CyberPsychology & Behavior
Volume 11, Number 1, 2008
© Mary Ann Liebert, Inc.
DOI: 10.1089/cpb.2007.9935

Depth Perception in Virtual Reality: Distance Estimations in Peri- and Extrapersonal Space

Dr. C. ARMBRÜSTER,[1,2] M. WOLTER, Dipl.-Inform.,[2] Dr. T. KUHLEN,[2]
Prof. Dr. W. SPIJKERS,[3] and Dr. B. FIMM[1]

ABSTRACT

The present study investigated depth perception in virtual environments. Twenty-three participants verbally estimated ten distances between 40 cm and 500 cm in three different virtual environments in two conditions: (1) only one target was presented or (2) ten targets were presented at the same time. Additionally, the presence of a metric aid was varied. A questionnaire assessed subjective ratings about physical complaints (e.g., headache), the experience in the virtual world (e.g., presence), and the experiment itself (self-evaluation of the estimations). Results show that participants underestimate the virtual distances but are able to perceive the distances in the right metric order even when only very simple virtual environments are presented. Furthermore, interindividual differences and intraindividual stabilities can be found among participants, and neither the three different virtual environments nor the metric aid improved depth estimations. Estimation performance is better in peripersonal than in extrapersonal space. In contrast, subjective ratings provide a preferred space: a closed room with visible floor, ceiling, and walls.

INTRODUCTION

Accurate depth perception is essential in daily life. Human spatial behavior depends on correctly perceived distances. Research concerning depth perception and judgments of distances in the real world is well documented since the mid-twentieth century.[1,2] Since the 1990s, virtual reality (VR) has found its way into psychological laboratories, and virtual environments have established multifaceted experimental possibilities. Both advantages and disadvantages of the use of VR applications in psychological research have been expressed:[3] on the one hand, high ecological validity, experimental control, generalizability of experimental findings, experimental realism, the use of "impossible" manipulations, and the ease of implementation and conduction of experiments; on the other hand, imperfection and high complexity of hardware and software, the difficulty of setting up high-quality virtual environments, high costs, and side effects. Additionally, when using VR applications, there are a couple of limitations concerning depth perception. First, in experimental psychological research, it is often neither possible nor useful to use environments with much visual information (e.g., secondary depth cues) because researchers have to avoid confounding effects. Second, interindividual differences in depth perception occur,[4,5] and it is not answered yet if generalizability is given when using VR as a research tool, particularly when the data depend on correctly perceived distances.

Human depth perception in general is based on different sources of information. Pictorial, oculo-

[1]Department of Computer Science, University of Applied Science, Sankt Augustin, Germany.
[2]Department of Psychology, RWTH Aachen University, Aachen, Germany.
[3]Virtual Reality Group, RWTH Aachen University, Aachen, Germany.

motor, and binocular depth cues are combined to give an observer the three-dimensional impression of a scene. Pictorial depth cues are two dimensional, and the visual system interprets them in three-dimensional terms. Oculomotor depth cues comprise convergence and accommodation, which are dependent on each other and also on the binocular depth cue's disparity or stereopsis. The impact of cue dominance depends on the observer's situation and on the distance between observer and object.[6] When looking at distances up to 5 meters, the visual depth sensitivity of accommodation, convergence, and binocular disparity drops, whereas the latter has the highest impact.[7]

The three-dimensional space surrounding our bodies can be divided in different zones.[6,8] The peripersonal space refers to the space that can be reached by our hands, generally distances up to 1 meter. Distances beyond 1 meter are classified as extrapersonal space.[8]

The present study examined the quality of depth perception in virtual peripersonal and extrapersonal space. The question was whether simple virtual environments with a minimized number of depth cues provide a satisfying and reliable depth perception, and if not, how depth impression can be improved. We hypothesized that depth estimation would be best in a closed environment (closed room with linear perspective) and that participants would benefit from a metric aid as well as from additional cues in terms of a frame of reference. In addition, the influence of visual parameters (hyperopia, myopia, and stereopsis) on depth estimation in VR was examined. The respective hypothesis was that hyperopia and myopia would be less effective, but stereopsis should be related to the ability to judge virtual distances. Furthermore, we assumed that overestimations would occur in peripersonal space[9] and underestimations in extrapersonal space.[2,4,5]

METHOD

A verbal estimation task was applied. Participants saw either one target sphere or ten target spheres in a virtual environment and had to give verbal estimations on the perceived distances, in centimeters, between themselves and the displayed objects. The experimenter noted the estimated distances.

Experimental variables

Independent variables were the type of the virtual environment (no space vs. open space vs. closed space), the distance between observer and target (40, 60, 80, 100, 150, 200, 350, 300, 400, 500 cm), the existence of a metric aid (with vs. without tape measure), and the type of presentation (single vs. ten). These four variables were treated as within-subject factors, whereas sex, hyperopia, myopia, and binocular ability were used as covariates.

Type of virtual environment. The first condition was called "no space" because no additional space surrounded the scene. This space was blue, infinite, and included no additional depth information. Participants had to rely on their binocular ability. The second condition was called "open" and included a green floor and a blue sky with some clouds. The perception of "infinity" was limited because the impression of a horizon was induced. The chosen textures did not provide any texture gradient information. In contrast to these two spaces, the third condition was a closed gray room (scaled width: 540 cm; scaled height: 380 cm; scaled length: 800 cm). Here linear perspective was available as secondary depth cue.

Distance. The objects were presented in four peripersonal distances (40 cm, 60 cm, 80 cm, and 100 cm) and six extrapersonal distances (150 cm, 200 cm, 250 cm, 300 cm, 400 cm, and 500 cm).

Metric aid. The tape was a flat white-and-yellow-striped bar located in front of the participants on the ground. Participants were told that the tape measure started exactly under their nose on the floor and that each segment was 1 meter in length.

Type of presentation. First, participants saw the ten target spheres one by one in succession (single condition), and then all spheres were presented simultaneously (ten condition).

The verbal estimation values (in centimeters) and classified values were the dependent variables. Estimations, which lay 10% over or under the scaled distance, were categorized as hits (h); values below this range as underestimations (u); and values above this range as overestimations (o). The 10% range was chosen because we know from reality that depth estimations are fairly accurate but not perfect.[1]

In addition, subjective ratings about physical complaints, the experience in the virtual world, and the experiment itself were collected at the end of the experiment.

Apparatus and materials

Visual test. The subtests 1, 4, and 9 of the TITMUS Vision Tester® were used to test visual acuity.

Test 1 measures myopia. Test 4 measures the ability to judge relative distances when all cues except binocular triangulation are eliminated. The level of difficulty is expressed as a percentage of the theoretical maximum stereopsis according to the Shepard-Fry formula, and results are given in angle of stereopsis in seconds of arc and Shepard-Fry percentages. Test 9 measures hyperopia.

VR hardware. The virtual environment was displayed on a rear projection screen (240 × 180 cm) with a stereo projector (resolution 1024 × 768 pixels). For stereoscopy, participants wore passive Infitec™ filter glasses. The participants' head motion was tracked using an electromagnetic tracking system (Flock of Birds® with long-range emitter).

VR software. The ReactorMan software[10] was used. It is based on the VR-toolkit ViSTA and its multimedia extensions. Experimental setups are defined by scripts, which contain the basic experimental structure of sessions, blocks, trials, and scenes. Chronological information about the user's reaction to events and the user's movement is saved with specific timing characteristics.

Postquestionnaire. The postquestioning in written form was divided into three sections. First, participants were asked about physical complaints. They had to indicate whether general discomfort occurred and then rate dizziness, malaise, eyestrain, and headache on a 3-ary scale (little, medium, severe). The second part comprised questions about the VR itself. Four dimensions were used: presence/immersion, external awareness, quality, and enjoyment (Table 1). Answers were given on a 5-ary scale (not applicable, rather not applicable, neither nor, rather applicable, and applicable).

The last part of the questionnaire contained six specific statements about the experiment with the same 5-ary scale as before. Every statement had to be rated for each environment. Statements were (1) The depth impression was realistic; (2) The objects in the VR appeared to be geometrically correct. They were correct in size and distance; (3) I had a three-dimensional impression of the displayed environments and objects; (4) I could estimate the distance of the objects well; (5) All objects were presented in the same distance; (6) I thought that the tape measure was very helpful.

Last, participants were asked to rank the three environments from good to bad according to their perceived/subjective depth impression. We hypothesized that the closed environment would be subjectively superior (statements 1–4) because participants were provided with a frame of reference and that the tape measure (statement 6) would have the same effect in each environment. Furthermore, statement 5 served as a control for social desirability in case participants gave different distances in the estimation task to meet the experimental expectations but actual did not perceive any different distances. No differences between the three environments were expected.

Procedure

First, participants worked on three subtests of the TITMUS Vision Tester, then the experiment started. During the experimental task, participants sat 100 cm in front of the rear projection screen wearing passive stereo glasses. Participants were asked to

Table 1. Eleven Questions on Four Dimensions of the Post-Questionnaire Concerning the Virtual Experience

Dimension	*Question*
Presence/immersion	(1) I had the feeling of being in a virtual room/space.
	(2) I had the feeling of seeing pictures only, like in the cinema or on TV.
	(3) I could imagine the virtual space.
	(4) The virtual environments and the displayed objects seem to be realistic.
	(5) I had the feeling that I could reach into the virtual world and touch the objects.
External awareness	(6) I was not aware of the real world—the laboratory
	(7) I knew all the time that I was in a real room—in the laboratory.
Quality	(8) I could see the virtual world clearly.
	(9) The quality of the graphical presentation was satisfying.
Enjoyment	(10) I was disappointed in the experience of the virtual reality.
	(11) The virtual experience was fascinating.

move as little as possible during the trials. Minor head movements were registered with the electromagnetic tracking device and used for the update of the displayed user-centered visual perspective. After the first instructions, one of the three virtual environments (no space, open space, or closed space) was displayed randomly with a target example 45 cm away from the observer. Participants were encouraged to look at the target, try to reach for it, and get used to the experimental situation. Furthermore, they received a real tennis ball of the same size as the target for comparison to ensure that all participants had the same size impression of the virtual sphere. Then the estimation trials started. First, one target was presented in ten different virtual distances from 40 cm to 500 cm in a random order, and participants had to verbally estimate the distances, in centimeters, between themselves and the target spheres. The experimenter noted the estimation results. Then all target spheres appeared at the same time, marked with numbers to distinguish them, and participants had to give their estimations again. This procedure continued for each virtual environment. No cues or time restrictions were provided. The condition without the virtual tape measure was always presented first. In the time between the different conditions, participants counted back from 200 in steps of seven to minimize memorizing of the estimation values. After the experimental task, participants filled out the postquestionnaire.

Participants

Twelve female and 11 male participants between 19 and 32 years of age (mean age $M = 25.8$) took part in the study. They all had a normal or corrected-to-normal visual acuity. Visual test results of the TITMUS Vision Tester revealed normal myopia values between 0.7 and 1.4 ($M = 1.2$, $SD = 1.8$) and normal hyperopia values between 0.9 and 1.4 ($M = 1.2$, $SD = 1.5$). Binocular ability ranged between 30% and 95% ($M = 85\%$, $SD = 27.93$). This range is equivalent to an angle of stereopsis between 200 to 20 seconds of arc.

RESULTS

The first part of the result section deals with the classified values. Results of repeated measures ANOVA and t-test and descriptive statistics are presented as well as Pearson correlations and linear regression analyses, including the variables *hyperopia*, *myopia*, and *binocular ability*. The second part describes the numerical results of the estimations. The data of the estimation tasks are treated by repeated measures ANOVA with the within-subject factors *virtual environment*, *distance*, *tape measure*, and *type of presentation* and with *hyperopia*, *myopia*, and *binocular ability* as covariates. Correlation and regression analyses were conducted. The last part deals with the results from the postquestionnaire.

Classified values

Overall, every participant made 120 estimations ($10 \times 3 \times 2 \times 2$). On average, 62.2 ($SD = 35.0$) underestimations, 23.6 ($SD = 13.1$) hits, and 34.2 ($SD = 32.8$) overestimations were registered over all conditions. An ANOVA shows that the difference between these values is highly significant: $F(2,44) = 7.38$ and $p < 0.01$. t-Test results for paired samples show that the significant difference between underestimations and hits ($t_{22} = 4.5$, $p < 0.01$) is mainly responsible for this F-test result. Underestimations and overestimations differ on a 10% level ($t_{22} = 2.0$, $p = 0.056$), and hits and overestimations do not differ significantly ($t_{22} = 1.4$, $p = 0.170$). This result pattern is consistent over the three environments. ANOVA results reveal significant differences between the three types of estimation (underestimation, hits, and overestimation) in each environment. In the no space condition, on average, 21.5 ($SD = 11.8$) underestimations, 7.3 ($SD = 4.3$) hits, and 11.3 ($SD = 11.4$) overestimations ($F[2,21] = 23.6$, $p < 0.001$) occurred; in the open space condition, 21.2 ($SD = 12.3$) underestimations, 8.0 ($SD = 5.5$) hits, and 10.9 ($SD = 11.3$) overestimations ($F[2,21] = 11.3$, $p < 0.001$); and in the closed space condition, 19.5 ($SD = 12.5$) underestimations, 8.4 ($SD = 5.2$) hits, and 12.0 ($SD = 11.5$) overestimations ($F[2,21] = 10.0$, $p < 0.001$). In none of the environments did type of presentation or presence of the tape measure have a significant influence on the classified values.

Correlations between degree of hyperopia, myopia, and binocular ability and the number of underestimations, hits, and overestimations, respectively, were only significant between underestimations and binocular ability ($r = 0.634$, $p < 0.01$) and overestimations and binocular ability ($r = -0.699$, $p < 0.01$). Regression analysis revealed that binocular ability can explain 40.2% of the variance of the underestimations and 48.8% of the variance of the overestimations.

In order to analyze the potential influence of the peripersonal and the extrapersonal space on depth estimation, underestimations, hits, and overestimations were transformed into percentage values and compared by use of repeated measures ANOVA with "3D space" as the within-subject factor. In peripersonal space, significantly fewer underestimations (40% vs. 66%; $F[1,22] = 16.00$, $p < 0.01$), significantly more overestimations (40% vs. 23%; $F[1,22] = 8.2$, $p < 0.01$), and significantly more hits (20 vs.10%; $F[1,22] = 8.5$, $p < 0.01$) occurred.

Taken together, these results imply that participants tend to underestimate in all three environments and that binocular ability as well as three-dimensional space play an important role.

Numerical estimations

The results of a repeated measures ANOVA including the factors virtual environment (3), distance (10), tape measure (2), and type of presentation (2) revealed only a significant main effect for the factor distance ($F[9,198] = 104.472$, $p < 0.01$) and a significant interaction between distance and type of presentation ($F[9,198] = 4.484$, $p < 0.01$). Pairwise comparisons (t-tests) between the scaled distances and the average estimations over all conditions showed that the estimations up to 300 cm did not differ significantly from the scaled distances (see Table 2). However, estimation results for the 400-cm and the 500-cm distances were significantly lower than the scaled values. The discrepancies in percentage increased up to 19.6% and 21.2% respectively.

In a second step, repeated measures ANOVAs with the between-subject factor sex and the covariates hyperopia, myopia, and binocular ability were conducted for the mean values of Table 3. No effect was found, which suggests that neither sex nor visual abilities have an influence on the main effect distance. Regression analysis showed a strong linear relationship between the scaled and the mean estimated distances with a determination coefficient of $R = 0.994$ ($F[1,9] = 1365.2$, $p < 0.01$) and a correlation coefficient of 0.997. Regression results for every single participant were between 0.930 and 0.995 and reflected this relationship on an individual level.

Postquestionnaire

Participants reported little discomfort. Eighteen subjects (78.3%) experienced no discomfort at all ($\chi^2_1 = 7.3$, $p < 0.01$). One person reported dizziness (little), eyestrain (medium), and headache (little), and another one malaise (little) and headache (little). Headache (little), eyestrain (little), and malaise (little) were mentioned by three participants as single symptoms. On the basis of these results, we conclude that the virtual experience did not cause severe physical problems and that the objective data are not confounded by discomfort.

Subjective ratings about the VR itself are quite good. Regarding the dimension presence/immersion, it can be stated that participants had the feeling of being in the virtual world (Table 1: statement 1, $\chi^2_1 = 26.348$, $p < 0.001$, and statement 5, $\chi^2_1 = 19.391$, $p < 0.001$) and that they could imagine the virtual world and did not feel as though they were at a cinema or in front of a television screen (Table 1: statement 2, $\chi^2_1 = 28.522$, $p < 0.001$, and statement 3, $\chi^2_1 = 30.261$, $p < 0.001$). Realism of the environment and the objects was rated as "rather not applicable," but here the chi-square test failed to be

TABLE 2. SCALED DISTANCES AND MEAN ESTIMATED DISTANCES OVER ALL CONDITIONS

Scaled distance	*Mean estimated distance*	*Standard deviation*	t-*Value*	p-*Value*	Δ *[%]*
40	39.8	13.0	−0.06	0.953	−0.33
60	65.1	18.2	1.35	0.190	8.55
80	89.2	23.1	1.91	0.069	11.53
100	110.9	32.4	1.61	0.122	10.85
150	146.16	49.59	−0.37	0.714	−2.56
200	178.5	66.5	−1.55	0.136	−10.74
250	222.9	84.3	−1.54	0.137	−10.86
300	260.6	106.7	−1.77	0.090	−13.14
400	321.7	128.4	−2.92	0.008**	−19.57
500	394.1	157.4	−3.23	0.004**	−21.19

$^{**}p < 0.01$.
Standard deviations, t-values, p-values, and discrepancy in percentages (Δ [%]).

Table 3. Statements about the Experiment and the Rank Order of the Three Virtual Environments and Chi-Squared Test Results Including p-Values

Statement	*Rank order*[a]	*Chi-squared test*
(1) The depth impression was realistic	1. closed space 2. open space 3. no space	$\chi^2_2 = 15.441$, $p < 0.001$
(2) The objects in the virtual reality appeared to be geometrically correct. They were correct in size and distance.	1. closed space 2. open space 3. no space	$\chi^2_2 = 12.087$, $p < 0.01$
(3) I had a three-dimensional impression of the displayed environments and objects.	1. closed space 2. open space 3. no space	$\chi^2_2 = 16.188$, $p < 0.001$
(4) I could estimate the distance of the objects well.	1. closed space 2. open space 3. no space	$\chi^2_2 = 18.591$, $p < 0.001$
(5) All objects were presented in the same distance.	—	$\chi^2_2 = 2.0$, $p = 0.368$
(6) I thought that the tape measure was very helpful.	—	$\chi^2_2 = 0.154$, $p = 0.926$

[a]Rank order according to Friedman-test.

significant. External awareness was not lost during the virtual experience (Table 1: statements 6 and 7), but again for those ratings, chi-square tests revealed no significant differences. Most participants regarded the quality of the virtual environment as fairly good (Table 1: statement 8 and 9). Concerning the dimension enjoyment, we can state that participants were not disappointed in the experience (statement 10, $\chi^2_1 = 18.957$, $p = 0.001$), but not all of them were fascinated (statement 11). Descriptively, there are two tendencies: either participants thought the experience was neutral in terms of fascination or they felt highly fascinated with the virtual experience.

Overall, the closed environment was preferred, followed by the open environment. The rank order for statements (1) to (4) is alike, and the chi-squared tests are significant (Table 3).

Participants preferred the closed environment and believed that depth impression and their estimations were best in this condition. As hypothesized, no significant rank order emerges for the control statement (5) or for the statement about the helpfulness of the tape measure (6). The results for the last question of the questionnaire complete the picture: participants rated the three environments from good to bad according to their perceived/subjective depth impression; the resulting rank order was 1, closed space; 2, open space; and 3, no space ($\chi^2_2 = 21.5$, $p < 0.01$).

DISCUSSION

The present study was conducted to provide further insight into the quality of depth perception in virtual environments. We tried to answer whether simple virtual environments with a minimized number of depth cues provide a satisfying and reliable depth perception, and if not, how depth impression can be improved without enriching the virtual environment with potentially confounding secondary depth cues.

Overall, virtual distances were perceived in correct order from the smallest to the largest displayed distance independently from the condition. However, virtual distances were basically underestimated, and the three virtual environments had no differential effect on precision of estimation. The hypothesized advantage for the closed environment was not found in the objective estimation data; only the subjective ratings showed that the participants preferred the closed environment. Furthermore, the virtual tape measure and the variation of the number of the displayed targets had no effect at all: participants did not benefit from the metric aid or the additional targets.

Regarding the influence of basic visual abilities on depth perception in VR, we found that the higher participants scored in the stereopsis test, the more underestimations they made; the lower they scored, the more overestimations they made. Therefore, we strongly suggest measuring binocular ability when using virtual applications either to select participants or to include that factor as covariate in statistical analyses to facilitate interpretation and avoid confounding effects.

In addition, in peripersonal space, fewer underestimations, more hits, and more overestimations than in extrapersonal space occur. However, it is not yet clear whether these results can be generalized to every virtual environment. Hardware-related interactions could have caused this phenomenon. For example, perhaps because the projection screen was 100 cm away from the observer, all peripersonal distances were projected in front of the screen and all extrapersonal distances behind the screen. Therefore, different parallaxes (i.e., zero parallax at the screen, negative parallax in front of the screen, and positive parallax behind the screen) could have influenced the estimation.

Finally, subjective ratings on physical discomfort and general experience in virtual environments were satisfying. Participants reported little discomfort and no severe strain. They felt they were in a virtual room and could imagine the virtual space. They did not lose external awareness, were quite satisfied with the three-dimensional quality, and enjoyed the new experience.

The study shows that depth perception is insufficient in simple virtual environments and that simple manipulations do not improve depth estimations. Future research will have to focus on the improvement of depth perception. Successful cue-combinations must be extracted, and interindividual calibrations of the VR systems on the basis of binocular ability are necessary to provide a satisfying depth impression.

ACKNOWLEDGMENT

This research project is supported by a grant from the Interdisciplinary Centre for Clinical Research BIOMAT within the Faculty of Medicine at the RWTH Aachen University (TV N57).

REFERENCES

1. Gilinsky AS. Perceived size and distance in visual space. Psychological Review 1951; 58:460–82.
2. Loomis JM, Da Silva JA, Philbeck JW, Fukusima SS. Visual perception of location and distance. Current Directions in Psychological Science 1996; 5:72–7.
3. Loomis JM, Blaskovich JJ, Beall AC. Immersive virtual environment technology as a basic research tool in psychology. Behavior Research Methods, Instruments, & Computers 1999; 31:557–64.
4. Lampton DR, McDonald DP, Singer M, Bliss JP. Distance estimation in virtual environments. Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting 1995; 1268–72.
5. Armbrüster C, Heber I, Valvoda JT, Kuhlen T, Fimm B, Spijkers W. Distance estimations in a VR application: interindividual differences and interindividual stabilities from a psychological point of view. Proceedings of the HCII '2005; CD-ROM.
6. Cutting JE, Vishton PM. (1995) Perceiving layout: the integration, relative potency, and contextual use of different information about depth. In: Epstein W, Rogers S, eds. *Handbook of perception and cognition: Vol. 5. Perception of space and motion*. San Diego: Academic Press, pp. 69–117.
7. Nagata S. (1993) How to reinforce perception of depth in single two-dimensional pictures. In: Ellis S, ed. *Pictorial communication in virtual and real environments*. London: Taylor & Francis, pp. 527–5
8. Previc FH. The neuropsychology of 3-D space. Psychological Bulletin 1998; 124:123–64.
9. Rolland JP, Gibson W, Ariely D. Towards quantifying depth and size perception in virtual environments. Presence 1994; 4:24–49.
10. Valvoda JT, Assenmacher I, Dohle C, Kuhlen T, Bischof CH. NeuroVRAC—a comprehensive approach to virtual reality-based neurological assessment and treatment systems. Medicine Meets Virtual Reality 2003; 11:391–3.

Address reprint requested to:
Dr. Claudia Armbrüster
RWTH Aachen
Institute of Psychology
Jägerstraße 17-19
52066 Aachen
Germany

E-mail: armbruester@psych.rwth-aachen.de

This article has been cited by:

1. Tatiana Ogourtsova, Philippe S. Archambault, Anouk Lamontagne. 2018. Post-stroke unilateral spatial neglect: virtual reality-based navigation and detection tasks reveal lateralized and non-lateralized deficits in tasks of varying perceptual and cognitive demands. *Journal of NeuroEngineering and Rehabilitation* **15**:1. . [Crossref]
2. Mauricio Loyola. 2018. The influence of the availability of visual cues on the accurate perception of spatial dimensions in architectural virtual environments. *Virtual Reality* **22**:3, 235-243. [Crossref]
3. Thuong N. Hoang, Travis N. Cox. 2018. Alternating Reality: An Interweaving Narrative of Physical and Virtual Cultural Exhibitions. *Presence: Teleoperators and Virtual Environments* **26**:4, 402-419. [Crossref]
4. Tatiana Ogourtsova, Philippe S. Archambault, Anouk Lamontagne. 2018. Post-stroke visual neglect affects goal-directed locomotion in different perceptuo-cognitive conditions and on a wide visual spectrum. *Restorative Neurology and Neuroscience* **36**:3, 313-331. [Crossref]
5. Bharat Dandu, Irene A. Kuling, Yon Visell. Where are my fingers? Assessing multi-digit proprioceptive localization 133-138. [Crossref]
6. Oliver Liu, Daniel Rakita, Bilge Mutlu, Michael Gleicher. Understanding human-robot interaction in virtual reality 751-757. [Crossref]
7. Mathias Klinghammer, Immo Schütz, Gunnar Blohm, Katja Fiehler. 2016. Allocentric information is used for memory-guided reaching in depth: A virtual reality study. *Vision Research* **129**, 13-24. [Crossref]
8. Gennaro Ruggiero, Francesca Frassinetti, Yann Coello, Mariachiara Rapuano, Armando Schiano di Cola, Tina Iachini. 2016. The effect of facial expressions on peripersonal and interpersonal spaces. *Psychological Research* **30**. . [Crossref]
9. Sahra Karolina Gomes e Silva, Cleber G. Correa, Fatima L.S. Nunes. Three-Dimensionality Perception Evaluation in Stereoscopic Virtual Environments: A Systematic Review 198-209. [Crossref]
10. Mathieu Paquier, Nicolas Côté, Frédéric Devillers, Vincent Koehl. 2016. Interaction between auditory and visual perceptions on distance estimations in a virtual environment. *Applied Acoustics* **105**, 186-199. [Crossref]
11. Tina Iachini, Yann Coello, Francesca Frassinetti, Vincenzo Paolo Senese, Francesco Galante, Gennaro Ruggiero. 2016. Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age. *Journal of Environmental Psychology* **45**, 154-164. [Crossref]
12. Adrian K. T. Ng, Leith K. Y. Chan, Henry Y. K. Lau. Depth Perception in Virtual Environment: The Effects of Immersive System and Freedom of Movement 173-183. [Crossref]
13. Abdeldjallil Naceri, Alessandro Moscatelli, Ryad Chellali. 2015. Depth discrimination of constant angular size stimuli in action space: role of accommodation and convergence cues. *Frontiers in Human Neuroscience* **9**. . [Crossref]
14. Chiuhsiang Joe Lin, Bereket Haile Woldegiorgis. 2015. Interaction and visual performance in stereoscopic displays: A review. *Journal of the Society for Information Display* **23**:7, 319-332. [Crossref]
15. Andrea Albarelli, Augusto Celentano, Luca Cosmo. Evaluating stereo vision and user tracking in mixed reality tasks! 81-88. [Crossref]
16. Chiuhsiang Joe Lin, Lai-Yu Cheng, Ming-Ching Wang. 2015. Performance of estimating depth in projection based stereoscopic virtual display. *Journal of the Society for Information Display* **23**:2, 76-83. [Crossref]
17. Chiuhsiang Joe Lin, Bereket Haile Woldegiorgis, Dino Caesaron, Lai-Yu Cheng. 2015. Distance estimation with mixed real and virtual targets in stereoscopic displays. *Displays* **36**, 41-48. [Crossref]
18. Andre Garcia, Ederlyn Tanangco, Daniel Roberts, Carryl Baldwin. 2014. Auditory-Spatial Executive Function across Spatial Frames of Reference. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* **58**:1, 1199-1203. [Crossref]
19. Chen-Fu Chen, Chin-Chiuan Lin, Kuo-Chen Huang. 2014. Effects of Spacing between Items and View Direction on Errors in the Perceived Height of a Rotated 3-D Figure. *Perceptual and Motor Skills* **119**:1, 215-227. [Crossref]
20. Björn van der Hoort, H. Henrik Ehrsson. 2014. Body ownership affects visual perception of object size by rescaling the visual representation of external space. *Attention, Perception, & Psychophysics* **76**:5, 1414-1428. [Crossref]
21. Chiuhsiang Joe Lin, Bereket H. Woldegiorgis, Dino Caesaron. 2014. Distance estimation of near-field visual objects in stereoscopic displays. *Journal of the Society for Information Display* **22**:7, 370-379. [Crossref]
22. K. Weigelt, J. Wiemeyer. The impact of stereo 3D sports TV broadcasts on user's depth perception and spatial presence experience 901103. [Crossref]

23. Paul Lubos, Rudiger Beimler, Markus Lammers, Frank Steinicke. Touching the Cloud: Bimanual annotation of immersive point clouds 191-192. [Crossref]

24. Hans-Joachim Maempel, Matthias Jentsch. 2013. Auditory and Visual Contribution to Egocentric Distance and Room Size Perception. *Building Acoustics* **20**:4, 383-401. [Crossref]

25. Garry Tew, Robert Copeland, Alexis Le Faucheur, Marie Gernigon, Shah Nawaz, Pierre Abraham. 2013. Feasibility and validity of self-reported walking capacity in patients with intermittent claudication. *Journal of Vascular Surgery* **57**:5, 1227-1234. [Crossref]

26. Paul Richard, Mickael Naud, Francois-Xavier Inglese, Emmanuelle Richard. 2012. Modeling Dynamic Interaction in Virtual Environments and the Evaluation of Dynamic Virtual Fixtures. *Presence: Teleoperators and Virtual Environments* **21**:3, 321-337. [Crossref]

27. Christopher Schlick, Carsten Winkelholz, Martina Ziefle, Alexander Mertens. Visual Displays 157-192. [Crossref]

28. Bo Hu, Wei Zhang, Gavriel Salvendy. 2012. Impact of multimodal feedback on simulated ergonomic measurements in a virtual environment: A case study with manufacturing workers. *Human Factors and Ergonomics in Manufacturing & Service Industries* **22**:2, 145-155. [Crossref]

29. Eliane C. Magdalon, Stella M. Michaelsen, Antonio A. Quevedo, Mindy F. Levin. 2011. Comparison of grasping movements made by healthy subjects in a 3-dimensional immersive virtual versus physical environment. *Acta Psychologica* **138**:1, 126-134. [Crossref]

30. Abdeldjallil Naceri, Ryad Chellali. 2011. Depth Perception Within Peripersonal Space Using Head-Mounted Display. *Presence: Teleoperators and Virtual Environments* **20**:3, 254-272. [Crossref]

31. Sandeep K Subramanian, Mindy F Levin. 2011. Viewing medium affects arm motor performance in 3D virtual environments. *Journal of NeuroEngineering and Rehabilitation* **8**:1, 36. [Crossref]

32. Bo Hu, Liang Ma, Wei Zhang, Gavriel Salvendy, Damien Chablat, Fouad Bennis. 2011. Predicting real-world ergonomic measurements by simulation in a virtual environment. *International Journal of Industrial Ergonomics* **41**:1, 64-71. [Crossref]

33. Massimiliano Valente, Davide Sobrero, Andrea Brogni, Darwin Caldwell. Intercepting Virtual Ball in Immersive Virtual Environment 214-222. [Crossref]

34. Abdeldjallil Naceri, Ryad Chellali. Can observers perceive depth in virtual environments within extrapersonal space? 26-31. [Crossref]

35. Lydia Beck, Marc Wolter, Nan F. Mungard, Rene Vohn, Mario Staedtgen, Torsten Kuhlen, Walter Sturm. 2010. Evaluation of Spatial Processing in Virtual Reality Using Functional Magnetic Resonance Imaging (fMRI). *Cyberpsychology, Behavior, and Social Networking* **13**:2, 211-215. [Abstract] [Full Text] [PDF] [PDF Plus]

36. Abdeldjallil Naceri, Ryad Chellali, Fabien Dionnet, Simone Toma. Depth Perception within Virtual Environments: A Comparative Study Between Wide Screen Stereoscopic Displays and Head Mounted Devices 460-466. [Crossref]

37. Chiara Saracini, Ronny Franke, Eberhard Blümel, Marta Olivetti Belardinelli. 2009. Comparing distance perception in different virtual environments. *Cognitive Processing* **10**:S2, 294-296. [Crossref]

38. John C. Adair, Anna M. Barrett. 2008. Spatial Neglect: Clinical and Neuroscience Review. *Annals of the New York Academy of Sciences* **1142**:1, 21-43. [Crossref]