The Effect of Haptic, Visual and Auditory Feedback on an Insertion Task on a 2-Screen Workbench

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Abstract

This paper reports on an experiment built to investigate the effect of haptic, visual and auditory additional information on the performances of a user operating an insertion task in virtual reality. Sensory information is added, during the insertion, when a collision occurs between the manipulated virtual object and some other part of the virtual scene.

The experimental apparatus uses a 2-screen workbench and a new wearable haptic interface: the Wearable Haptic Handle (W2H) which provides tactile stimulation inside the user's hand.

It seems that none of the additional information has a positive impact on the completion time of the task, when compared to the control condition (the visual feedback of the virtual scene alone). However, the movement of the subject when colliding is more limited in the presence of an additional information. The subject apparently pays more attention to the collision but, in return, achieve the task more slowly.

Furthermore, the directional information of the W2H seems to be difficult to understand and to use. The perceptive characteristics of the human hand are directly questioned by this surprising result.

At last, the different types of haptic feedback are mostly appreciated by the subjects. They are perceived as useful, pleasant and able to improve the realism of the simulation.

1 Introduction

The challenge of VR immersive technologies applied to the simulations of aeronautics maintenance or assembly operations [6] [10] is the backdrop of the study.

This paper addresses the question of the best hardware configuration for such applications and of the optimal combination of the different sensory modalities involved in the virtual environment. With this aim in view, this paper reports on an experiment built to investigate the effect of various types of sensory feedback - i.e. haptic, visual, and auditory information – on the performances of a user operating an insertion task in virtual reality.

The experimental apparatus used is based on a Holobench™ - a 2-screen workbench commercialized by Tan Company [1]. It also uses the Wearable Haptic Handle (W2H) - a new kind of wearable haptic interface developed by CEA[1] [7] and designed to fit the user's hand in immersive virtual environments (see Figure 1).

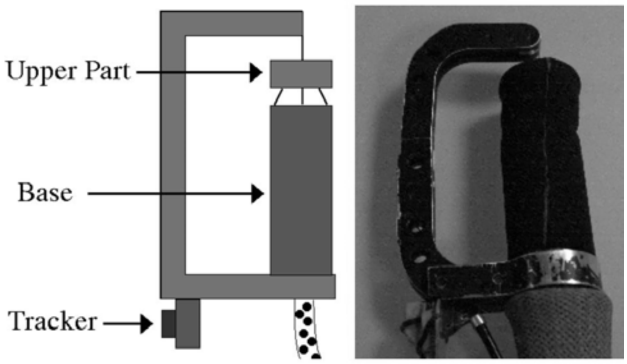

Figure 1. The Wearable Haptic Handle

The originality of the W2H device is that its upper part is a small platform which moves in 6 Degrees Of Freedom[2] (DOF) according to its base (see Figure 1). The motion of the upper part is actuated by a wire-driven Stewart platform. The user feels the displacements of the platform inside his/her hand while interacting with the virtual environment.

The workspace of the upper part corresponds to a cylinder that has height of 20mm and a radius of 8mm. The total weight of the handle is of 250g.

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[1] CEA: French Atomic Energy Commission.
[2] Degree Of Freedom (DOF): number of authorized motion of an object.

The choice of the W2H is due to two main characteristics which differ from the ones of most fixed-base haptic interfaces. First, the W2H has a wide workspace which can match the large space of visualization of the workbench. Second, the W2H is small enough not to hide the field of view of the user and thus not to truncate the stereoscopic display of the workbench.

Furthermore, the W2H is not intrusive and does not need any personalized calibration. However, contrary to a fixed-base haptic interface, the W2H can not stop the user's motion and will not prevent the user's hand from penetrating inside a virtual encountered object.

This study represents the first exploratory evaluation of the W2H concept.

This paper begins with an overview of related work concerning the effect of haptic feedback in a virtual environment. Then, it presents the experimental method used, followed by a description of the results. The paper ends with a general discussion.

2 Related work

The integration of haptic feedback inside an immersive virtual environment is a challenging field of research. Researchers already integrated force-feedback arm with large screen [16], force-feedback pen with workbench [5] [6] [8] or with fish-tank system [2]. All these examples emphasized the difficulty to make the haptic space match the visual one.

Haptic feedback was first shown to improve the user's performances in the field of teleoperation [9] [11]. Hill [9] showed that some complex tele-operated tasks are sometimes performed two times faster with force feedback. In telemanipulation tasks, visual feedback is assumed to be useful for aligning objects, whereas force feedback both ensures reasonable contact forces [14] and facilitates the control of the manipulated object trough physically constrained paths. However, the benefit of coupling haptic feedback with vision has received contrasted support.

In virtual reality, haptic feedback is useful to reinforce the feeling of immersion or to ameliorate telecollaboration [3] [20]. When simulating the information of reaction force, several researchers [2] [4] [19] showed that an additional information provided by force feedback or sensory substitutions can largely improve the performances of the users. For example, it is possible to represent reaction forces in the virtual environment on the visual mode (by using a symbolic arrow [4]), on the haptic mode (by using a vibration [12]) or on the auditory mode (by using a controllable sound [19]). Some studies showed that the performances of the users with such sensory substitutions can be roughly identical to those with straight force feedback [12]. The best performances are sometimes reached for bimodal combinations [19] (haptic plus visual or haptic plus auditory).

However, the presence of an additional information – haptic or other - may also impair the performance level [12] [18]. Massimino and Sheridan [12] studied different "peg-in-a-hole" tasks in teleoperation. Several types of additional feedback were provided to the user when a collision between the grasped object and the rest of the environment occurred. A sensory substitution proposed by the researchers consisted in a haptic vibration applied to different parts of the subject's hand (palm, thumb, index) according to the direction of the reaction force. In some tasks, force feedback or sensory substitutions failed in decreasing the task completion time of the insertion when compared with the situation with the visual feedback of the scene alone (provided to the subject by a TV monitor). The researchers assumed that "visual feedback alone appears to have dominated and was sufficient to allow the subject to perform the task as quickly as possible" [12]. They also stated that, concerning sensory substitution, it "overloaded the operator with information and decreased performance" [12].

Such results underline the "importance of carefully selecting the appropriate sensory stimuli" [13], when designing multimodal virtual environments.

3 Experimental Method

3.1 Hardware Platform

The hardware platform (see Figure 2) uses a SGI ONYX II graphic workstation. The graphic workstation runs the graphic rendering and the simulation loop – i.e. the collision detection between the manipulated object and the rest of the virtual scene and the modeling of the haptic and audio commands. The frequency of the simulation loop and of the graphic rendering is of 48Hz.

The visual feedback of the virtual scene is provided by a 2-screen workbench (see Figure 4) with a stereoscopic display and a headtracking system (the Fastrak^{TM} electromagnetic system from Polhemus Inc.). The refresh rate of the trackers output is of 60Hz.

The haptic command is sent to a "PC controller" which communicates with the "Motors' bloc" containing 6 DC motors. Each DC motor controls one of the wires of the Stewart platform of the W2H.

The motion of the manipulated object in the simulation corresponds to the one of the W2H – measured by one electromagnetic tracker (see Figure 1). To simplify the experiment, the object can exclusively be moved in translation, in 3 DOF. The grasping/dropping of the manipulated object is activated by a simple click on a button of a Pinch Glove which fits the non-dominant hand.

An audio helmet completes the hardware platform (see Figure 4). The audio signal is provided by the audio output of the graphic workstation.

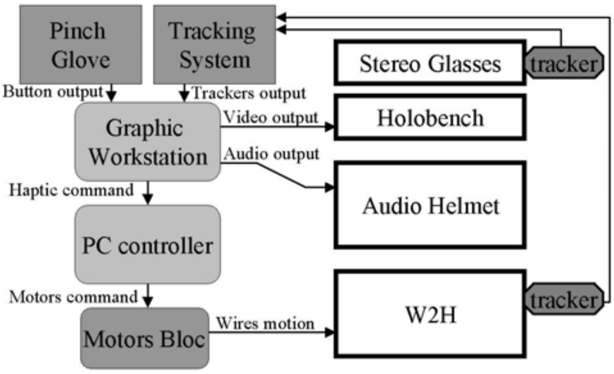

Figure 2. Hardware Platform

3.2 Task

The task proposed in the experiment corresponds to the insertion of a virtual white ball through five apertures (see Figure 3).

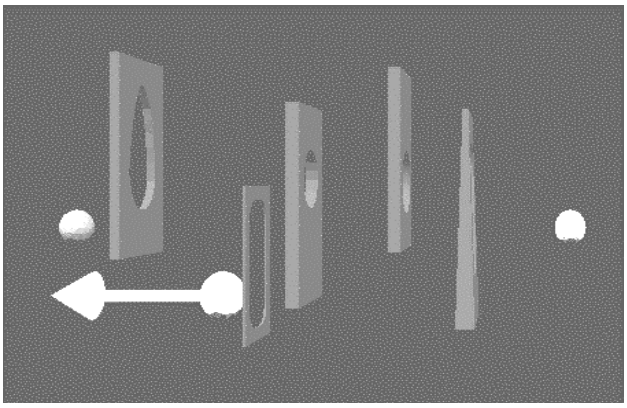

Figure 3. Insertion of a ball through five apertures

To initialize a trial, the subject first had to hit a green ball located on one side of the scene (on the right of Figure 3). Then the white ball had to pass through the five apertures. The trial was concluded when the white ball had hit a red ball (on the left of Figure 3).

The subject was told to achieve the insertion as fast as possible.

3.3 Experimental Design

The experimental design has six experimental conditions: one control condition and five other experimental conditions defined in terms of additional information.

The control condition (CL) corresponds to the visual feedback of the workbench alone – i.e. with no additional information when a collision occurs between the white ball and other objects of the virtual scene. Whenever a collision occurs, the white ball is simply stopped visually at the surface of the encountered object. There is no inter-penetration between the colliding objects in the simulation, thanks to the use of CONTACT – a continuous collision detection technique developed by Redon et al. [17]. However, the gliding of the ball is not simulated - i.e. when a collision is detected, the white ball remains stuck at the surface of the encountered object until the subject moves the W2H in the direction of "avoidance" of the current contact. The direction of avoidance of contact corresponds to the normal of the graphic contact in the simulation (i.e. Nc on Figure 5).

The other experimental conditions correspond to the control condition augmented by five possible additional sensory information. The additional information is fed back to the subject when the white ball collides with another object (an aperture). The additional information remains active until the subject moves the W2H in the direction of avoidance of contact.

The five types of additional information are:

1. Visual Directed Assistance (VDA)
   VDA is a visual arrow of contact (see Figure 3). The arrow starts from the point of contact in the simulation and gives the direction of avoidance of contact. The amplitude of the arrow is proportional to the amplitude of "error" of the subject – i.e. the amplitude of the user's penetration "inside" the encountered object. The refresh rate of the visual feedback of the workbench is of 48Hz (per eye).
2. Haptic Directed Assistance (HDA)
   HDA is a haptic multidirectional information. The upper part of the handle moves in 3 DOF, in the direction of avoidance of contact (the one of the visual arrow on Figure 3). The amplitude of the upper part's motion is proportional to the amplitude of error, with a minimum and a maximum value of displacement (2mm and 8mm). The frequency of the haptic feedback of the W2H is of 100Hz.
3. Haptic Simplified Assistance (HSA)
   HSA is a haptic unidirectional information. The upper part of the W2H moves in a constant direction (to the right of the subject). The amplitude of the

motion is proportional to the amplitude of error, with a minimum and a maximum value of displacement (2mm and 8mm). The frequency of the haptic feedback is of 100Hz.

4. Auditory ALarm (AAL)
AAL is a continuous "beep-like" sound with a frequency of 48kHz. The volume of the beep is determined by the subject before the tests.

5. Haptic Vibrating Alarm (HAL)
HAL is a haptic vibration. The vibration corresponds to an oscillating motion of the upper part of the W2H inside the hand. The platform moves laterally, with an amplitude of 2mm and a frequency of 50Hz.

The VDA and HDA conditions provide 3 types of indication to the user (alarm, amplitude of error, direction of avoidance of contact) on 2 different sensory modes (vision and touch). The HSA condition provides 2 types of indication (alarm, amplitude of error) on the haptic mode. At last, AAL and HAL provide only 1 indication (alarm) on 2 different sensory modes: hearing and touch.

HDA, HSA and HAL correspond to 3 types of haptic feedback offered by the W2H, with different levels of complexity.

3.4 Test Population

24 subjects took part in this experiment (see Figure 4).

The subjects were aged between 20 and 50. There were 19 men and 5 women. Only one person was left handed. All the subjects used their dominant hand to catch the W2H when performing the trials. The non dominant hand of the subject was fit with a Pinch Glove.

None of the subjects were familiar to the proposed virtual environment.

3.5 Procedure

The presentation order of the 6 conditions was controlled by using the *Latin Square* method applied to the following sequence: VDA-HDA-HSA-AAL-HAL-CL.

Each subject tested all the combinations defined by a triplet made of: one serie of five apertures (among 4 possible series, with different levels of difficulty), one direction of insertion through the apertures (among 2 possible directions: *left-right* or *right-left*) and one experimental condition (among the 6 possibilities: VDA, HDA, HSA, AAL, HAL and CL).

This makes a total amount of trials per subject of: (4 series) x (2 directions) x (6 conditions) = 48 trials.

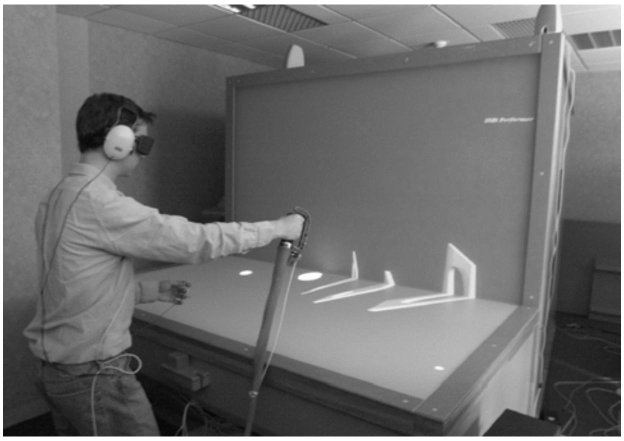

Figure 4. Subject performing the test

Before testing a new condition, the subject had the learning time that he judged necessary to get used to the new additional information.

According to the subjects, the experiment lasted from 60 to 90 minutes.

3.6 Collected Data

Measurable Variables

Several data were systematically recorded for each subject and each trial.

These data are:

1. Task Completion Time (TCT)
TCT is the average time spent by the subject to achieve the trials. Each trial's completion time begins with the first collision with the green ball (see Figure 3) and ends - after the insertion through the five apertures - with the first collision with the red ball (see Figure 3).

2. Number of Collisions (NC)
NC is the average amount of collisions detected between the manipulated ball and the other objects of the virtual environment (the apertures) during the trials.

3. Response Time to Contact (RTC)
RTC is the average time spent by the subject to respond to a contact, i.e. to move the handle in the direction of avoidance of contact (direction of Nc on Figure 5). On Figure 5, RTC corresponds to the time spent between positions *Pbc* and *Pec*.

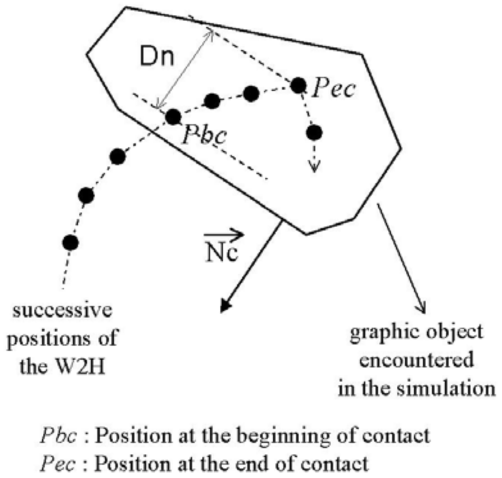

Figure 5. Normal Amplitude of Movement in Contact

4. Normal Amplitude of Movement in Contact (NAMC)
   NAMC represents the average amplitude of error when a contact is detected. It corresponds to the motion of the subject inside the encountered object until he/she moves the W2H in the direction of avoidance of contact. On Figure 5, this amplitude corresponds to the distance Dn.

Subjective Judgments

After the last trial of the experiment, the subjects had to fill in a questionnaire.

They first had to characterize the differences they felt between the three types of haptic feedback.

The subjects were also asked several questions about the five types of additional information. They had to evaluate the potential of each information to: provide an efficient information of alarm, provide an efficient information of direction of avoidance of contact, improve performances on the task, improve the realism of the simulation, be useful for the insertion task, and finally be pleasant.

At last, subjects had to choose among the various types of feedback the one they would like to keep for a future use.

4 Results

4.1 Measurable Variables

An ANalysis Of VAriance (ANOVA) was performed on the recorded data. The factors included in the analysis are the 6 conditions, the 4 series of apertures, the 2 possible directions (*left-right* or *right-left*) and the latin square.

Task Completion Time

Task Completion Time (TCT) is affected by the type of feedback in favor of the control condition (F[5,90]=3.004; p < 0.05). Figure 6 shows that TCT is shorter in the control condition than in other conditions (i.e. with additional information).

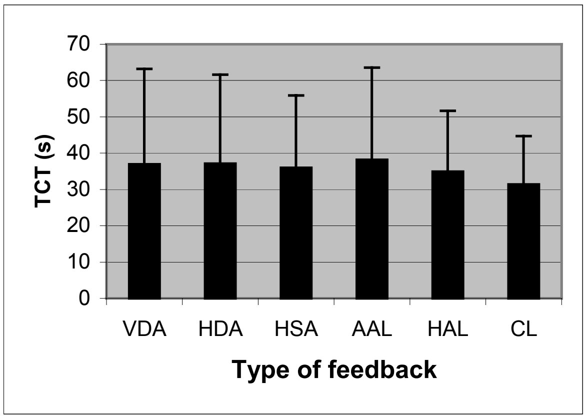

Figure 6. Task Completion Time as a function of the type of feedback

A post hoc analysis showed that the control condition is significantly shorter than: the auditory alarm condition (AAL) (t[1,191]=4.04; p<0.0001), the visual arrow condition (VDA) (t[1,191]=5.506; p<0.005), the Haptic Directed Assistance condition (HDA) (t[1,191]=5.647; p<0.005) and the Haptic Simplified Assistance condition (HSA) (t[1,191]=3.142; p<0.005).

The TCT is also dependant on the series of apertures (F[3,54]=32.51; p<0.01). Longer TCTs are observed in the two more difficult series of apertures. However, TCT is not influenced by the direction of insertion of the ball – i.e. *left-right* or *right-left* (F[1,18]=1.814; n.s.).

The effect of the latin square modalities is not significant (F[5,18]=1.51; n.s.). But there is a two-way interaction between latin square and the type of feedback (F[5,25]=6.44; p<0.001).

Figure 7 shows that TCT decreases strongly with the rank of trials (for nearly all the modalities of the latin square). However, for the subjects who began with the control condition (modality 6 of the latin square), the TCT seems to remain constant over trials. At the last trial (trial 6), differences between types of feedback tend to disappear.

Number of Collisions

The average Number of Collisions (NC) as a function of the type of feedback is given on Figure 8. There is no global effect of the types of feedback on the average number of collisions (F[5,90]=0.64; n.s.).

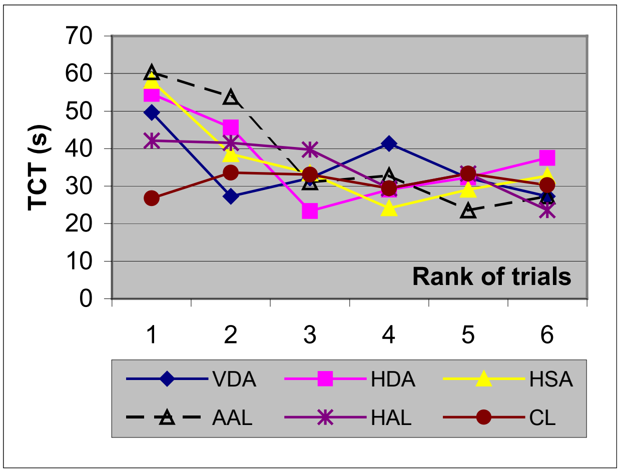

Figure 7. Task Completion Time as a function of the rank of trials

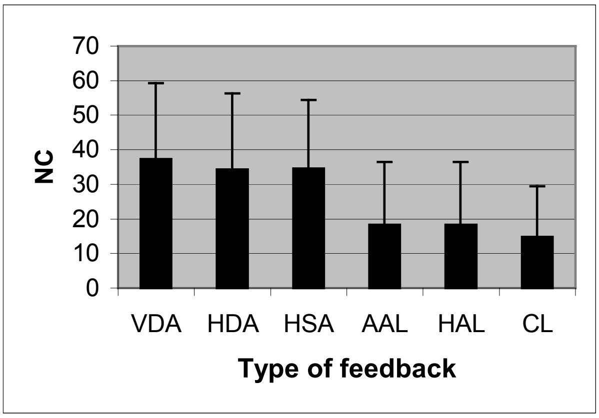

Figure 8. Number of Collisions as a function of the type of feedback

However, the VDA-CL comparison is statistically significant (t[1,191]=2.5; $p<0.05$). The control condition leads to the least number of collisions, whereas the visual arrow leads to the highest number of collisions.

There is an effect of the series of apertures (F[3,54]=64.81; $p<0.001$), which is similar to the effect on TCT. There is no effect of the latin square modalities. There are no significant two-ways or higher order interactions.

Besides, NC seems also dependant on the ranks of trials. The subjects who began with the visual arrow condition obtain an important number of collisions with the arrow, but this performance decreases and stabilizes itself for the other conditions. The same kind of observation can be made for the other modalities of the latin square, apart from modality 6 (beginning with the control condition) who leads to a stable number of collisions whatever conditions and trials.

Response Time to Contact

Response Time to Contact (RTC) is statistically affected by the type of feedback (F[5,90]=8.637; $p<0.01$).

Figure 9 shows that alarm-type information (sound or vibration) leads to a shorter RTC. RTC with HDA or HSA conditions (multidirectional or unidirectional haptic information) are longer than with any other feedback, even when compared with the control condition (CL).

There is an effect of the series of apertures, similar to the effect on TCT and on NC (F[3,54]=6.74; $p<0.005$). There are no significant two-ways or higher order interactions.

Normal Amplitude of Movement in Contact

The Normal Amplitude of Movement in Contact (NAMC) reflects the way the subjects succeeded in using the additional information. The average NAMC as a function of the type of feedback is represented on Figure 10.

No statistical difference can be found between the different types of additional feedback (F[5,90]=2,66; n.s.). However, the control condition (i.e. without any additional information) seems to impair the NAMC.

There is no effect of the series of apertures (F[3,54]=1,878; n.s.). There is no effect of the latin square modalities. At last, there are no significant two-ways or higher order interactions.

4.2 Discrimination Between the Different Types of Haptic Information

Answers of the Subjects

At the end of the experimental session, subjects were asked, in a questionnaire, to discriminate and differentiate the 3 types of haptic feedback.

First, it seems that all the subjects differentiate easily the vibration (HAL) from the 2 other types of haptic information.

Then, surprisingly, 63% of the subjects (15 out of 24) do not feel any difference between the multidirectional haptic information (HDA) and the unidirectional one (HSA). 25% of the subjects (6 out of 24) feel a difference between HDA and HSA, but without being able to characterize this difference. At last, only 12% of the subjects (3 out of 24) succeed in differentiating HDA and HSA, and in characterizing the perceived difference (the direction of movement of the upper part of the W2H).

These 3 subjects will be called from now on the "haptic subjects".

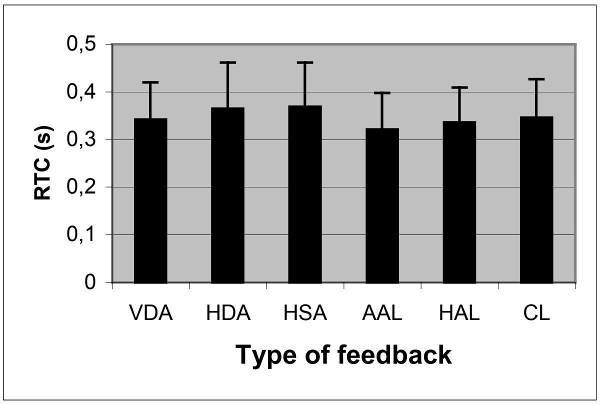

Figure 9. Response Time to Contact as a function of the type of feedback

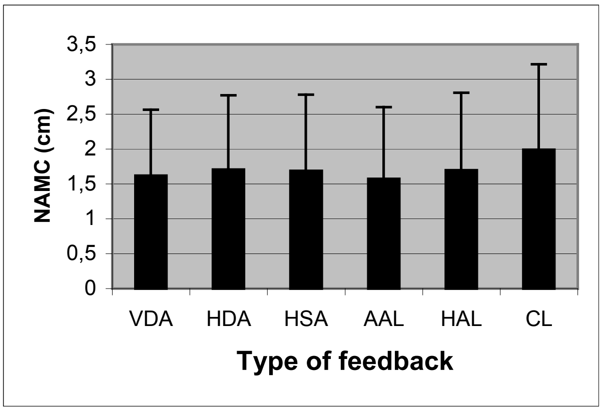

Figure 10. Normal Amplitude of Movement in Contact as a function of the type of feedback

Performance of the "haptic subjects"

Even though no statistical analysis can be made on the basis of these 3 people's results, it seems that the performances of the haptic subjects are much better than the performances of the 21 other subjects.

The haptic subjects performed the task very efficiently in terms of TCT. Their RTC and NAMC are also better than the ones of the other subjects.

The TCT of the haptic subjects are comparable in HDA, HSA and CL conditions. Nevertheless, even for these "haptic subjects", HDA, HSA or HAL condition does not lead to better RTC and NAMC than the control condition.

4.3 Qualitative Results

In the final questionnaire, subjects had to evaluate the different types of sensory information according to several criteria on a 10-level scale.

The main results are presented as follows:

Alarm information: the auditory feedback is considered as the most efficient alarm signal. Vibration is also considered as very efficient.

Directional information: the visual arrow is considered as the best "directional" information. The haptic directional information (HDA) comes second.

Performance amelioration: subjects are lucid since they think that additional information does not improve their TCT. However, the 3 "haptic subjects" judge the haptic feedback as very efficient in improving their performance.

Realism amelioration: subjects think that the three types of haptic information (HDA, HSA and HAL) and the auditory information (AAL) improve the realism of the simulation. Both the HSA and HDA information seem equally efficient, even though most of the subjects did not differentiate between the two of them.

Usefulness: the three types of haptic information are considered the most useful to achieve the insertion task.

Pleasantness: the three types of haptic information are globally considered as more pleasant than the other effects.

Choice of feedback: at last, the subjects were asked to select the additional information they would keep for a future use. The results are presented Figure 11. Subjects chose generally more than one type of feedback.

88% of the subjects (21 out of 24) chose at least one haptic information. 63% of the subjects (15 out of 24) chose the auditory feedback thanks to its alarm potential. Only 37% of the subjects (9 out of 24) chose the visual arrow.

The preferred haptic information is the multidirectional haptic information (HDA).

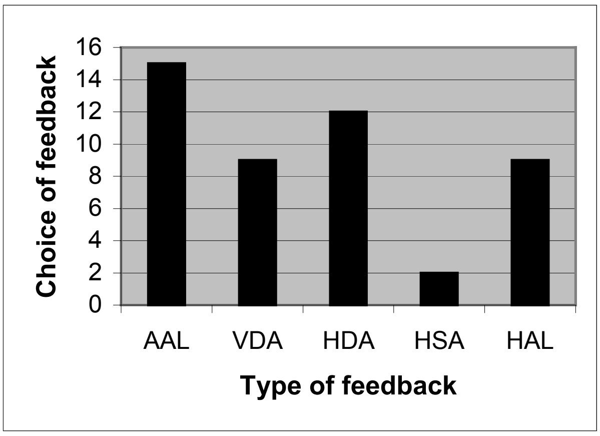

Figure 11. Choice of feedback for a future use

5 Discussion

5.1 Discussion on the Quantitative Results

Task Completion Time is not improved by any additional information, either haptic or non-haptic. TCT is significantly better without any additional information. This could be explained by the fact that the task may be performed, relying exclusively on the efficient visual feedback provided by the workbench. This assumption is the same as the one made by Massimino and Sheridan [12] to explain their results.

Furthermore, TCT is quite constant whether information is directional or not. Two hypotheses can be made to explain this remark:

1. The task does not require any directional cues to be performed. The subject can memorize the motion of the ball to generate corrections in the opposite direction.
2. The task requires directional cues to be performed but the different types of directional information, which were proposed, are difficult to understand and to use. The subjects rely more on the visual cues of the control condition rather than on the additional ones.

The fact that "haptic subjects" had good results with directional haptic information supports the second hypothesis. It seems that the insertion task requires directional cues to be optimally performed, but the directional additional information proposed were not adapted enough to the task and to the human perception to enhance performance.

This could also imply that the haptic feedback of the W2H deserves a longer training period. The 3 highly skilled subjects have maybe shown a more efficient level of adaptation than the other subjects.

The Number of Collisions is only sensitive to the task difficulty and does not reveal any difference between the various types of feedback, apart from the visual arrow which apparently impairs the number of collisions.

The Number of Collisions inside the virtual environment reflects the sensory-motor capacity of the subject to move the W2H in the 3D space. Since the W2H grasping is the same in all conditions, it seems correct to find no differences between the various types of feedback.

Response Time to Contact shows statistical differences among different types of feedback. RTC is longer with haptic information (HDA and HSA) than with others. The RTC with the haptic vibration (HAL) is also longer than with the other alarm information – i.e. the auditory information (AAL). Two hypotheses can be made to explain this result:

1. The mechanical performances (response, dynamic, magnitude of displacements) of the current model of the W2H (which is a prototype) are not good enough.
2. The cognitive treatment of the haptic signal by the subjects is not immediate and lengthens the response time to the stimulation. Future work is to be done to investigate human possibility to perceive and use tactile stimulation inside the hand.

The Normal Amplitude of Movement in Contact is decreased by additional information when compared with the control condition. It seems that the presence of an additional feedback makes the subject slow down the motion of his/her arm when colliding.

This result could also explain the poor results of the different types of additional feedback concerning the TCT: in presence of an additional information, the subject pays more attention to collisions but, in return, achieves the task more slowly.

5.2 Discussion on the Qualitative Results

The auditory information is considered as being the best alarm signal, even though the frequency of the signal is judged too high by a lot of subjects. This is coherent with the quantitative results.

The visual arrow is considered as giving the best directional information to escape from collision situations. This result is also logical since very few subjects understood the other directional information (the HDA information). However, the arrow is not really appreciated because of its visual behavior (too dynamic) in the simulation.

The three types of haptic feedback are highly appreciated by the subjects: 88% of the subjects chose at least one haptic information for a hypothetical future use. Haptic feedback is perceived as being useful and pleasant. It is also perceived as an efficient way to improve the realism of the simulation.

At last, 71% of the subjects (17 out of 24) found that the evaluation puts a strain either on vision (eye tickling, sickness due to visual movements of the graphic environment) or on the haptic sense (hand, arm, shoulder or back strain). But all the subjects were very motivated by testing this virtual environment again.

6 Conclusion

This experiment studied the integration and the effect of different types of sensory feedback within a virtual environment based on a 2-screen workbench and a Wearable Haptic Handle. It evaluated the effect of additional haptic, visual and auditory information on the performances of several subjects performing an insertion task in virtual reality. The additional information was activated when the manipulated object collided with some other part of the virtual scene.

The Task Completion Time is affected by the type of feedback, in favor of the control condition (the visual feedback of the virtual scene alone). On the one hand, these results show that the insertion task can be performed by relying simply on the efficient visual feedback of the workbench. On the other hand, adding an inappropriate feedback may impair performance level - as it is apparently the case with the symbolic visual arrow.

Response Time to Contact was systematically longer in the haptic conditions than in the others. This result may be explained by the slow response of the device or by the cognitive treatment of the haptic signal.

After the occurrence of a collision, the motion of the subject's hand was smaller in presence of an additional feedback than in the control condition. When receiving redundant information, subjects are more attentive to collisions but, in return, perform the task more slowly.

A subjective questionnaire showed that, surprisingly, only 3 subjects out of 24 were able to consciously discriminate the multidirectional haptic feedback of the W2H from the unidirectional one. This suggests that the directional information of the W2H is difficult to understand and to use within the context of the proposed experiment. This might be due to the difficulty of the human haptic perception to use tactile stimulation inside the hand.

Future work deals with perceptual studies concerning the ability of human to perceive and use tactile stimulation inside the hand.

Another evaluation, based on the same insertion task, seems also necessary to compare the haptic feedback provided by the W2H with the one of a fixed-base haptic interface. It would be interesting to measure the impact of the possibility to stop the user's motion during the insertion.

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