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Short paper : Role of force-cues in path following of 3D trajectories in Virtual Reality

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Abstract

This paper examines the effect of adding haptic force cues (simulated inertia, compensation of gravity) during 3D-path following in large immersive virtual reality environments. Thirty-four participants were asked to follow a 3D ring-on-wire trajectory. The experiment consisted of one pre-test/control bloc of twelve trials with no haptic feedback; followed by three randomized blocs of twelve trials, where force feedbacks differed. Two levels of inertia were proposed and one level compensating the effect of gravity (No-gravity). In all blocks, participants received a real time visual warning feedback (color change), related to their spatial performance. Contrariwise to several psychophysics studies, haptic force cues did not significantly change the task performance in terms of time completion or spatial distance error. The participants however significantly reduced the time passed in the visual warning zone in the presence of haptic cues. Taken together, these results are discussed from a psychophysics and multi-sensory integration point of view.

Categories and Subject Descriptors (according to ACM CCS):
H.5.2 [Information Systems]: User Interfaces—Haptic I/O
H.5.2 [Information Systems]: User Interfaces—Evaluation/methodology

1. Introduction

Haptics is a sensory field increasingly used in virtual environments. By nature, introducing haptic feedback in a virtual reality (VR) experience necessarily change the action/perception loop for the user. According to [HA96], inertia and damping specification play an important role in the performance of such haptic devices, thus influencing human performance. Human performance can be defined as the efficiency in terms of spatial criteria (spatial error, final target precision,...), muscular efforts, dynamic criteria (speed, accelerations,...) and several other objective criteria influencing the effectiveness of the task [San93]. Other gravitational cues, such as the mass of the manipulated object, gravity or friction are implicitly used during the movement or manipulation of objects. Although the role of these indices on haptic perception is quite well described in literature [BHMA92, COP96, MBL98, LMMJ07], few experiments have paid attention to simulated inertia or compensation of gravity on human performance in virtual reality. [OGTV05] report "a positive influence on the reduction of muscular fatigue" in gravity compensation conditions. [EIL96] emit the hypothesis that gravity and device inertia can distort the operator's perception. Following this recommendation, [KWC99] implement a disturbance observer to compensate for these effects, which revealed to increase operator's perception by about 70%. In these studies, artificial compensation of gravity and reduction of inertia are described as having a positive influence on participants. Other researchers examined the effect of gravity level on arm movements [FLD93, LD05]. These results show that the accuracy of aimed arm movements deteriorates under modified gravity. Along the same vein, [PHRB96] proposed an experiment comparing haptic devices to usual I/O devices (mouse) in a micro-gravity environment, thus restoring gravitational

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cues for pointing control. Pointing with force feedback in microgravity gravity conditions revealed to be more time efficient and more accurate compared to traditional pointing control (mouse) in normal gravity conditions. Regarding the influence of inertia/apparent mass, [BM06] show a correlation between the level of inertia and the decrease in completion time for fine positioning tasks.

We then face two contradictory hypotheses:
- (1) gravity compensation and reduction of apparent mass/inertia revealed a positive influence on participants.
- (2) changes in gravitational cues (e.g. gravity compensation) in the haptic perception lead to degradation of human performance while an increase in simulated inertia lead to better human performance.

In this study, we are interested in contributions and psycho cognitive effects of such haptic force feedbacks for path following of a 3D trajectory in gravity compensation and simulated inertia conditions in virtual environments.

We present in the first part of the paper the specific virtual reality configuration and the experimental protocol we designed to evaluate our method. In the second section, we present the results, while the final part discusses the benefits and implications of such force cues in path following of 3D trajectories.

2. Materials and Method

2.1. Stringed Haptic Workbench

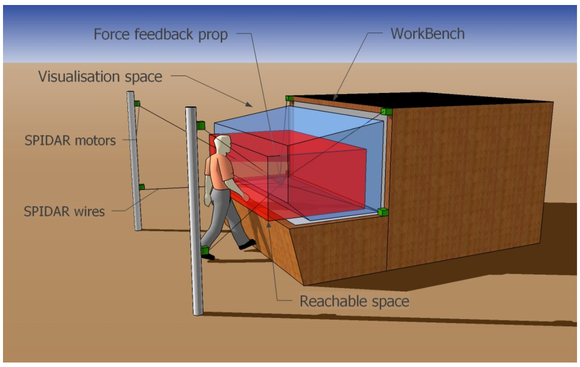

Figure 1: *The Stringed Haptic Workbench.*

To examine the influence of gravity compensation and different levels of simulated inertia on human performance, we used a configuration called the stringed haptic workbench [TCH*03]. The stringed haptic workbench is a virtual reality configuration composed of two large stereoscopic projection screens (stereoscopic display via active shutter glasses - 1280x1024 at 96 Hz per screen), surrounded by a string-based force feedback device (spidar) [HS92] [cf. figure 1]. This configuration allows a co-localized interaction space, and thus, a better immersion for the user [She92].

It allows large visualization of environments such as geologic landscape visualization, aerodynamics flow display, and virtual artistic creation. In our experiment, the user was facing the workbench, holding a plexiglas wand (semi transparent material to limit occlusions) as the interaction prop, where the strings of the haptic device were attached. During the path following task, the user felt simulated haptic cues (compensation of gravity, simulated inertia or even contacts with other objects).

2.2. Trajectory

In order to investigate the path following of a 3D trajectory, we imitated the "ring on a wire" task [RAB*00, BHSS00, EBM*97] by designing a specific trajectory. Moreover, it took into account the technical limitations (mainly in rotation due to strings knots) of our force feedback device. It followed the natural flow of movement for European countries (i.e. from left to right) [see Figure 2].

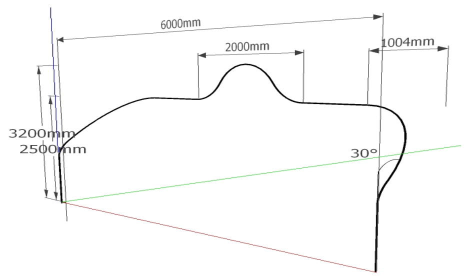

Figure 2: *Experimental 3D Trajectory.*

[FKT02] showed that visuo-haptic feedbacks lead to better performance than under haptic only or visual only conditions. Thus, we designed our experiment to be in this visuo-haptic case. As visual feedback, we implemented a visual "warning" by a color change. If distance between user position and theoretical trajectory was lower than 1 cm, the sphere representing the user's position was displayed in green. If the distance increased over 1 cm, the sphere became orange. Finally, if the distance was over 2 cm, the sphere turned red. As we wanted to assess the effect of haptic feedback, the visual feedback remained active during all the sessions and was delimited by a starting and ending sphere.

2.3. Haptic force feedback: simulated inertia and gravity compensation

The compensation of gravity was done by applying a constant upward force by the value of the mass of the manipulated system. Gravity compensation was theoretically estimated and experimentally tuned to 0.5N (plexiglas wand $\approx$ 0.050 Kg). This compensation implied a reduction of gravitational cues. We expected that it would decrease human performance for path following tasks.

The simulation of inertia was implemented by force opposing the movement in all directions. We defined two levels of stiffness to simulate inertia: Inertia: **2N/mm**; Strong Inertia: **5N/mm**. By increasing kinesthetic feedbacks, we expected to increase the participant's performance.

2.4. Measured Variables

The SPIDAR device allowed us to record the position and time stamp of the prop at about 0.5 kHz for each trial. Three main criteria were used to evaluate the performance of the movement:

-**Duration** (in seconds) consisted in the difference between the end time stamp and the beginning time stamp of the experimental trajectory. It can be done as soon as we assume that the recording is starting/stopping when the user passes through spheres at the beginning/end of theoretical displayed trajectory.

-**Root Mean Square error** consisted in the temporal-spatial error between the theoretical trajectory and the experimental trajectory. This measure represented a spatial accuracy criterion but required the same sampling for both trajectories. We performed a constant spatial re-sampling (sampling distance = 0.1mm).

- **Percent of time where visual feedbacks** where displayed consisted in counting the number of times where the user was within the visual "warning" zone, divided by the number of samples.

2.5. Experimental protocol

Participants consisted of 34 right-handed adults (11 women, 23 men), with no significant visual, motor or neurological dysfunctions. Their age average was 30 ($\pm$ 7.6). The present study was conducted in accordance with the Declaration of Helsinki. It was conducted with the understanding and the written consent of each participant which was obtained and approved by the local ethics committee.

People performed a first 12 trials session without haptic feedback to assess their baseline level (No Haptic). Then, they performed 12 trials for each of the three force feedback conditions (Inertia, Strong Inertia, No Gravity). The order of the conditions was given by a Latin square plan. Each participant was affected to a different order to avoid "order-effect". In total, participants executed 48 trials in about 35 minutes. Between each session of 12 trials, participants were allowed to rest in order to avoid fatigue.

3. Results

Preliminary analysis of variance (ANOVA) showed that the order of training sessions had no effect and did not interact with any other factors (all $p > .25$). Then, for each criterion, repeated-measures ANOVA was performed with 12 trials and 4 haptic conditions (No Haptic, Inertia, Strong Inertia, No Gravity) as independent factors. A summary of raw data can be found in Table 1:

	Control	No Gravity	Inertia	Strong Inertia
Duration	6.15 ± 0.89	5.56 ± 0.78	5.60 ± 0.97	5.55 ± 0.77
RMS	172.61 ± 19.97	174.75 ± 19.69	180.81 ± 20.18	181.34 ± 11.85
% VF	8.2 ± 2.8	4.95 ± 1.9	5.1 ± 1.2	5.7 ± 2.1

Table 1: *Table 1. Summary of raw data of Experiment 1 (mean $\pm$ SE).*

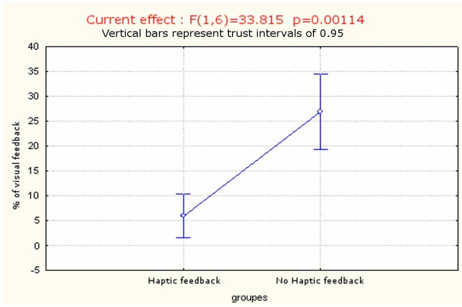

Figure 3: *% of visual feedback depending on haptic conditions.*

Concerning duration and root mean square error, the interaction between training mode and test was not significant (all p.>.25). The interaction between training mode and test was significant (F(1, 6)=33,815, p=,00114) for the percent of visual feedback criterion. A post hoc Newman-Keuls test revealed a trend (closely significant) difference between the no haptic feedback condition and the Strong Inertia condition (p=0.06) and no significant differences between control condition and other haptic conditions (see Figure 3). In addition, correlation tests between difficulty indexes [ZW03] and performance criteria were not significant.

4. Discussion and Conclusion

The present study focused on the effects of gravity compensation and simulated inertia on human performance criteria in a 3D-visuo-haptic following task. Three criteria were used: duration, root mean square error between theoretical trajectory and experimental trajectory and percentage of time during which the user was within a visual warning zone. The results showed significant decrease of the time passed in the visual warning zone, but no significant effects where observed for duration or spatial accuracy criteria in haptic conditions. We can also observe positive trends: simulated inertia contributes to an increase in the spatial accuracy but at the cost of increased production duration, regardless of the difficulty. The addition of resistance to the system (inertia) affects duration of realization. This same obstruction also reduces error, thus increasing spatial accuracy. Furthermore, we do not have cognitive conflict as soon as inertia addition can be found in a real situation (manipulation of massive objects, manipulation in viscous fluids). In the case of compensated gravity, we face the problem of cognitive conflict: the user is not used to gravity compensation. This condition may lead to a degradation of his/her performance. But the lack of stronger difference in user performance might also be explained by the relative simplicity of the trajectory and by the simplicity of our criteria. Futher experiments, involving more complex trajectories and more tricky criteria (such as dynamic time warping - DTW, maximum error distance, kinematics criterions [BCPG08]) need to be conducted. The close similarity of haptic rendering used (gravity compensation or simulated inertia are both modifications of gravitational cues) and the specificity of the SPIDAR device can also interfere in the generalization of our results. In conclusion, we found that simulated inertia tends to increase human performance by bringing additional kinesthetic cues. However, compensation of gravity tends to be detrimental to human performance and should only be used in very specific situations (e.g. to avoid fatigue).

5. Acknowledgments

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