



**HAL**  
open science

## Spatial linear navigation: Is vision necessary?

Isabelle Israël, Aurore Capelli, Anne-Emmanuelle Priot, I. Giannopulu

► **To cite this version:**

Isabelle Israël, Aurore Capelli, Anne-Emmanuelle Priot, I. Giannopulu. Spatial linear navigation: Is vision necessary?. *Neuroscience Letters*, 2013, 554, pp.34-38. 10.1016/j.neulet.2013.08.060 . hal-02395669

**HAL Id: hal-02395669**

**<https://hal.science/hal-02395669>**

Submitted on 5 Dec 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Elsevier Editorial System(tm) for Neuroscience Letters  
Manuscript Draft

Manuscript Number:

Title: Spatial linear navigation : is vision necessary ?

Article Type: Research Paper

Keywords: Path integration; self-motion perception; multisensory integration

Corresponding Author: Dr. Isabelle Israel, PhD

Corresponding Author's Institution: CNRS

First Author: Isabelle ISRAEL, PhD

Order of Authors: Isabelle ISRAEL, PhD; Aurore CAPELLI, PhD; Anne-Emmanuelle PRIOT, MD, PhD;  
Irina GIANNOPULU, PhD, D.Sc.

Abstract: In order to analyze spatial linear navigation through a task of self-controlled reproduction, healthy participants were passively transported on a mobile robot at constant velocity, and then had to reproduce the imposed distance of 2 to 8 m in two conditions: "with vision" and "without vision". Our hypothesis was that the reproduction of distances would be longer with than without visual information. Indeed, in the "without vision" condition, the participants were accurate when reproducing short distances, but undershot long distances. With visual information the reproduction of all distances was overshoot. With vision the reproduction was more accurate than without vision; however this was not always significant, and therefore vision was not necessary.

Suggested Reviewers: Markus LAPPE  
Prof.  
mlappe@uni-muenster.de  
He devises models on visual navigation.

Glasauer STEFAN  
Prof.  
S.Glasauer@lrz.uni-muenchen.de  
Specialist of the vestibular system and self-motion perception.

Jean BLOUIN  
jeanblouin@univ-provence.fr  
Expert in visuo-vestibular interactions.

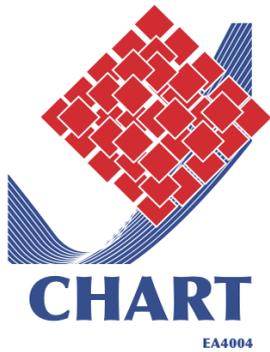
Adolfo BRONSTEIN  
Prof.  
a.bronstein@imperial.ac.uk

Laurence R HARRIS  
harris@yorku.ca  
Models on self-motion perception.

Jennifer CAMPOS  
campos.jennifer@torontorehab.on.ca

Frank DURGIN  
fdurgin1@swarthmore.edu

Brice Isableu  
brice.isableu@u-psud.fr  
Expert in spatial frames of reference.



**Laboratoire Cognitions Humaine et Artificielle CHArt**

**Ecole Pratique Des Hautes Etudes  
41 rue Gay Lussac  
75005 Paris  
EA 4004**

Paris, the 10th February 2013

I. ISRAEL  
EPHE - CHArt  
Isabelle.israel@free.fr

Dear Editor,

Please find herewith our manuscript :  
Spatial linear navigation : is vision necessary ?

written by :  
I. Israël, A. Capelli, A-E. Priot, and I. Giannopulu,

that we would like to submit for publication in Neuroscience Letters. It has not been submitted elsewhere and is not intended to. We think that our experimental findings on multisensory interaction and spatial orientation should interest the readers of Neuroscience Letters.

Waiting for the first reviewers comments, we thank you for your attention.  
Sincerely yours,

Isabelle Israël

- \* Without vision short distances were accurately reproduced but long ones were undershot.
- \* With visual information the reproduction of all distances was overshoot.
- \* With vision the reproduction was most often more accurate than without vision.

## Spatial linear navigation : is vision necessary ?

**I. Israël<sup>1</sup>, A. Capelli<sup>2</sup>, A-E. Priot<sup>3</sup>, I. Giannopulu<sup>4</sup>**

1 EPHE-CHArt, 41 rue Gay-Lussac, 75005 Paris, France email : [isabelle.israel@free.fr](mailto:isabelle.israel@free.fr)

2 University of Bordeaux and CNRS USR 3413 : Sommeil, Attention et Neuropsychiatrie, Bordeaux, France, [aurorecapelli@hotmail.com](mailto:aurorecapelli@hotmail.com)

3 Institut de recherche biomédicale des armées (IRBA), BP 73, 91223 Brétigny-sur-Orge cedex, France e-mail: [anne-emmanuelle.priot@irba.fr](mailto:anne-emmanuelle.priot@irba.fr)

4 Medical Engineering and Rehabilitation, Pierre and Marie Curie University, 4, place Jussieu 75005 Paris email: [igiannopulu@psycho-prat.fr](mailto:igiannopulu@psycho-prat.fr)

Corresponding author :

Isabelle ISRAEL

EPHE-CHArt, 41 rue Gay-Lussac, 75005 Paris, France

email : [isabelle.israel@free.fr](mailto:isabelle.israel@free.fr)

Tel: 01 40 44 76 41

## **Abstract**

In order to analyze spatial linear navigation through a task of self-controlled reproduction, healthy participants were passively transported on a mobile robot at constant velocity, and then had to reproduce the imposed distance of 2 to 8 m in two conditions: “with vision” and “without vision”. Our hypothesis was that the reproduction of distances would be longer with than without visual information. Indeed, in the “without vision” condition, the participants were accurate when reproducing short distances, but undershot long distances. With visual information the reproduction of all distances was overshoot. With vision the reproduction was more accurate than without vision; however this was not always significant, and therefore vision was not necessary.

## **Keywords**

Path integration, self-motion perception, multisensory integration

## **Introduction**

Perception and estimation of self-motion are based on multisensory information: visual, vestibular, and somatosensory. Their selection depends upon the experimental conditions, but also upon individual preferences such as the cognitive style [18, 42, 23, 28, 32, 40].

Through spatial navigation based on idiothetic signals (the signals produced by the organism itself, according to Mittelstaedt and Mittelstaedt, 1973 [29]) a subject should continuously know his/her position with respect to the starting point [30, 19].

In the frame of spatial navigation and self-motion, we had found that during the self-driven (and self-computed) triangle hypotenuse with constant velocity, the travelled distances were longer in light than in darkness [31]. These results suggested that distances are underperceived during self-motion with visual information. Indeed the subjects went on moving in light because they perceived (and believed) their own self-motion to be too short. However in the above study the travelled distance had really to be computed, it was not a simple copy as in reproduction tasks [2, 20]. Thus the role of vision cannot be attributed to motion perception since vision could have interfered with the distance computation. Therefore we devised a new reproduction task dedicated to understanding the role of vision in linear navigation.

It has been reported that the accuracy of spatial navigation increases when lightness decreases [6]. Therefore, visual information seems to cause underperception of passive self-linear navigation which leads to an overshoot of this displacement. This visual information effect perseveres during active movement (e.g. walking). Sun et al. (2004) [37] found that the availability of visual information during walking led to an

underperception of movement (leading to overshoot) relative to conditions in which visual information was absent.

It has been also shown that participants were able to reproduce the imposed distance by walking without vision, and that in some conditions they were able to use nonvisual information, i.e., somatosensory information, to arrive at distance estimates as accurate as those given by vision [27, 3, 12, 22, 30]. The mechanisms through which nonvisual somatosensory information can be used to perform self-navigation have long been studied [35, 36, 11, 8].

Continuous multimodal information interacts in the brain. Visual sensitive neurons in the medial superior temporal area [9, 10] and in the ventral intraparietal area [4, 5] have visual receptive fields and are selective for visual patterns similar to those seen during self-motion [24]. The neurons of both areas are also selective for motion in darkness, suggesting that they receive vestibular information [14, 15, 16, 39]. The medial parietal cortex is assumed to provide spatial information tied to a specific view [21]. This cortex is widely interconnected with other cortical areas (including lateral PFC) and subcortical structures [7]. A recent fMRI study of spatial navigation found that the medial parietal cortex is the area in which activation increases during visually signaled forward navigation [41]. The frontal lobes have been associated with working visuo-spatial memory and planning, which all depend on the recognition and integration of a vast network of information. Neuroimaging studies have also shown that somatosensory afferent information reach the frontal and ventral prefrontal cortex also contribute to spatial navigation [1, 13].

The aim of the present study is to analyze spatial linear navigation through a task of self-controlled reproduction. Healthy participants were passively transported at constant velocity on a mobile robot and then had to reproduce the imposed distance, using a

joystick to drive the robot, in two conditions: “with vision” and “without vision”. Four distances (2, 4, 6, and 8 m) had to be reproduced. Our hypothesis was that the reproduction of distances would be longer with visual information than without.

## **Material and Methods**

### Participants

Twenty-two volunteers, 10 males and 12 females participated in the study. They were aged from 20 to 33 years old (mean age 25 years SD 3 years). All were free from any known vestibular and somatosensory disorders.

### Experimental device

A four-wheeled robot (Robuter, Robosoft SA, France), equipped with a racing-car seat was used (Fig. 1) (see Berthoz et al., 1995 [2]). Its velocity was recorded from an odometer. The acceleration was  $0.80 \text{ m/s}^2$  and the peak velocity was  $0.90 \text{ m/s}$ . Steering was achieved by controlling the relative speed of the two drive wheels. The robot could be controlled either remotely (by a personal computer through a wireless modem) or directly (by a joystick on the robot itself). The joystick controlled the robot's linear velocity in steps of  $0.05 \text{ m/s}$  (robot velocity directly proportional to joystick angle), with a  $0.2\text{-s}$  delay. Positioning accuracy and linearity of the trajectory were ensured by proportional integral derivative control loops operating at  $100 \text{ Hz}$  (using optical encoding of position with a resolution of  $1 \text{ mm}$ ) and a trajectory generation and control algorithm operating at  $250 \text{ Hz}$ .

Insert figure 1 here

## Procedure

The participants were seated on the robot. They were secured to the seat by means of three safety belts. Their head was restrained by a cushioned support (to impede displacements and jaw rotations). They wore headphones that relayed a wide-band noise ("pink" noise) to prevent external acoustic cues [2]. Optically encoded digital odometry (50 Hz) was transferred from the robot through the modem after each trial. Two phases were designed: training and experimental. During the training phase, all participants were called to use the joystick to control the robot's navigation with their head restrained and with headphones. They were left free to move forward along a 50-m corridor until they felt confident in manipulating the robot with and without light. During the experimental phase, a displacement of 2, 4, 6, or 8 m was imposed in pseudo-random sequence in two conditions: "with vision" and "without vision". In both conditions and each distance the participants were passively transported by the robot forward along the sagittal X-axis (stimulus). In the "with vision" condition the subject was instructed to orient the head and his/her gaze straight ahead; in the "without vision" condition the subject was blindfolded and was required to close the eyes. In both conditions, after the robot came to a complete stop, the experimenter touched the participant's shoulder. This was the signal for the participant to continue straight ahead, moving the robot with the joystick (response). The task was to reproduce, as accurately as possible, in the same direction the distance previously imposed (2, 4, 6, or 8 m). All participants were assigned to both conditions "with vision" and "without vision". The dependent variable was the reproduced distance for each displacement. This distance was calculated in m (meters). Only the data from the experimental phase were considered.

The study was approved by the local ethics committee and was in accordance with the Helsinki convention. All subjects signed an informed consent. Preliminary results have previously been published as abstracts [33, 34].

## **Results**

The distribution of responses according to the reproduction of distances in the two conditions approximates a non-parametric shape. With such distribution, the median has been chosen as a central index of reproduced distance for each movement. The statistical comparisons have been conducted with the Wilcoxon matched-pairs signed-ranks test.

The intraindividual comparisons between the four reproductions of distances have been computed between the two experimental conditions: “with vision” and “without vision”. As can be seen in the Fig. 2, the reproduction of all the tested distances was longer when participants were in the light, than when they were in the dark ( $T = 3$ ,  $n=11$ , one-tailed test,  $p < 0.005$  for 2 m,  $T=1$ ,  $n=11$ , one-tailed test,  $p < 0.005$  for 4 m,  $T = 1$ ,  $n=11$ , one-tailed test,  $p < 0.005$ ,  $T=1$ , for 6 and 8 m). In the Fig. 3, the group’s median distance of reproduction was 1.99 and 3.96 for 2 and 4 m and 4.86 and 6.67 for 6 and 8 m in darkness; it was 2.24 and 4.27 for the 2 and 4 m and 6.36 and 8.49 for 6 and 8 m in the light.

Moreover, “without vision” (with somatosensory information only), the reproduction of distance was more accurate for short distances (2 and 4 m) (reproduction error -0.01 m for 2 m of distance; and -0.04 m for 4 m of distance). Similarly, “with vision” (both visual and somatosensory information), the reproduction of distances was less accurate for long distances (6 and 8 m) than for short distances

(error reproduction 0.36 m for 6 m of distance; 0.49 m for 8 m of distance) but in contrast the error here (with vision) was overshoot.

In other words, with visual information participants seem to underperceive the four distances (which leads to an overshoot of the reproduced distances), and without visual information they seem to overperceive the tested distances (which leads to an undershoot of all the distances).

Insert figures 2 and 3 here

## **Discussion**

Our study focalized on the way visual information could influence spatial linear navigation, using a task of distance reproduction. Four distances (2, 4, 6 and 8 m) were used. Compatible with our hypothesis, the results of the study can be summarized as follows: 1) in both conditions (with and without vision), the reproduction of distances was accurate for small distances; 2) with visual information the reproduction of all distances was underperceived, i.e., participants overshoot the distances to be reproduced; 3) without visual information the participants undershot the longer distances. While with vision the reproduction seems more accurate than without vision, this was not always significant; therefore vision was not necessary but useful.

As in [2] the present results demonstrate that healthy humans can reproduce a linear path (of a simple dynamic profile) without visual cues, using somatosensory information, and show a remarkable degree of accuracy of the reproduced distance with small inter-individual variability. With vision, our results tell that the participants went on moving because they perceived (and believed) their own self-navigation to be too short.

Sun et al. (2004) [38] found that the availability of visual information during locomotion led to underperception of movement (leading to overshoot) relative to conditions in which visual information was absent during locomotion. On the other hand, for [17] when subjects moved in darkness they overperceived how far they had previously traveled: they pressed the button when they had travelled through only about half the actual distance (i.e., undershoot). Lappe et al. (2007) [25] tried to resolve this apparent contradiction: they showed that underperception of navigated distance occurs when the task involves a judgment of distance from the starting position, while overperception occurs when the task requires a judgment of the remaining distance to a particular target position. They presented a leaky integrator model that explains both effects with a single mechanism. The model integrates over the space covered by the movement, rather than over time, which predicts that leakage should only occur during movement. Lappe and Frenz (2009) [26] moreover showed that similar errors occur in the estimation of travel distance in the real world as in a virtual environment, consistent with the leaky integration model.

Our present results agree with those of [31], where participants had to close a triangle of which they were passively submitted to the first two sides. When the triangle two sides were travelled with vision, the last one self-driven without vision was too short, i.e., the two passive visual sides had been underperceived. And when the first two sides were without vision and the last self-navigated one with vision, this very last side was too long, i.e., the traveled distance with vision was being underperceived. Expressly, the participants overshoot the distance they had to compute. These results and our present ones suggest that an overshoot of distances can occur regardless the experimental task: estimation, production, reproduction or computation.

Moreover, when healthy participants were asked to drive without vision (in darkness) repeatedly a distance of 2 m, the produced distance was  $1.55 \text{ m} \pm 22.5\%$  at the first trial and  $1.90 \text{ m} \pm 5\%$  at the end of the trials [20]. Therefore, without visual information the production of distance is always overperceived (i.e., undershot). Similarly, the reproduction of 2 m distance via active movement (walking) without vision, is characterized by overperception, i.e., the participants undershot that distance [22].

Altogether, our data are compatible with neurophysiological findings which show that a vast network of signals including visual, vestibular and somatosensory ones reaches the medial superior temporal area [41], the ventral intraparietal area [9,10], the frontal and prefrontal cortex during passive/active forward navigation [1, 13], cortices which are important for spatial navigation.

In our case, because of constant velocity the vestibular afferences were minimized. The somatosensory information is characterized by precise somatotopy which leads to an accurate body representations in space. When visual information is combined with somatosensory information (“with vision” condition), the visual available information predominates (and dampens the other signals) the elaboration of body representation in space. As a consequence, during visual navigation the perception of somatosensory information is impoverished which leads to overshoot. When only somatosensory information is available (“without vision” condition), the participants are extremely accurate for small distances, but they are less accurate when they reproduce long distances, i.e., they undershoot the long distances. In other words, path integration is not successfully achieved for long distances, where external cues are certainly useful.

## Reference List

- [1] Angelaki,D.E., Gu,Y., DeAngelis,G.C., Visual and vestibular cue integration for heading perception in extrastriate visual cortex, *J. Physiol.*, 589 (2011) 825-833.
- [2] Berthoz,A., Israël,I., Georges-François,P., Grasso,R., Tsuzuku,T., Spatial memory of body linear displacement: What is being stored ?, *Science*, 269 (1995) 95-98.
- [3] Bigel,M.G., Ellard,C.G., The contribution of nonvisual information to simple place navigation and distance estimation: an examination of path integration, *Can. J. Exp. Psychol*, 54 (2000) 172-185.
- [4] Bremmer,F., Klam,F., Duhamel,J.R., Ben Hamed,S., Graf,W., Visual-vestibular interactive responses in the macaque ventral intraparietal area (VIP), *Eur. J. Neurosci.*, 16 (2002) 1569-1586.
- [5] Bremmer,F., Duhamel,J.R., Ben Hamed,S., Graf,W., Heading encoding in the macaque ventral intraparietal area (VIP), *Eur. J. Neurosci.*, 16 (2002) 1554-1568.
- [6] Cavallo,V., Colomb,M., Dore,J., Distance perception of vehicle rear lights in fog, *Hum. Factors*, 43 (2001) 442-451.
- [7] Cavanna,A.E., Trimble,M.R., The precuneus: a review of its functional anatomy and behavioural correlates, *Brain*, 129 (2006) 564-583.
- [8] Cheung,A., Zhang,S., Stricker,C., Srinivasan,M.V., Animal navigation: the difficulty of moving in a straight line, *Biol. Cybern.*, 97 (2007) 47-61.
- [9] Duffy,C.J., Wurtz,R.H., Sensitivity of MST neurons to optic flow stimuli. I. A continuum of response selectivity to large-field stimuli, *J. Neurophysiol.*, 65(6) (1991) 1329-1345.
- [10] Duffy,C.J., Wurtz,R.H., Response of monkey MST neurons to optic flow stimuli with shifted centers of motion, *J. Neurosci.*, 15 (1995) 5192-5208.
- [11] Durgin,F.H., Akagi,M., Gallistel,C.R., Haiken,W., The precision of locomotor odometry in humans, *Exp. Brain Res.*, 193 (2009) 429-436.

[12] Ellard,C.G., Shaughnessy,S.C., A comparison of visual and nonvisual sensory inputs to walked distance in a blind-walking task, *Perception*, 32 (2003) 567-578.

[13] Ghazanfar,A.A., Schroeder,C.E., Is neocortex essentially multisensory?, *Trends in Cognitive Sciences*, 10 (2006) 278-285.

[14] Gu,Y., Watkins,P.V., Angelaki,D.E., DeAngelis,G.C., Visual and nonvisual contributions to three-dimensional heading selectivity in the medial superior temporal area, *J. Neurosci.*, 26 (2006) 73-85.

[15] Gu,Y., DeAngelis,G.C., Angelaki,D.E., A functional link between area MSTd and heading perception based on vestibular signals, *Nat. Neurosci.*, 10 (2007) 1038-1047.

[16] Gu,Y., Angelaki,D.E., DeAngelis,G.C., Neural correlates of multisensory cue integration in macaque MSTd, *Nat. Neurosci.*, 11 (2008) 1201-1210.

[17] Harris,L.R., Jenkin,M., Zikovitz,D.C., Visual and non-visual cues in the perception of linear self motion, *Exp. Brain Res.*, 135 (2000) 12-21.

Notes: Article

[18] Isableu,B., Ohlmann,T., Cremieux,J., Vuillerme,N., Amblard,B., Gresty,M.A., Individual differences in the ability to identify, select and use appropriate frames of reference for perceptuo-motor control, *Neuroscience*, 169 (2010) 1199-1215.

[19] Israël,I., Bronstein,A., Kanayama,R., Faldon,M., Gresty,M.A., Visual and vestibular factors influencing vestibular "navigation", *Exp. Brain Res.*, 112 (1996) 411-419.

[20] Israël,I., Grasso,R., Georges-François,P., Tsuzuku,T., Berthoz,A., Spatial memory and path integration studied by self-driven passive linear displacement .1. Basic properties, *J. Neurophysiol.*, 77 (1997) 3180-3192.

[21] Jahn,G., Wendt,J., Lotze,M., Papenmeier,F., Huff,M., Brain activation during spatial updating and attentive tracking of moving targets, *Brain Cogn.*, 78 (2012) 105-113.

[22] Klatzky,R.L., Loomis,J.M., Golledge,R.G., Cicinelli,J.G., Doherty,S., Pellegrino,J.W., Acquisition of route and survey knowledge in the absence of vision, *J. Mot. Behav.*, 22 (1990) 19-43.

- [23] Kozhevnikov,M., Kosslyn,S., Shephard,J., Spatial versus object visualizers: a new characterization of visual cognitive style, *Mem. Cogn.*, 33 (2005) 710-726.
- [24] Lappe,M., Bremmer,F., Pekel,M., Thiele,A., Hoffmann,K.P., Optic flow processing in monkey STS: A theoretical and experimental approach, *J. Neurosci.*, 16 (1996) 6265-6285.
- [25] Lappe,M., Jenkin,M., Harris,L.R., Travel distance estimation from visual motion by leaky path integration, *Exp. Brain Res.*, 180 (2007) 35-48.
- [26] Lappe,M., Frenz,H., Visual estimation of travel distance during walking, *Exp. Brain Res.*, 199 (2009) 369-375.
- [27] Loomis,J.M., Da Silva,J.A., Fujita,N., Fukusima,S.S., Visual space perception and visually directed action, *J. Exp. Psychol. Hum. Percept. Perform.*, 18 (1992) 906-921.
- [28] Lopez,C., Lacour,M., Magnan,J., Borel,L., Visual field dependence-independence before and after unilateral vestibular loss, *NeuroReport*, 17 (2006) 797-803.
- [29] Mittelstaedt,H., Mittelstaedt,M.L., Mechanismen der Orientierung ohne richtende Außenreize, *Fortschr. Zool.*, 21 (1973) 46-58.
- [30] Mittelstaedt,M.L., Mittelstaedt,H., Idiothetic navigation in humans: estimation of path length, *Exp. Brain Res.*, 139 (2001) 318-332.
- [31] Nico,D., Israël,I., Berthoz,A., Interaction of visual and idiothetic information in a path completion task, *Exp. Brain Res.*, 146 (2002) 379-382.
- [32] Nori,R., Giusberti,F., Predicting cognitive styles from spatial abilities, *Am. J. Psychol.*, 119 (2006) 67-86.
- [33] Priot,A.E., Israël,I. Visual and non visual informations in perception of passive linear displacement. XXIIIth meeting of the Barany Society, Paris, France, July 7-9, 2004
- [34] Priot,A.E., Israël,I. Effect of vision on perception of self-motion in linear displacement. 5<sup>th</sup> Annual Meeting of the International Multisensory Research Forum, 2-5<sup>th</sup> June 2004, Barcelona, Spain.

- [35] Rieser,J.J., Ashmead,D.H., Talor,C.R., Youngquist,G.A., Visual perception and the guidance of locomotion without vision to previously seen targets, *Perception*, 19 (1990) 675-689.
- [36] Schwartz,M., Haptic perception of the distance walked when blindfolded, *J. Exp. Psychol. Hum. Percept. Perform.*, 25 (1999) 852-865.
- [37] Sun,H.J., Campos,J.L., Young,M., Chan,G.S., Ellard,C.G., The contributions of static visual cues, nonvisual cues, and optic flow in distance estimation, *Perception*, 33 (2004) 49-65.
- [38] Sun,H.J., Campos,J.L., Chan,G.S., Multisensory integration in the estimation of relative path length, *Exp. Brain Res.*, 154 (2004) 246-254.
- [39] Takahashi,K., Gu,Y., May,P.J., Newlands,S.D., DeAngelis,G.C., Angelaki,D.E., Multimodal coding of three-dimensional rotation and translation in area MSTd: comparison of visual and vestibular selectivity, *J. Neurosci.*, 27 (2007) 9742-9756.
- [40] Vianin,P., Baumberger,B., Fluckiger,M., Distance estimation in a dynamic simulated environment: a visual field dependence problem?, *Perception*, 33 (2004) 561-568.
- [41] Wolbers,T., Hegarty,M., Buchel,C., Loomis,J.M., Spatial updating: how the brain keeps track of changing object locations during observer motion, *Nat. Neurosci.*, 11 (2008) 1223-1230.
- [42] Young,L.R., Oman,C.M., Merfeld,D.M., Watt,D.G.D., Roy,S., Deluca,C., Balkwill,D., Christie,J., Groleau,N., Jackson,D.K., Law,G., Modestino,S., Mayer,W., Spatial orientation and posture during and following weightlessness: human experiments on Spacelab-1, *J. Vestib. Res.*, 3 (1993) 231-240.

## **Figures captions**

Fig.1 : Image of the robot.

Fig.2 : Distribution of the responses in (a) light and (b) darkness, following the four distances.

Fig.3 : Traveled distances (median + interquartile range)

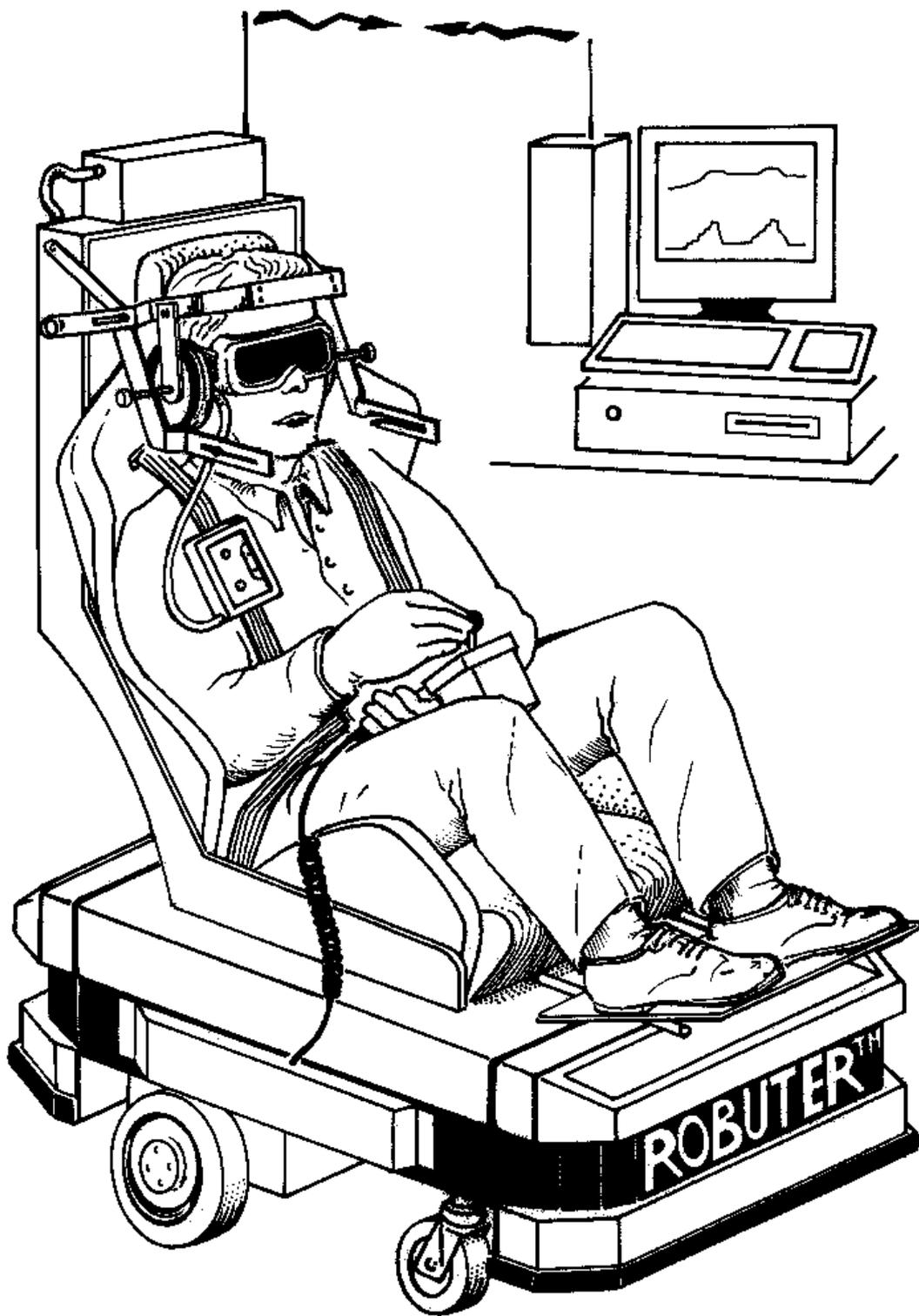


Fig.1

