictions. Further analysis is needed to investigate this effect systematically. The finding that the time required to traverse the obstacle course increased with decreasing extent of field of view also agrees with the linear decrease in postural stability which has been observed with decreasing size of field of view (Turano, *et al.*, 1993). The aforementioned factors may all contribute to the overall reduction in speed and accuracy observed in the present study.

Both task and the environment used in the present study were simple. Further studies with systematic varying of the complexity of both the environment and the task are required to derive guidelines for minimum field-of-view sizes required to keep performance at a constant and acceptable level for a given application and task. From the video recordings of the experiments, participants walking with field-of-view restrictions appeared to adopt systematically different walking styles to compensate for loss of peripheral information. Further analysis is needed for systematic investigation of this effect. Also, the effect of wearing goggles *per se* could influence the locomotion. In the present study, the dimensions of the frames of the safety goggles used did not allow field-of-view sizes larger than 75°. To establish a performance baseline the unrestricted field-of-view condition was tested; in this, participants wore no goggles. In subsequent studies devices must be constructed to allow wider variation of horizontal field-of-view sizes to eliminate a possible confounding.

Together with other 'performance-reducing' effects of virtual environments such as disorientation and spatial memory (Patterson, *et al.*, 2006), field-of-view restrictions constitute a serious impairment for generalization of quantified human performance in a virtual environment to real-world settings. Exactly how close performance in a virtual environment should come to performance in reality with respect to speed and accuracy depends on the specific application. To test operational procedures, for instance, a qualitative evaluation may very well be done with current virtual reality techniques (Delleman, 2004).

The relations between field-of-view restriction and speed and accuracy of manoeuvring performance which were assessed in this study can be used to formulate requirements for devices to restrict field of view which are deployed to perform time-limited human-locomotion tasks within complex structured environments, such as night-vision goggles and head-mounted displays used in training and entertainment systems.

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