Tilt Perception by Constant Tactile and Constant Proprioceptive Feedback through a Human System Interface

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Abstract

Tilt perception through a haptic human system interface is experimentally investigated. Tactile feedback is provided by vibration motors and proprioceptive feedback by the Cybergrasp exoskeleton. Enriching mere vibrotactile feedback by additional constant force feedback has not been found to influence human tilt perception. Participants' verbal and haptic estimations of the displayed tilt were highly accurate. As expected, tilt estimations depend on the actual tilt.

1 Introduction

Human system interfaces enable human operators to perceive and act in virtual or remote environments. Improving the operator´s feeling of presence and enabling him to perform the given task well is a major topic in research of human system interaction. Not only visual, but also haptic (tactile and proprioceptive) information, should be fed back to the human operator (e.g. [1]). Most displays provide either vibrotactile (e.g. [2], [3]) or force feedback (e.g. [4], [5]). Therefore, enhancing vibrotactile feedback by additional force feedback should improve the human operators' feeling of presence and performance (e.g. [1], [6]).

The aim of this study is twofold: First, human tilt perception through a human system interface which can display either vibrotactile feedback alone or additional constant force feedback to three fingers is examined. Secondly, influence of enriching mere vibrotactile feedback by additional force feedback on tilt perception and feeling of presence is experimentally investigated.

When perceiving angles of e.g. tilted surfaces or edges of real objects, finger position and movement of fingers (proprioceptive information) as well as contact (tactile) information is necessary (e.g. [7]). The importance and the high precision of the proprioceptive sense in perceiving the actual finger position is well known (e.g. [8], [9], [10]). Actively discriminating differences in angles has shown high resolution acuity (e.g. [11], [12]).

When humans explore objects haptically, they build an internal representation of the touched object and map their limb positions within a reference frame (e.g. [13]). To perceive tilt information provided to three fingers by a haptic display, integration of information across fingers is demanded. This has been found to bear some difficulties and to depend on variability of interfinger-distance (e.g. [14], [15], [16]). Nevertheless, due to the high precision of the proprioceptive sense, participants should be able to perceive the displayed tilts and to reproduce them accurately either haptically or verbally. Inconsistent differences between response modes have been reported: They show either superior performance with intramodal (e.g. [17]) or cross-modal reproduction (e.g. [16], [18]). Additionally, prior research indicated that performance is influenced by tilts (e.g. [13], [18], [19]): Errors of estimating the principal axis are known to be smaller than when estimating the oblique axes, i.e. the 45° and the 135° tilts. This anisotropy is called the oblique effect [20].

The questions to be answered by the presented experimental study are whether acuity of human tilt perception provided by the human system interface depends on response mode, actual displayed tilt, and feedback mode. Additionally, influence of feedback mode on presence ratings was assessed.

This paper is organized as follows: In Section 2 the method of the conducted experiment is introduced, and the human system interface is described in detail. The results are presented in Section 3 and discussed in Section 4.

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2 Method

2.1 Participants

Fifteen right-handed men of the University der Bundeswehr München and Technische Universität München participated in the study. They were on average 27 years old.

2.2 Human System Interface

Hardware and Software. The human system interface provides proprioceptive and vibrotactile feedback. Furthermore, it measures finger positions. See Figure 1 for a photo and Figure 2 for a sketch of the device.

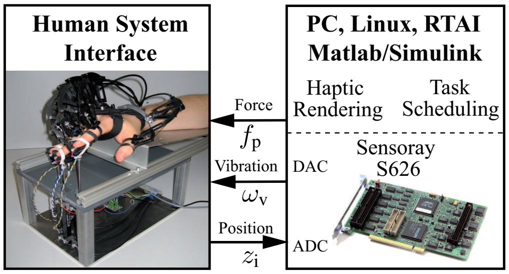

Figure 1. Human system interface and real-time processing unit: Vibrotactile and proprioceptive forces are commanded and positions are sensed.

Proprioceptive information is induced by the CyberGrasp^{TM} exoskeleton (Immersion Corporation). It exerts feedback forces separately to each finger perpendicular to the fingertips pulling the fingers to the rear. Maximum possible force is 12 N per finger with a resolution of 12 bit. Position information is measured by linear motion potentiometers covering a range of about 100 mm. These analog sensors independently measure the position of each finger, z_i, relative to the support plate of the device (see figure 2). Space between the sensor of the index finger and the middle finger is 36 mm, space between the sensor of the middle finger and the ring finger is 32 mm. Sensors are adjustable in y-direction to match finger lengths of different participants. Vibrotactile information is induced by vibration motors mounted in suspensions on the top of the position sensors. The motors, normally used in cellular phones, operate at a constant frequency of 40 Hz. The suspensions consist of stiff plastic and are trough-shaped fitting the form of the fingertips. The fingertips are fixed with velcro assuring that participants could be unfastened easily when asked to report their haptic estimates. An additional armrest fixes palm and forearm to be in the same position for all trials.

The system is connected to a PC running RTAI-RealTime Application Interface for Linux. Actuator and sensor signals are exchanged through a "Sensoray 626" DAQ-Card providing 16 bit sensing resolution. Hence, accuracy of position information is higher than 0.1 mm. Control and signal processing algorithms are implemented as Matlab/Simulink models with realtime code generated automatically. The system operates at 1 kHz sampling frequency.

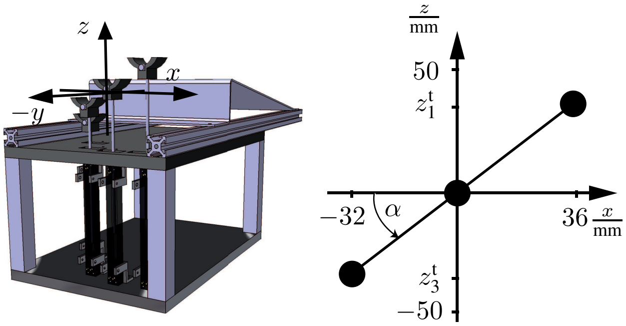

Figure 2. Position sensing system: Tilt is controlled by measuring z-positions of the finger tips.

Control Structure. The tilt is defined by the angle α and transformed to positions z^t according to

$$z^t(x) = -\tan(\alpha)x. \tag{1}$$

Tilt positions for each finger are defined by $z_1^t := z^t(36\,\text{mm})$ (index finger), $z_2^t(0) := 0$ (middle finger), and $z_3^t := z^t(32\,\text{mm})$ (ring finger). See Figure 2 for an illustration. Constant proprioceptive stimuli applied to the fingers are generated according to the given tilt positions

$$f_p = \begin{cases} 0\,\text{N} & \text{for } z_i > z_i^t \\ 6\,\text{N} & \text{for } z_i \leq z_i^t \end{cases}, \quad i = 1, 2, 3. \tag{2}$$

Where z_i is the position of the i-th finger. A hysteresis function is applied to avoid chattering around the tilt positions. Constant vibrotactile stimuli are only exerted around the tilt positions by commanding angular velocities according to

$$\omega_v = \begin{cases} 0 & \text{for } z_i > z_i^t \\ 40\,\text{Hz} & \text{for } (z_i^t - 5\,\text{mm}) < z_i \leq z_i^t \end{cases}. \tag{3}$$

2.3 Stimuli

Haptic feedback was given to three fingers of the right hand, namely the index, the middle and the ring finger. Two feedback modes were realized: Vibrotactile feedback alone or vibrotactile and additional proprioceptive feedback.

The displayed tilt was defined as an angle between the three fingers toward the horizontal plane. Range of stimuli which could be displayed by the human system interface described in Section 2.2 was restricted to a maximum of 37°. Eight tilts ranging between 0° to 35° in steps of 5° were selected. The oblique effect having been addressed in prior research by comparing errors of estimating the principal axis against 45° or 135° tilted axis (e.g. [17]) should also be apparent in the 35° tilts compared to 0° tilts.

Each of the eight tilts was presented four times, two times under each feedback mode.

2.4 Tilt Board

Participants had to report their estimations of the perceived tilt in two ways: verbally and haptically. In order to allow haptic estimation of the displayed tilt a tilt board was constructed (see Figure 3) according to Proffitt et al. [16]. It consisted of a palm rest which allowed to adjust the perceived tilt by moving the plate. The palm rest could be moved below the horizontal plane by 10°. The starting position of haptic estimation was perpendicular to the horizontal plane.

Figure 3. The tilt board allowed participants to haptically report the perceived tilt displayed by the human system interface.

2.5 Procedure

Participants received a twenty-minute-training in order to get used to the experimental procedure. In the first part of the training session, participants could view the presented stimuli, in the second part they were blindfolded. Tilts explored during the training session were different from those presented afterward (3°, 13°, and 37° under both feedback modes).

During the test session participants were blindfolded and wore headphones providing pink noise to prevent them from hearing the vibration motors. Indicated by an auditory signal participants moved their three fingers down till they received haptic feedback. Time for testing the virtually presented tilt was unlimited. Afterward, participants reported the tilt either verbally and then haptically or vice versa as the instructor told them to do. The order of estimating the tilt (verbally and haptically) was balanced across the stimuli. Therefore, each tilt displayed by each feedback mode was estimated under both estimation types. Haptic estimation was done through the tilt board: Participants turned around to reach the tilt board which was positioned at a 45°-angle to the haptic display. They adjusted the tilt by tilting their wrist (abducting or adducting) and thereby moving the handle bar of the tilt board. This assured that participants did not match the previously perceived finger position and forced them to estimate the perceived tilt [16], [13].

After each stimulus presentation participants rated their confidence with their haptic tilt estimation on a 5-point scale with 1 representing ”low confidence” and 5 ”high confidence” and the quality of the received haptic feedback on a 10-point scale with 1 ”low perceived quality” and 10 ”high perceived quality”. Different scales were chosen to make subjects rate each questions separately. The trial ended with the participants replacing their fingers on the human system interface.

An additional control task measured the participants' ability to haptically adjust verbally commanded angles on the tilt board (e.g. [16]). Eight of them were those already presented during the test session; the two additional ones were 55° and 70°.

Furthermore, participants ranked their feeling of presence. Three questions of the Witmer& Singer ([6]) questionnaire translated into German by Scheuchenpflug ([21]) were selected. Participants rated on a 7-point scale with 1 ”low feeling of presence” and 7 ”high feeling of presence” their feeling of presence evoked by each of the two feedback modes separately, namely how natural the interaction with the environment seems to them, how strongly they felt immersed in the virtual environment and how much their experience in the virtual environment seemed consistent with their real-world experience. The order of rating tactile feedback alone and afterward tactile and additional proprioceptive feedback was balanced across participants.

Lastly, participants had to directly compare both feedback modes on a 7-point scale with -3 ”vibrotactile feedback alone” and 3 ”both feedback modes” and to decide under which feedback mode they felt it easier to perceive the displayed tilt.

2.6 Data Analysis

Before testing the assumptions it was controlled whether the order of estimating the tilt (first haptically and then verbally or vice versa) influenced the tilt estimations. A 2x8x2x2 analysis of variance (ANOVA) with repeated measurements (order of estimation type, tilt, feedback mode, response mode) yielded no significant main effect of order ($F(1,14) = 0.001, p = 0.974$). The assumption could therefore be tested without regarding order of response mode. Significance level was chosen to be $\alpha = 0.05$. If necessary, test statistics were corrected for assumed sphericity by the Greenhouse Geisser correction.

To test whether participants were able to perceive and reproduce the displayed tilt, a 8x2x2 ANOVA with repeated measurements was computed.

Assumptions concerning influence of displayed tilt, feedback mode and response mode on human tilt estimation accuracy were addressed by computing mean and absolute errors (e.g. [17]) which entered two separate 8x2x2 ANOVA with repeated measurements (tilt, feedback mode, response mode). The oblique effect was tested by comparing errors of estimating 0° and 35° tilts by a paired t-test.

Influence of feedback mode on confidence and quality rating was assessed by a 8x2 ANOVA with repeated measurements. The three presence ratings were summed and entered an univariate ANOVA to assess influence of feedback. Lastly, the preference rating, which was a direct comparison of both feedback modes, was reported by computing the medium and its interquartile distances.

3 Results

3.1 Influence of Tilt and Response Mode

Performance of participants showed high accuracy with the displayed tilt. Response mode seems to affect estimation differently, although errors are rather small: There was a trend to haptically overestimate tilts around the horizontal plane and to verbally overestimate tilts approaching the 45° axis (see Figure 5).

Participants were able to discriminate between the displayed tilts: The main effect of tilt was statistically significant ($F(3,39) = 88.877$ corrected by Greenhouse Geisser correction, $p < 0.05$) and accounted for most of the variance (partial $\eta^2 = 0.864$). Accuracy of estimating the perceived tilt was rather high (see Figure 4): Absolute errors of verbal tilt estimates amounted to on average 7.24 (standard deviation sd=2.52) and of haptic tilt estimates 8.54 (sd=1.12). Mean errors of verbal estimates yielded on average 2.78 (sd=2.25) and 5.47 (sd=2.57) when haptically estimating the perceived tilt. Absolute errors between displayed and estimated tilt turned out to be neither influenced by tilt ($F(3,42) = 2.544$ corrected by Greenhouse Geisser correction, $p = 0.069$) nor by response mode ($F(1,14) = 0.913$, $p = 0.355$), but were differently affected by response mode and tilt ($F(2,29) = 4.356$ corrected by Greenhouse Geiser correction, $p < 0.05$; partial $\eta^2 = 0.24$). This effect was due to an increase of absolute error of verbal estimates with increasing tilt (see Figure 5), but effect size is rather low. Additionally, neither tilt ($F(3,39) = 1.364$ corrected by Greenhouse Geisser correction, $p = 0.269$) nor response mode ($F(1,14) = 2.044$, $p = 0.175$) has an influence on mean errors of tilt estimation. But accuracy depended on tilt and response mode ($F(2,24) = 11.662$, $p < 0.05$) accounting for 45% of the variance. This effect was mainly due to an decrease in mean error of haptic estimates with increasing tilt (see Figure 5).

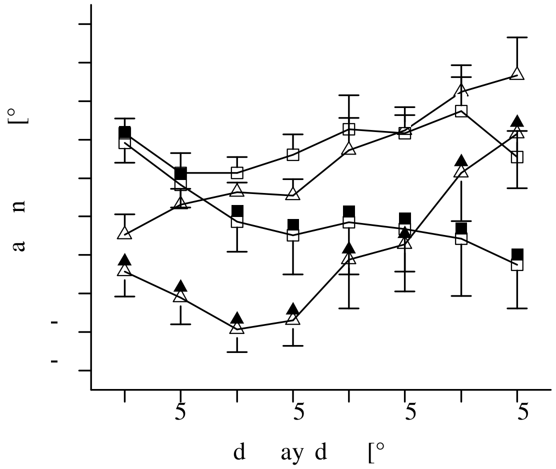

Figure 4. Absolute errors (unfilled signs) and mean errors (filled signs) of tilt estimates: Verbal estimates (triangles) show a systematic increase of errors with increasing tilt, whereas errors of haptic estimates (squares) increase with smaller tilts.

No difference between the estimation types has been found, but an interaction between estimation type and tilt. This might be due to the expected oblique effect which indicates differences in accuracy depending on tilt: The estimation of the horizontal plane should be more accurate than the estimation of the 35° tilt. As can be seen from Figure 5, this effect seems to be only true for verbal, but not for haptic estimates which show the inverse trend. T-tests of paired groups yielded no statistically significant difference of absolute error between no tilt and 35° tilt in haptic estimates ($t(14) = 0.139$, $p = 0.891$), but in verbal estimates ($t(14) = -2.991$, $p < 0.05$; ; $\eta^2 = 0.390$). There was no statistical significant difference of mean error when tilt had to be estimated verbally ($t(14) = -0.977$, $p = 0.345$), but estimating no tilt and 35° tilt influenced the haptic estimates ($t(14) = 2.502$, $p < 0.05$; $\eta^2 = 0.309$). Contrary to the assumption, accuracy of the haptic tilt estimation was higher in the 35° tilt.

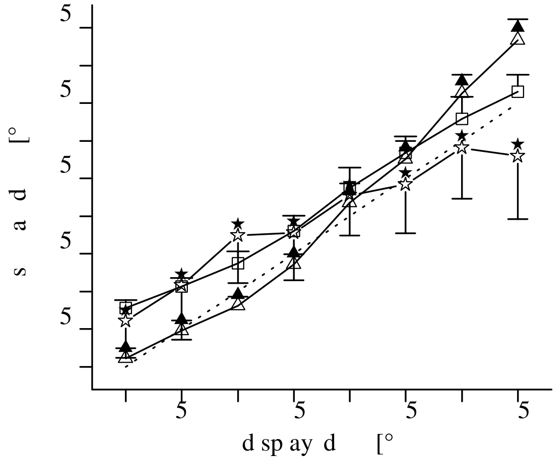

Figure 5. Haptic (squares) and verbal estimates (triangles) are close to the identity line (dashed line). Participants are able to haptically adjust a verbally commanded tilt (stars) and tend to underestimate the tilt when tilt increases.

3.2 Influence of Feedback Mode

Displaying the tilt information by either vibrotactile feedback alone or by vibrotactile and constant force feedback was expected to influence the tilt estimates. Accuracy of tilt estimations yielded no significant influence of feedback mode (*absolute errors*: $F(1, 14) = 0.845, p = 0.374$; *mean error*: $F(1, 14) = 0.478, p = 0.501$).

When vibrotactile feedback alone was given, participants ranked their confidence to be 3.5/5 (standard deviation sd = 0.2) and quality to be 7.1/10 (sd=0.4). Using both feedback modes their confidence amounted again on average 3.5/5 (sd = 0.2) and quality 7.3/10 (sd=0.2). However, feedback mode has no statistically significant influence on the ratings (*confidence*: $F(1, 14) = 0.120$, $p = 0.735$; *quality*: $F(1, 14) = 1.255, p = 0.281$).

At the end of the experiment, participants additionally answered three questions concerning their feeling of presence induced by the human system interface. Their general feeling of presence using vibrotactile feedback alone yields 13.5/21 (sd=4.2) and 13.4/21 (sd=2.9) using both feedback modes: The difference is not statistically significant ($F(1, 14) = 0.023, p = 0.881$).

Finally, participants were asked to directly compare both feedback modes. Participants tended to prefer vibrotactile feedback alone (median = -1.0/-3, toward tactile feedback alone). One fourth preferred tactile feedback alone (first interquartile distance -2.0/-3) and one fourth both feedback modes together (third interquartile distance 2.0/3).

4 Discussion and Conclusion

Independently of displayed feedback, overall performance of estimating tilt is high. Humans are able to perceive tilt by the presented human system interface and to report their estimate either by haptically or verbally. No strong tendency toward overestimation was found when participants verbally estimated displayed tilt information. This is contrary to Proffitt et al. [16] where participants had to estimate the slant of hills. This indicates a smaller bias between verbal estimation and haptic perception of tilts than between verbal estimation and visual perception.

Furthermore, estimation performance of participants depended on the displayed tilt. This so-called oblique effect which has been shown in vision (e.g. [20]) as well as in haptics (e.g. [18], [19]) is only apparent in verbal estimates: Accuracy of estimating the horizontal plane was higher than that of estimating the 35° tilt. No such effect could be found in haptic estimates; this might be due to the fact that supporting the arm reduces the oblique effect (e.g. [22]).

Although expected, the feedback mode has no influence on tilt perception. Adding proprioceptive feedback enhances neither performance nor ratings. This might be ascribed to the fact that constant force feedback provided by the CyberGrasp exoskeleton is less realistic. However, participants rated both feedback modes to not differ in evoking a feeling of presence or in displayed quality. Only a direct comparison of both feedback modes indicated a preference of constant tactile feedback over displaying constant tactile and constant proprioceptive feedback. Whether using more realistic (e.g. tilt of a solid surface) instead of constant force feedback would affect human performance has to be addressed in future research.

Another explanation for the missing influence of additional proprioceptive feedback might be attributed to the participants' overall high performance of estimating tilt in this study. In order to overcome this time for testing the virtually presented tilt should be constrained.

Acknowledgments

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References

[1] W. Barfield, D. Zeltzer, T. Sheridan, and M. Slater, *Virtual Environment and Advanced Interface Design.*,

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Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
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chapter Presence and Performance Within Virtual Environments., pp. 473–513, Oxford University Press., 1995.

[2] D. A. Kontarinis and R. D. Howe, "Tactile display of vibratoryinformation in teleoperation and virtual environment.," *Presence: Teleoperators and Virtual Environments.*, vol. 4(4), pp. 387–402, 1995.

[3] A. M. Murray, R. L. Klatzky, and P. K. Khosla, "Psychophysical characterization and testbed validation of a wearable vibrotactile glove for telemanipulation.," *Presence: Teleoperators and Virtual Environments*, vol. 12(2), pp. 156–182, 2003.

[4] Angelika Peer, Bartlomiej Stanczyk, and Martin Buss, "Development of a high performance haptic telemanipulation system with dissimilar kinematics," *Advanced Robotics*, vol. -, pp. –, 2006.

[5] A. Kron, G. Schmidt, B. Petzold, M. I. Zäh, P. Hinterseer, and E. Steinbach, "Disposal of explosive ordonances by use of a bimanual haptic telepresence system.," in *Proceedings of the 2004 IEEE International Conference on Robotics & Automation, New Orleans, L.A.*, 2004, pp. 1968–1973.

[6] B.G. Witmer and M.J. Singer, "Measuring presence in virtual environments: A presence questionnaire.," *Presence: Teleoperators and Virtual Environments.*, vol. 7(3), pp. 225–240, 1998.

[7] J. Voisin, G. Benoit, and C.E. Chapman, "Haptic discrimination of object shape in humans: contribution of cutaneous and proprioceptive inputs.," *Experimental Brain Research*, vol. 145, pp. 251–260, 2002.

[8] R. J. Van Beers, A. C. Sittig, and J. J. Denier van der Gon, "The precision of proprioceptive position sense.," *Experimental Brain Research*, vol. 122, pp. 367–377, 1998.

[9] L. A. Hall and D. I. McCloskey, "Detections of movements imposed on finger, elbow and shoulder joints.," *Journal of Physiology*, vol. 335, pp. 519–533, 1983.

[10] L. Bevan, P. Cordo, L. Carlton, and M. Carlton, "Proprioceptive coordination of movement sequences: discrimination of joint angle versus angular distance.," *Journal of Neurophysiology*, vol. 71(5), pp. 1862–1872, 1994.

[11] M.W.A. Wijntjes and A.M.l. Kappers, "What influences angular acuity in raised line drawings?," in *Proceedings of the EuroHaptics 2006*, 2006, pp. 333–338.

[12] J. Voisin, G. Benoit, and C.E. Chapman, "Haptic discrimination of object shape in humans: two-dimensional angle discrimination.," *Experimental Brain Research*, vol. 145, pp. 239–250, 2002.

[13] R. L. Klatzky and S. J. Lederman, "Representing spatial location and layout from sparse kinesthetic contacts," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 29(2), pp. 310–325, 2003.

[14] M. Hollins, *Steven's handbook of experimental psychology, vol 1. (sensation and perception)*, chapter Touch and haptics, pp. 585–618, N.Y.: Wiley., 2002.

[15] S.C. Pont, A.M.L. Kappers, and J.J. Koenderink, "Similar mechanisms underlie curvature comparison by static and dynamic touch.," *Perception & Psychophysics*, vol. 61(5), pp. 874–894, 1999.

[16] D. R. Proffitt, M. Bhalla, R. Gossweiler, and J. Midgett, "Perceiving geographical slant.," *Psychonomic Bulletin & Review*, vol. 2(4), pp. 409–428, 1995.

[17] F. J. Clark and K. W. Horch, *Handbook of Perception and Human Performance, volume 1*, chapter Kinesthesia, N.Y.: Wiley and Sons, 1986.

[18] E.C. Lechelt and A. Verenka, "Spatial anisotropy in intramodal and cross-modal judgements of stimulus orienatation: the stability of the oblique effect.," *Perception*, vol. 9, pp. 581–589, 1980.

[19] E. Gentaz and Y. Hatwell, "The haptic "oblique effect" in children's and adults' perception of orientation.," *Perception*, vol. 24, pp. 631–646, 1995.

[20] S. Appelle, "Perception and discrimination as a function of stimulus orientation: The "oblique effet" in man and animals.," *Psychological Bulletin*, vol. 78(4), pp. 266–78, 1972.

[21] R. Scheuchenpflug, *HCI International 2001.*, chapter Measuring presence in virtual environments, pp. 56–58, New Orleans: HCI International, 2001.

[22] E. Gentaz and Y. Hatwell, "Role of gravitational cues in the haptic perception of orientation.," *Perception & Psychophysics*, vol. 58(8), pp. 1278–1292, 1996.