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STUDY ON TELE-EXISTENCE (II)

- THREE-DIMENSIONAL COLOR DISPLAY WITH SENSATION OF PRESENCE -

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ABSTRACT

A method of the realization of the display with sensation of presence is proposed and its design procedure is discussed. A test display hardware is made and its efficacy is psychophysically evaluated. Human head movement is measured in real time using the head-mounted 6-degree of freedom goniometer.Two TV cameras are mounted on a mechanism which follows the movement of the human head. The pictures taken by the two cameras are transformed and displayed on the CRTs with proper lens systems so that they fuse to give sensation that the operator sees the remote scene directly.

1. INTRODUCTION

It is quite desirable for a remote operator if he can control a robot at a remote environment by using real time sensory information which is being fed back by the robot through the sensors on board the robot and is rich both quantitatively and qualitatively. Such an ideal teleoperator system could allow a human operator at a remote control site to perform remote tasks dexterously with feeling that (s)he exists in the slave anthropomorphic robot in the remote environment.

This type of advanced teleoperation system with real time sensation of remote presence is called tele-existence system [1]. There are two main characteristics in the tele-existence system. One is that a robot in the remote environment is not a manipulator or manipulators with sensors as have been conventionally used but an independent total robot system with manipulation, locomotion and communication capabilities and intelligence. The other feature is the use of the special sensory display with real-time sensation of presence.

There are two main problems to be solved associated with the above two main characteristics of the tele-existence system. The first problem is the communication between an operator and autonomous intelligent mobile robots in the remote environment. How and when should an operator take over the control of the autonomous robot which is in trouble [2,3] ?

Second problem is the realistic sensory feedback of the remote environment to the operator. In the previous paper [1], a new type of visual display using robot technology was proposed, a monochromatic binocular display system with one degree of freedom of movement was experimentally made, and the feasibility of the concept was demonstrated by both theoretically and experimentally.

In this paper the principle of the visual display with sensation of presence is first described. Next the design procedure of the display is explicitly explained. Two experimental hardwares are experimentally made according to the design procedure. One is for the psychophysical evaluation and the other is more practical light weight display, which has five degrees of freedom of movevement and is servo-controlled to follow the head movement of the operator. Psychophysical experiments are conducted and design data for an advanced display system are obtained.

2. TELE-EXISTENCE SYSTEM

An ideal tele-existence system should consist of intelligent mobile robots, their supervisory subsystem, a remote-presence subsystem, and a sensory augumentation subsystem, which allows an operator to use the robot's ultrasonic, infrared and otherwise invisible sensory information with the computer-graphics-generated pseudo-realistic sensation of presence. In the remote-presence subsystem, realistic visual, auditory, tactile, kinesthetic, and vibratory displays must be realized [1].

The fundamental studies for the realization of this tele-existence system are now being conducted in the authors' division of the Mechanical Engineering Laboratory as part of the National Large Scale Project called JUPITER (JUvenescent PIoneering TEchnology for Robots), which is a research and development program of the advanced robot technology for a system that avoids the need for humans to work in potentially hazardous working environments, such as nuclear power plants, under sea, and disaster area.

For the first step of the development, a visual display with sensation of presence using robot technology is being studied. This is based on the principle that the world we see is reconstructed by the human brain using only two real time images on the two retinae of a human. What we get from the environment are only two-dimensional pictures on the retina changing in real time according to the movement of the eyeballs and the head. We reconstruct the three-dimensional world in the brain and project the reconstructed world to the real three-dimensional world.

In our new type of robotic display;
(1) human movements including a head and eyeballs are precisely measured in real time,
(2) robot sensors and effectors are constructed anthropomorphically in function and size,
(3) movements of the robot sensors are controlled precisely to follow the human operator's movement, and
(4) the pictures taken by the robot sensors are displayed directly to the human eyes in a manner which assures the the same visual space as is observed directly at the robot's location.

This disply enables an operator to see the robot's upper extremities, which are contrlled to track in real time precisely the same movement of the operator's, instead of his/hers at the position his/her upper extremities should be.

3. DESIGN PRINCIPLE OF THE VISUAL DISPLAY

Essential parameters for human perception of the three-dimensional space are : (1) accomodation of the crystalline lens, (2) visual angle, i.e., retinal image size, and (3) convergence of two eyes or disparity of two retinal images. Adding to the above monochromatic parameters, fidelity in color is also important for the realistic display.

Ideal visual display system should control in real time all these parameters of a display device so that it would coincide with the parameters which would be observed at the robot's location if an operator see directly with his/her naked eyes at the location. These condition is realized as in Fig. 1.

Two posture-controlled TV cameras on board the robot in the remote environment see the object at the distance of Xr as is shown in the right hand side of the Fig. 1. This distance is measured by the robot using the disparity method [4] or ultrasonic measurement [5]. The foci of the two cameras are adjusted to the distance Xr. Two camers are controlled so that the two lines of sight converge at the object location. The convergence angle θr and visual angle Vr (or object size Ir) for each camera are calculated.

These images with measured parameters are transmitted. Transmitted images are displayed to the operator, while the parameters of the display are controlled according to the transmitted parameters as is shown in the left hand side of Fig. 1. Two CRT displays with appropriate lens systems are placed immediately in front of an operator's eyes. Remote scene taken by left and right cameras are displayed on left and right CRT's, which in turn are transformed by corresponding lenses to make images just at the right position and orientation: The visual angle Vh with which each eye sees the virtual image of the object is controlled so that Vh = Vr. The location of a virtual image is controlled at the distance Xh = Xr. The convergence angle for the two virtual images is also servoed to θh = θr.

Fig. 2 shows design parameters of the lens system. The design procedure of the display system is as follows:

(1) The maximum object size to be seen at the distance b is set as 2*l.

$$\alpha = 2 \arctan \frac{l}{b} \quad .... (1),$$ determines the maximum visual angle of the scene.

(2) The focal length of the TV cameras fc used for the robot is set as follows:

$$fc = \frac{k}{2 \tan \alpha/2} \quad ....(2),$$ where k is the effective size of the imaging device used, e.g. CCD, MOS.

(Auto-irising and auto focusing should be done according to the measurement by the robot's sensors.)

(3) When the effective size of the disply device, e.g. CRT, is 2*l', then

$$\beta = \frac{l'}{l} \quad .... (3),$$ can be determined.

(4) Then the distance a to the display lens system from the display face plate and the focal length of the display lens system fd can be determined as follows:

$$a = \beta * b \quad .... (4), \qquad fd = \frac{-ab}{a - b} \quad .... (5)$$

(5) The distance to the object is measured by the robot, and a and fd are calculated by the computer of the display device. By using a and fd parameters, the distance and the focal length of the display are servo-controlled. (It is possible to fix b, e.g. 1 meter, and fix a and fd for a simplified design.)

4. EXPERIMENTAL SYSTEM

Fig. 3 shows the experimental hardware system for the evaluation study. The movement of the head of the human subject is measured in real time by the light weight goniometer with six degrees of freedom. Three translational coordinates (x,y,z) and three rotational angles (roll,pitch, yaw) are calculated by a microprocessor, and both the camera position/ orientaion and the display position/orientaion are servo-controlled to follow the head movement. Video signals from the two TV cameras are transmitted either directly or through image memories.

The previously designed display [1] was supported mechanically by a mechanism with one degree of freedom. A potentiometer was integrated in the mechanism, and the movement of the head is measured. The mechanism is moved by the torque produced by a human operator's head movement.

When the number of degrees of freedom of the allowed head movement increases, however, it is impossible to use the torque produced by the operator's head movement as the energy source of the movement of the display device. Even if the weight is removed by a counter balance mechanism, the inertia can not be eliminated. Therefore, it is necessary to servo-control the display device.

Fig. 4 shows the active display mechanism with five degrees of freedom experimentally produced. Each degree of freedom is actuated by a direct drive torque motor (Inland Rare Earth D.D. Torque Motor).

The movement of the head is measured by the goniometer which is attached to the helmet as is shown in Fig. 4.

Experiments with this hardware revealed that the position/ orientation control is not enough. Subjects usually want a compliant motion which follows their head movement. Therefore, force assisted control based on the measurement of the head movement and/or force/torque associated with the head movement.

Visual displays were designed according to the procedure proposed in section 3.

Two color display systems were designed and made. One is a display of high picture quality with two 4 inch CRTs (18 kg). This is mechanically supported by a mechanism with one degree of freedom (Fig. 5).

The other is a light weight (4.7 kg) display with two 1.5 inch CRTs, the convergence angle of which can be computer controlled. This display is mounted on a five-degrees of freedom mechanism which is position controlled according to the head movement to ensure the right direction of sight (Fig. 6).

The visual tele-existence system with these displays were experienced by several subjects. All subjects had an impression that this type of display produces very realistic feeling of remote presence. These evaluations are, however, very subjective and qualitative. Therefore, following objective and quntitative experiments were conducted.

5. EVALUATION BY PSYCHOPYSICAL EXPERIMENTS

A metric of the visual space for a subject was measured both for the direct observation and through the tele-existence visual display designed. Several parametrs of the tele-existence visual display were chosen, and the results for the different parameters were compared.

Helmholtz Horopter [6] was chosen as the basis of the measurement of the metric of visual space [1]. An observer, placed in a dark room with his/her head fixed by means of a head rest, was given the task of arranging a number of light points (three in this case) so that they appear to lie on a horizontal straight line, symmetric to the median plane.

The points were set consistently on certain physical curves which were not straigh in the physical sense (Fig. 8, left). The form of these horopter curves depended on the distance x of the center point. At a certain distance x = a, the horopter was practically straight. At a shorter distances, x < a, the horopters were concave to the operator, at greater distances, x > a, they were convex.

Next the similar experiments of the horopter were repeated under indirect observation using the tele-existence system of Fig. 5, with several values of the object lens focal length. Fig. 7 shows the general view of the experiment.

The right hand side of Fig. 8 shows the result for the object which is at the distance of 1 [m] with the display parameters a = 161 [mm] and fd = 190 [mm]. Equivalent value of β changes according to the change of the focal length of the object lens fc. At the focal length fc = 12.5 [mm], β becomes 0.16, which is the theoretical parameter for the display. With that value of β, the horopter through the tele-existence display becomes almost the same pattern as that of the direct observation.

6. CONCLUSIONS

(1) A design procedure of the three-dimensional binocular visual display with sensation of presence, which was a part of the tele-existence system, was proposed, explicitly explained, and theoretically evaluated.

(2) A binocular color display, the spatial position and orientaion of which were servo-controlled to follow the movement of the head of an operator, was designed, experimentally constructed, and evaluated. Adding to the position/orientation control, force control was found to be important to ensure the necessary compliance of the display system.

(3) A binocular high quality color display with one degree of freedom was experimentally constructed and the quality of the three-dimensional visual space was qualitatively and quantiatatively evaluated.

(4) The correspondance between directly observed three-dimensional visual space and indirect three-dimensional visual space observed through a tele-existence display was measured quantitatively by the psychophysical experiment of the Helmholtz Horopter.

(5) The system designed using theoretically calculated parameters was proved to have the best correspondance with the direct observation.

REFERENCES

[1] S.Tachi et al.,"Study on tele-existence (I) -Design and evaluation of a visual display with sensation of presence-," Proceedings of the 5th Symposium on Theory and Practice of Robots and Manipulators (RoManSy 84) CISM-IFTomm, Udine, Italy, June, 1984.

[2] T.B.Sheridan,"Toward a general model of supervisory control," in T.B. Sheridan and G.Johannsen, Monitoring Behavior and Supervisory Control, Plenum, New York, 1976.

[3] S.Tachi,"Sensors for robots," Proceedings of the Xth World Congress of International Measurement Confederation (IMEKO), Prague, Czechoslovakia, April, 1985.
[4] B.Julesz,"Foundations of cyclopean perception," The University of Chicago Press, 1971.
[5] S.Tach et al.,"Guide dog robot - Feasibility experiments with MELDOG Mark III," Proceedings of the 11th International Symposium on Industrial Robots, pp.95-102, Tokyo, Japan, September, 1981.
[6] H.V.Helmholtz,"Treaties on psychological optics," vol.3, J.P.C.Southall, Ed., Optical Society of America, 1925.

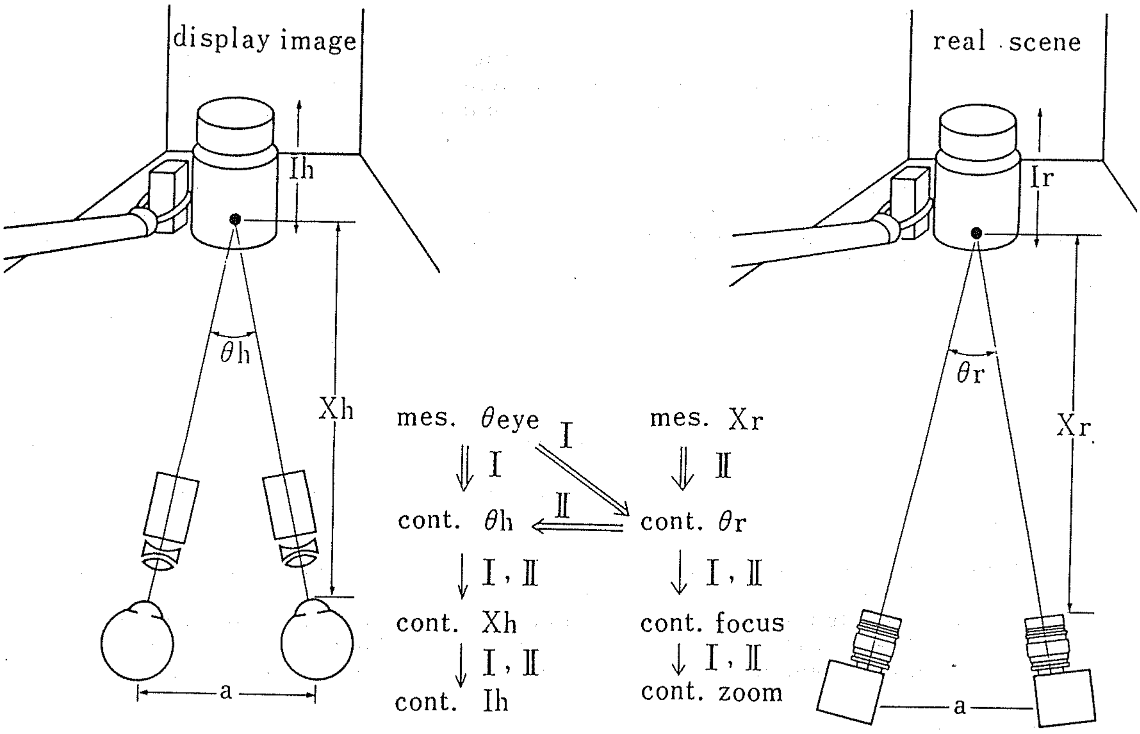


Fig. 1 Design concept of the display with sensation of presence [1].

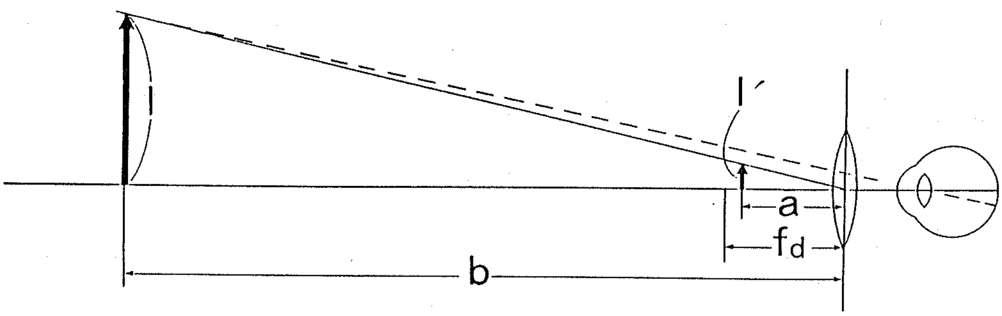


Fig. 2 Parameters of the visual display system.

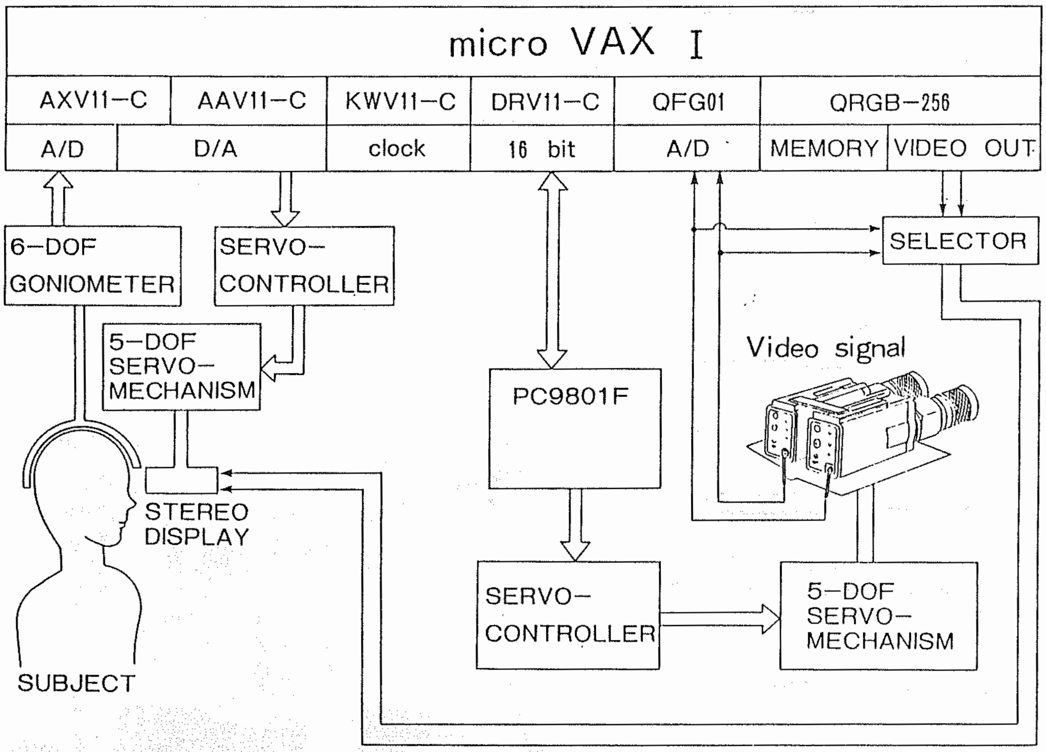


Fig. 3 Schematic diagram of the experimental system.

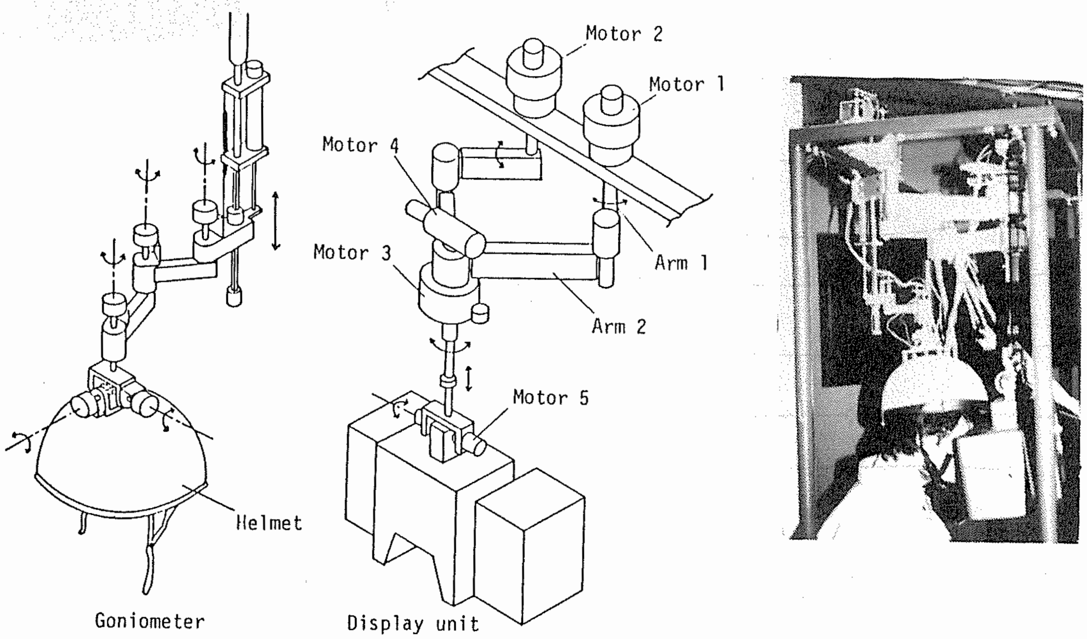
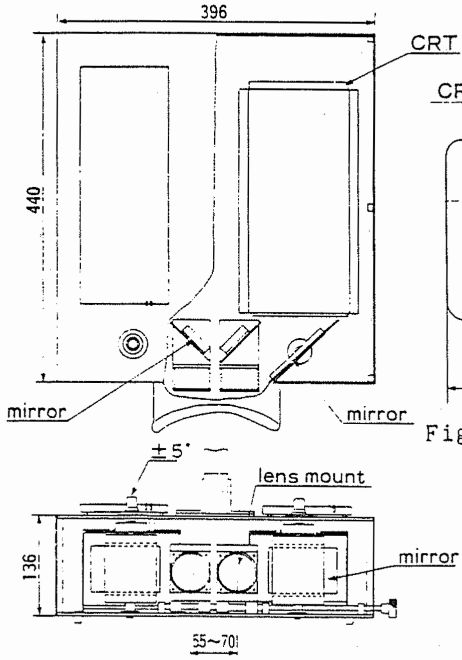


Fig. 4 Goniometer with six degrees of freedom (left), servo-controlled display mechanism with five degrees of freedom (middle), and the experimental hardware (right).



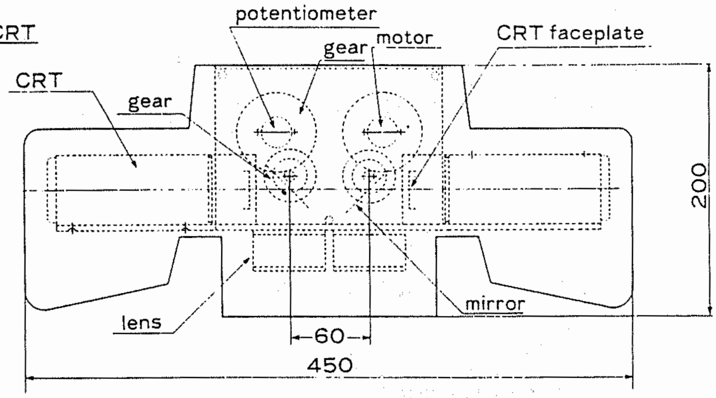
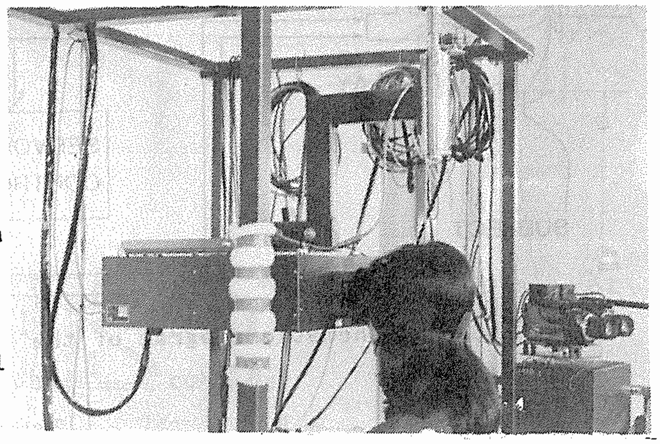


Fig. 6 Display employing 1.5 inch color CRT's with servo-controlled convergence.

Fig. 5 Display employing 4 inch color CRT's.

Fig. 7 Evaluation of the visual display by psychophysical experiments.



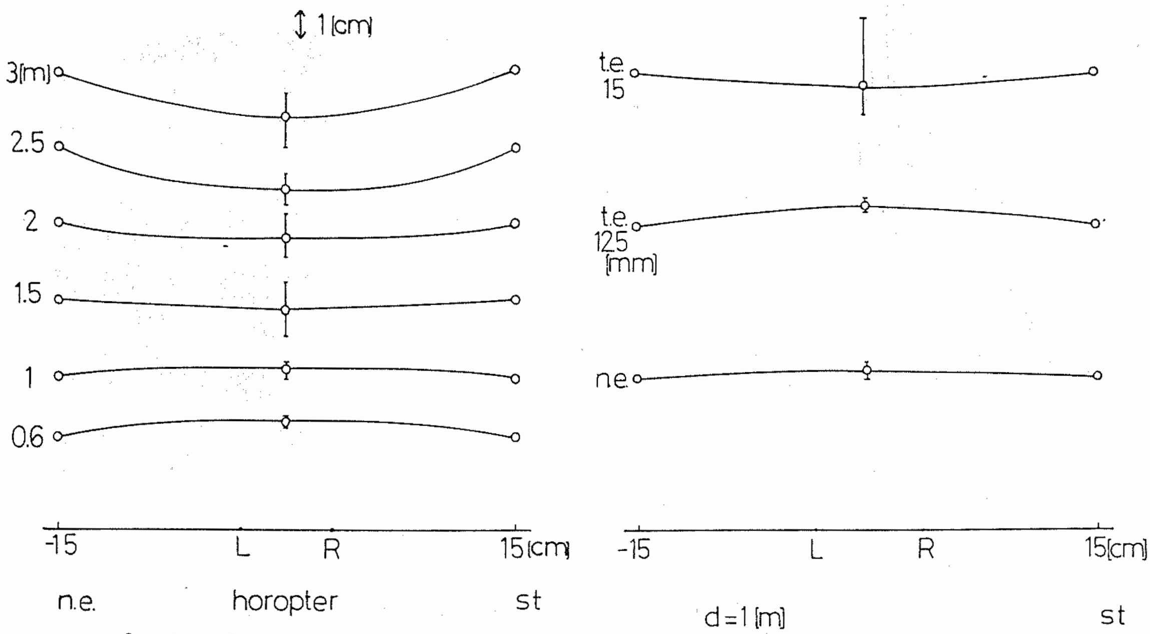


Fig. 8 Results of the measurement of the Helmholtz horopter curves for direct observation and through tele-existence display.