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INVESTIGATION OF THE ACCURACY OF SPACE PERCEPTION IN VIRTUAL ENVIRONMENTS

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Abstract

This paper investigates the accuracy and identifies the features of spatial information perception in virtual reality (VR). Virtual environments provide promising solutions for training personnel to manage complex technological objects and situations. This study conducts two full-scale experiments, one in the real world and the other in VR, with subjects estimating distances to objects without reference objects or metric assistance. Results indicate a compression of the immersive virtual environment and show that distances are underestimated in VR compared to the real world. These findings underscore the need for metric support in VR training environments, especially for long distances. This research provides valuable insights for the development of virtual training simulators for transport and technological machine operators.

Keywords: virtual reality, spatial perception, training simulators, distance estimation, metric support, immersive environments, ergonomics.

Introduction

To date, the most crucial direction in engineering psychology and ergonomics is the study of training methods for operational personnel to manage complex technological objects, high-precision robots and manipulators, and actions in emergency situations. A common feature of all these methods is the challenge of reproducing control tasks in the learning process due to the deep integration of an individual into both the process of controlling technological equipment and the environment [1]. For instance, it is not possible to develop and consolidate the professional skills of a logging equipment operator (forwarder) without reproducing the task of controlling technological equipment during log loading under logging operation conditions. A specific problem here is the reproduction of environmental conditions, i.e., creating the effect of operator immersion in the environment corresponding to the control task, and the operator's perception of the environment and the subject of work.

The most promising solution to this problem is the creation of virtual learning environments using three-dimensional technologies, virtual reality, reproducing or simulating physical environments and enabling interaction with them [2]. The widespread use of virtual reality is due to the creation of a sufficiently deep immersion effect without any risks to the environment, patients, technological equipment, or the operator.

Three-dimensional technologies and virtual reality are used to simulate surgical procedures with robotic complexes [3], develop laparoscopic surgery skills for surgeons [4], train dentists [5], test resistance to motion sickness [6], simulate the process of controlling motor vehicles [7], aircraft [8], logging equipment [9], and sports training [10]. It is evident that, in terms of environment and subject of work perception, all these application areas of virtual environments are fundamentally different. In medicine, the primary task of the virtual learning environment is to simulate technological equipment – robotic surgical complexes, instruments, and patient organs and tissues. From the ergonomics and engineering psychology perspective, the environment's influence in such a virtual environment is insignificant, and the virtual environment's working area is the operator's normal hand-working area. However, when creating virtual environments for learning to drive vehicles, control aircraft, or special technological machines, the environment's influence and the accuracy of its perception increase significantly due to the control process's peculiarities. For example, when teaching motor vehicle drivers, it is necessary to simulate the environment and its interaction with the driver and the car, i.e., the driver must perceive spatial information – the relative location of objects in the virtual world, the distance to objects in the virtual world, and the speed and direction of their movement. Moreover, when training logging equipment operators and other technological machine operators, the requirements for perceiving spatial information in virtual environments are even more stringent, as the operator must evaluate space in metric units that are not familiar to human perception – meters, centimeters, inches – and not compare distances with reference objects. Spatial perception and orientation are the most important professional skills for many types of operator activities [11].

Thus, this work aims to investigate the accuracy and identify the features of spatial information perception in virtual reality. This work's peculiarity is that, during the full-scale experiment, the subjects were asked to estimate the distances to objects and between objects in a virtual environment in metric units without the presence of reference objects with known dimensions in the virtual environment.

Theoretical Analysis

The immersion effect is the most important attribute of virtual reality [12]. At the same time, “immersion” is understood as an internal subjective experience, which consists of blocking the perception of the physical world and replacing it with a virtual environment [13]. Researchers often differentiate the concepts of the “immersion” effect and the “presence” effect, noting that "immersion" corresponds to a more emotional, psychological aspect of interaction with virtual environments.

In the work of J. Diemer et al., "presence" refers to the degree to which a user feels present in a virtual reality environment [14]. Descriptive models of presence in a virtual environment focus on distinguishing the components of presence, such as spatial presence, engagement, and reality. Thus, the accuracy of spatial perception can be an objective characteristic of the depth of the presence effect in a virtual environment.

Numerous studies have been dedicated to investigating the accuracy of spatial information perception. In Armbrüster C.'s study, the accuracy of spatial perception was examined by 23 subjects in various virtual environments at distances ranging from 40 to 500 cm, with metric assistance. The results showed that the accuracy of spatial perception in virtual environments was reduced compared to perception in the real world [15]. Moreover, interindividual differences and intraindividual stability were observed among participants, and neither three different virtual environments nor metric assistance improved the depth estimates. Performance evaluation was better in peripheral than extrapersonal space. The accuracy of the estimates increased in a closed room with a visible floor, ceiling, and walls. However, the maximum distance in the virtual environment proposed for perception in this study is 5 meters, which offers valuable insights into the operator's perception of space in and around the peripheral space, but does not provide ideas about the accuracy of perceiving larger distances, more than 15 meters, needed for designing training virtual environments for drivers, pilots, etc.

In a study by Cutting J. E. et al., it is also noted that there are interindividual differences in the perception of spatial information [16]. The heterogeneity of spatial information perception is also highlighted. The authors distinguish the operator's personal space (up to approximately 1.5 m), the action space (from 1.5 to 30 m), and the long-range view (more than 30 m).

In Interrante V.'s study, a relatively high accuracy of spatial perception of the virtual environment by the operator was obtained [17]. The authors conclude that the problem of "compression" of perception in virtual environments may not necessarily be inherent in technology, but may largely stem from higher-level cognitive problems in interpreting the presented visual stimulus. Specifically, the authors achieved relatively high accuracy of information perception without removing the operator from the physical environment, i.e., the physical environment affecting the operator's other senses and the virtual environment visualized to the operator coincided.

In a study by Steinicke F., walking in virtual environments was examined, noting that operators' skills in estimating distances in virtual environments gradually improved [18].

In a study by Willemsen P., it is mentioned that the differences between distance estimates in virtual photographic panoramic environments and virtual visualized environments are small, suggesting that the display device affects distance estimates in virtual environments [19].

In a study by Walch M. [20], with 20 participants using a driving simulator as an example, it was demonstrated that the use of virtual reality could potentially separate participants more from the real world compared to using screens and provide a greater immersion effect. However, the participants experienced more discomfort when using virtual reality devices. The authors conclude that, contrary to expectations, modern virtual reality technologies may not be a better choice than flat screens for driving instruction.

The description of subjective discomfort in virtual reality and postural instability is defined as VR-sickness. It is hypothesized that the neural mechanism of VR-sickness is associated with a mismatch of visual-vestibular information and/or postural instability [21].

Experimental studies

To assess the accuracy of spatial information perception in a virtual environment, a comprehensive experiment consisting of two stages was conducted.

In the first stage, the initial group of 24 subjects was formed to conduct a full-scale experiment in the real world, each assigned a unique number according to the experiment's order. The subjects were selected individuals aged 17 to 24 years who have good health with normal or corrected-to-normal vision using glasses or lenses. This experiment was carried out outdoors in favorable weather conditions during daylight hours (from 13:00 to 15:00), ensuring adequate illumination. The site was prepared in advance for the experiment: five numbered markers were installed, not in a straight line, at distances of 8, 15, 13, 30, and 15 meters. The layout of the markers in a full-scale real-world experiment is shown in Figure 1. The markers are arranged in order from the first to the fifth from left to right. All the markers were of the same size, shape, font, color, and size of the applied serial number.

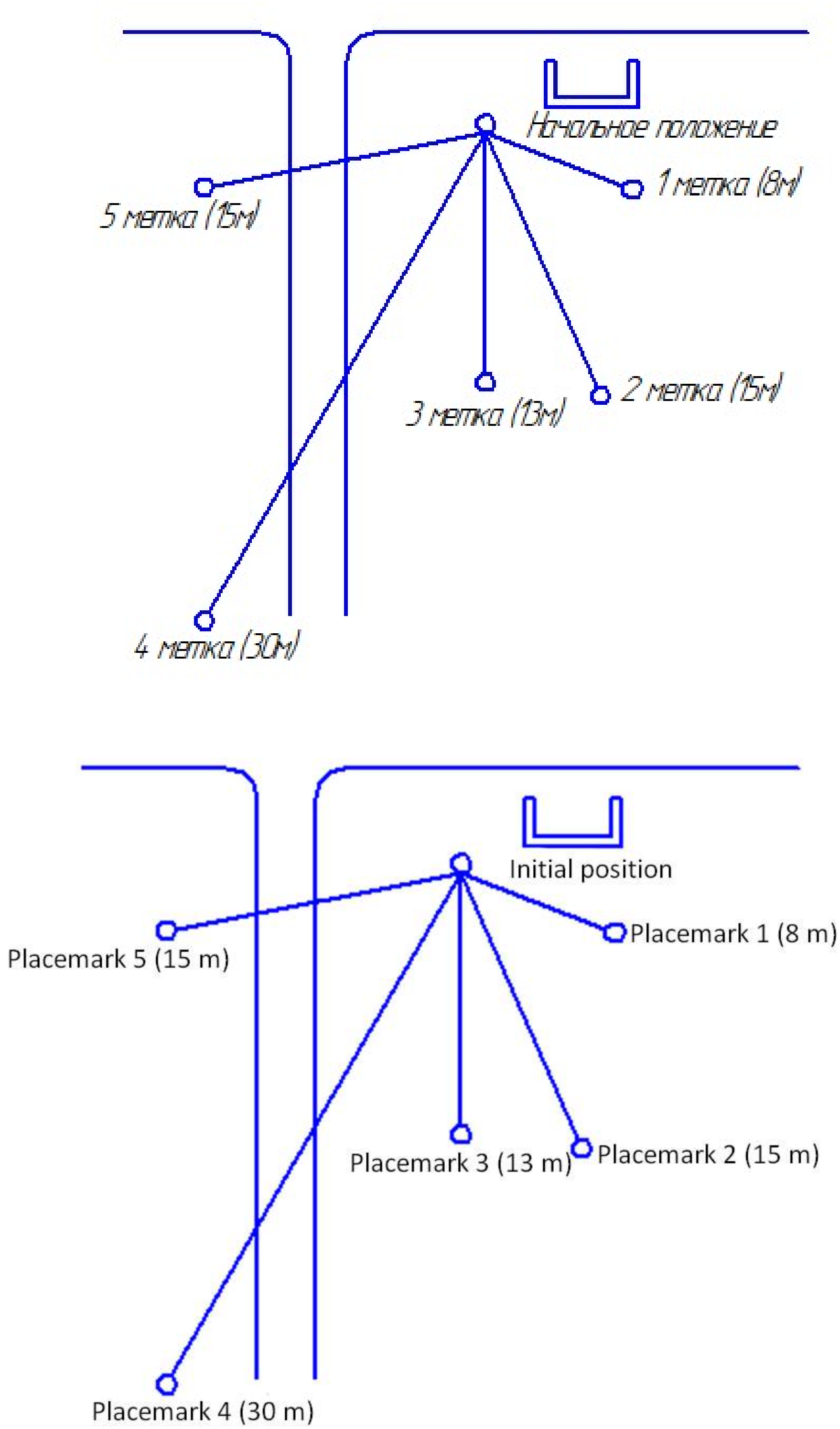


Figure 1 – The layout of the markers in a full-scale real-world experiment

In the second stage, a second group of 26 subjects was formed to conduct a full-scale experiment in virtual reality, each assigned a unique number according to the experiment's order. The experiment was conducted using the HTC Vive virtual reality system, a PC, and specially developed software – a three-dimensional model of the real world, in which testing was carried out at the second stage of the experiment. Figure 2a and Figure 2b show the developed three-dimensional model and a photograph of the real object where the experiments were conducted.

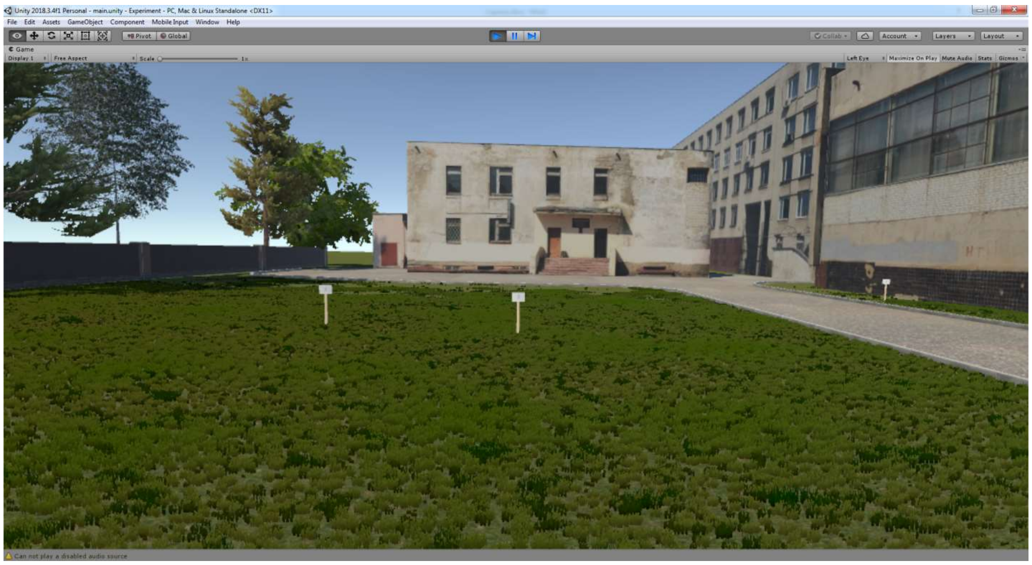


Figure 2a – Three-dimensional model of the object

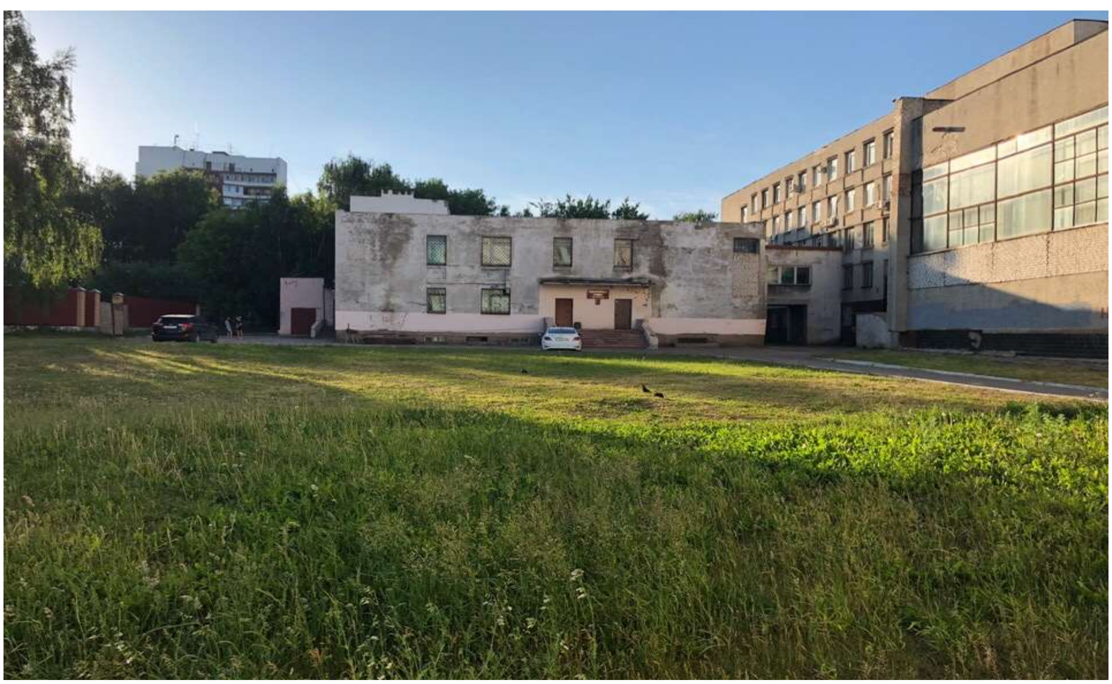


Figure 2b – Photo of a real object

The model in this study has a static nature since there is no need to provide visualization of any process or interaction of the subject with other objects. However, the subject can freely rotate their head in a virtual environment. The experiment was conducted in a laboratory room, meaning there was no impact of the real environment on the subject's senses.

The experiment was carried out in the following sequence:

1. The subjects were divided into two subgroups – control X (full-scale experiment in the real world) and experimental Y (full-scale experiment in virtual reality). The control group included 24 people, and the experimental group included 26 people.
2. A test site with a control subgroup was prepared - five numbered marks were installed (not in a straight line) at distances of 8, 15, 13, 30, and 15 meters.
3. Experiments were conducted individually with the control subgroup following these instructions: "There are five markers in front of you, located from left to right, from the first to the fifth, respectively. Your task is to determine the distances to each of these markers with an accuracy of up to a meter in order from the first to the fifth". The data obtained from the control group X as a result of the full-scale experiment in the real world are presented in Table 1.

No. test	Distance to the placemark				
	1	2	3	4	5
Standard	8 m	15 m	13 m	30 m	15 m
1	5	10	8	15	12
2	5	9	13	20	17
3	6	12	8	30	15
4	9	18	16	50	20
5	6	12	9	30	20
6	8	20	19	35	25
7	8	20	19	35	25
8	8	12	18	35	30
9	8	20	19	30	20
10	8	20	19	30	20
11	9	23	22	45	30
12	7	18	17	26	15
13	4	6	6	11	7
14	5	8	8	14	11
15	5	11	10	22	15
16	6	10	9	25	15
17	7	13	12	32	15
18	4	6	6	25	8
19	4	12	11	65	30

20	6	12	10	27	18
21	6	11	10	27	16
22	6	11	10	47	26
23	5	12	10	25	12
24	7	11	6	22	28

4. Software (virtual environment) was prepared for conducting an experiment with the experimental subgroup – five numbered markers were installed at distances equal to 8, 15, 13, 30, and 15 meters, similar to paragraph 2.

5. Individually, tests were carried out with the experimental subgroup following these instructions: "There are five markers in front of you, located from left to right, from the first to the fifth, respectively. Your task is to determine the distances to each of these markers with an accuracy of up to a meter in order from the first to the fifth." The data obtained as a result of the full-scale experiment in virtual reality conditions of experimental group Y are presented in Table 2.

Table 2 – Obtained data of experimental group Y

No. test	Distance to the placemark				
	1	2	3	4	5
Standard	**8 m**	**15 m**	**13 m**	**30 m**	**15 m**
1	10	20	15	30	13
2	1	5	4	10	6
3	5	16	15	40	15
4	10	40	35	60	45
5	5	8	7	12	6
6	5	15	10	50	15
7	3	6	5	20	7
8	4	9	8	13	7
9	3	4	4	6	7
10	10	25	20	40	25
11	5	13	10	20	10
12	2	4	3	7	4
13	2	1	3	4	5
14	7	3	6	11	12
15	3	6	5	12	6
16	4	7	6	12	9
17	3	7	6	10	6
18	3	6	5	11	5
19	2	5	4	8	5

20	3	6	5	12	6
21	5	15	12	25	15
22	3	10	7	15	10
23	5	10	8	15	7
24	2	3	2	5	3
25	5	10	9	17	8
26	6	9	8	12	10

The final stage involved checking samples of average error values for compliance with the normal distribution law and testing the hypothesis according to the Student's t-criterion.

According to the Shapiro-Wilk criterion, the obtained data were checked for compliance with the normal distribution law using the following formulas

.

If a series of n independent observations, arranged in non-decreasing order, is denoted by the symbols X_1,X_2, ...,X_n, then the intermediate sum S is calculated by the formula:

$$b = \sum a_i \cdot (X_{n+1-i} - X_i),$$

where i - is an index having values from 1 to n/2;
a_i is a coefficient that has special values for each sample size n.

The sample size in this experiment is n=24.

The tabular coefficients *a* are taken from the table of values of the Shapiro-Wilk criterion coefficient to calculate the statistics of the criterion W.

The square of deviations from the sample mean:

$$S = \sum (X_i - \bar{X})^2 ;$$

$$\bar{X} = \frac{\sum X_i}{n};$$

The calculated value of the Shapiro-Wilk criterion:

$$W_{\text{calcul}} = \frac{b^2}{S};$$

For the convenience of calculating sums by formulas, separate terms are calculated. The calculations are given in Table 3.

Table 3 – Calculation of the value of the Shapiro-Wilk criterion for the control group X

i	X_i	X_{n-i+1}	a_i	b_i	b	$\overline{x}$	S_i	S	W_{calcul}
1	-9,4	9,6	0,4493	8,5367	23,8509	-0,0583	87,2667	270,6708	2,1017
2	-7	8,2	0,3098	4,7090			48,1867		
3	-6,4	6,4	0,2554	3,2691			40,2167		
4	-6,2	5,2	0,2145	2,4453			37,7201		
5	-3,6	5,2	0,1807	1,5902			12,5434		
6	-3,4	4,4	0,1512	1,1794			11,1667		
7	-3,4	3,8	0,1245	0,8964			11,1667		
8	-3,2	3,2	0,0997	0,6381			9,8701		
9	-2,2	3,2	0,0764	0,4126			4,5867		
10	-2	0,4	0,0539	0,1294			3,7701		
11	-1,6	-0,4	0,0321	0,0385			2,3767		
12	-1,4	-0,8	0,0107	0,0064			1,8001		
13	-0,8								
14	-0,4								
15	0,4								
16	3,2								
17	3,2								
18	3,8								
19	4,4								
20	5,2								
21	5,2								
22	6,4								
23	8,2								
24	9,6								

The tabular value of the W_{table} criterion is taken from the table of values of the Shapiro-Wilk criterion.

Thus, we got that W_{calcul} =2,1017. At the significance level α= 0.05, the tabular value of the criterion W_{table} =0.916. Since $W_{table}<W_{calcul}$_allocation of X corresponds to the normal distribution law.

Similarly, calculations were carried out for the sample of the experimental group Y, the sample size of which is n= 26. The calculations are given in Table 4.

Table 4 – Calculation of the value of the Shapiro-Wilk criterion for the experimental group Y

i	X_i	X_{n-i+1}	a_i	b_i	b	$\overline{x}$	S_i	S	W_{calcul}
1	-13,2	21,8	0,4407	15,4245	33,8818	-5,8538	53,9660	323,3792	3,5499
2	-13,2	7,8	0,3043	6,3903			53,9660		
3	-12,2	2,8	0,2533	3,7995			40,2737		
4	-11,4	2	0,2151	2,8823			30,7598		
5	-11,4	1,4	0,1836	2,3501			30,7598		
6	-11	-1,8	0,1563	1,4380			26,4829		
7	-10,2	-4,6	0,1316	0,7370			18,8891		
8	-9,8	-6,4	0,1089	0,3703			15,5721		
9	-9,8	-7,2	0,0876	0,2278			15,5721		
10	-9,8	-7,2	0,0672	0,1747			15,5721		
11	-8,6	-7,2	0,0476	0,0666			7,5414		
12	-8,6	-8	0,0284	0,0170			7,5414		
13	-8,4	-8	0,0094	0,0038			6,4829		
14	-8								
15	-8								
16	-7,2								
17	-7,2								
18	-7,2								
19	-6,4								
20	-4,6								
21	-1,8								
22	1,4								
23	2								
24	2,8								
25	7,8								
26	21,8								

Thus, we got that $W_{calcul} = 3.5499$. At the significance level $\alpha = 0.05$, the tabular value of the criterion $W_{table} = 0.920$. Because $W_{table} < W_{calcul}$ the distribution of Y corresponds to the normal distribution law.

2. The hypothesis H_0 was tested by the Student's t-criterion:

$$t = \frac{|\bar{X} - \bar{Y}|}{\sqrt{\frac{(n_1^2 - 1)\sigma_1 + (n_2^2 - 1)\sigma_2}{f} \cdot \frac{n_1 + n_2}{n_1 n_2}}}$$

where $\bar{X}, \bar{Y}$ is the mean value of the samples; n_1,n_2 is the dimension of the samples; σ_1,σ_2 is the mean square deviation of the samples; f - is the degree of freedom.
The mean square deviation is calculated by the formula:

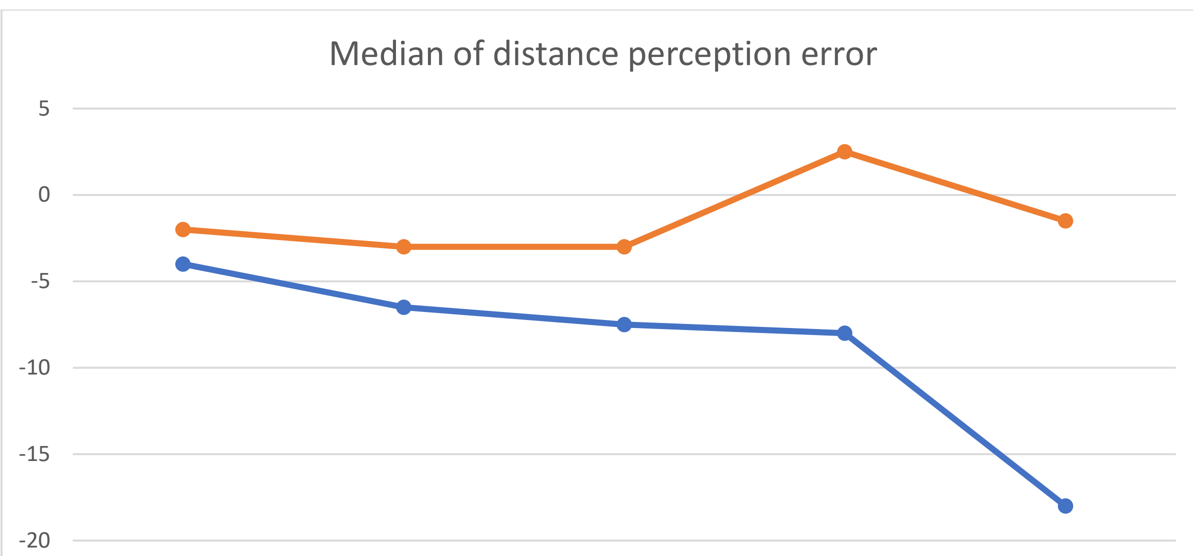
$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}};$$

The degree of freedom is calculated by the formula

$$f = n_1 + n_2 - 2;$$

Using the available values, we get that $t_{calcul} = 0.0605$. At the significance level $\alpha = 0.05$, the tabular value of the criterion $t_{table} = 2.011$. Since $t_{table} > t_{calcul}$ hypothesis H_0 is confirmed, which means that the adequacy of the experimental data is confirmed and their comparison within the framework of this experiment is permissible.

The graph of the median error by distance is shown in Figure 4.



Discussion of the results

The peculiarity of this work was the complete absence of metric assistance in estimating distances. The experiment's results align with known data, confirming the compression of the immersive virtual environment. Considering this work's focus on developing virtual training environment simulators for transport and technological machine operators, only distances in the action space and long-range view (more than 8 meters) were estimated.

It was found that in the complete absence of metric support in the action space in the real world, subjects estimated metric distances with an error of about 2 meters at 8 meters, 3 meters at 13-15 meters, and 2 meters at 30 meters. In contrast, in a virtual environment, the subjects estimated a distance of 8 meters with an error of 4 meters, a distance of 13-15 meters with an error of 7-8 meters, and a distance of 30 meters with an error of 18 meters. Introducing metric support is likely to significantly improve the result, and abandoning the metric distance measurement scale, which is not natural for humans, will considerably increase the accuracy of spatial information perception. However, it should be noted that in the field of long-range vision (30 meters or more), the accuracy of information perception is extremely low. This may be due to the technological limitations of the equipment used at the time.

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