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Antoine LASSAGNE, Andras KEMENY, Javier POSSELT, Frédéric MERIENNE - Performance Evaluation of Passive Haptic Feedback for Tactile HMI Design in CAVEs - IEEE Transactions on Haptics (ToH) - Vol. 11, n°1, p.119-127 - 2018

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Performance Evaluation of Passive Haptic Feedback for Tactile HMI Design in CAVEs

Antoine Lassagne, Andras Kemeny, Javier Posselt, and Frederic Merienne

Abstract—This article presents a comparison of different haptic systems, which are designed to simulate flat Human Machine Interfaces (HMIs) like touchscreens in virtual environments (VEs) such as CAVEs, and their respective performance. We compare a tangible passive transparent slate to a classic tablet and a sensory substitution system. These systems were tested during a controlled experiment. The performance and impressions from 20 subjects were collected to understand more about the modalities in the given context. The results show that the preferences of the subjects are strongly related to the use-cases and needs. In terms of performance, passive haptics proved to be significantly useful, acting as a space reference and a real-time continuous calibration system, allowing subjects to have lower execution durations and relative errors. Sensory substitution induced perception drifts during the experiment, causing significant performance disparities, demonstrating the low robustness of perception when spatial cues are insufficiently available. Our findings offer a better understanding on the nature of perception drifts and the need of strong multisensory spatial markers for such use-cases in CAVEs. The importance of a relevant haptic modality specifically designed to match a precise use-case is also emphasized.

Index Terms—Haptics, human-machine interfaces, virtual reality

1 Introduction

Due to the recent improvements in high performance immersive systems, haptic feedback has become increasingly sought after by users who want to touch what seems real. Furthermore, haptic modalities seem to be an efficient way to improve interactive capabilities of Virtual Reality (VR) systems. The feeling of touching virtual objects is not easily attained as technological barriers are numerous. Currently few companies offer devices for natural interactions with the environment which can be used in an industrial context.

2 Related Work

2.1 Brief History

Haptic systems have been proposed since the very beginning of the development of VR. For example, in 1967 the GROPE project [1] was attempting to develop a force feedback mechanical arm with 2, 3 and finally 6 degrees of freedom (DOFs). Various more advanced systems emerged as VR started to grow in the early 90s, due to significant technological advancements which allowed for much greater computing power. For instance, *Cybergloves Systems* © proposed various products, from simple vibrotactile gloves to full haptic workstations with whole hand kinesthetic and cutaneous feedback. The SPIDAR collection [2], human-scaled systems made of taut strings and stepper motors, also emerged and became popular during these years. Meanwhile, *Sensable*© was releasing the Phantom Omni [3] (now called Geomagic Touch), which was one of the first affordable haptic devices. For over a decade, Haption©has been largely deploying haptic devices in spite of finding only a few early customers among the largest OEMs.

It has been established that haptic systems are necessary to improve the presence, the immersion and the performance [4], but also to reduce the cognitive load generated when vision is required to compensate for a lack of other perceptual cues [5]. With the recent maturity of high performance display systems and the large consumer deployment of head mounted displays (HMD), one can expect an increased interest in haptics in the years to come.

2.2 Haptics & CAVEs

Cave Automatic Virtual Environments (CAVEs) and HMDs have different constraints which often require a specific implementation. CAVEs do not overshadow the real environment, while HMDs do. HMDs thus do not need to deal with real objects mixed with virtual ones, like the human body, or with the intrusiveness of the systems.

CAVEs and similar display systems are broadly used by the automotive industry as VR tools. This is partly due to the high graphic quality and the ergonomics required by driving simulators, which deploy a lot of common technologies with CAVEs [6], but also to the simplified conception process offered by VR. However, haptic implementation is still troublesome in these immersive systems where the real environment cannot be fully hidden by the virtual one.

These devices thus have major criteria to meet to be compatible with CAVEs and industrial applications.

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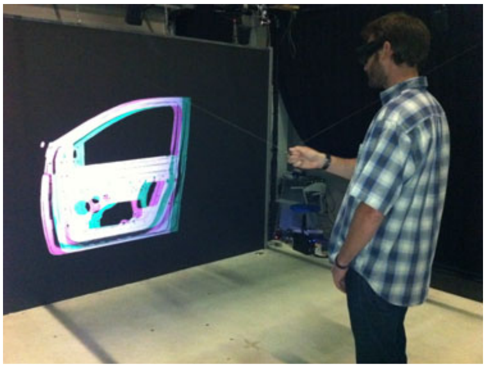

Fig. 1. A SPIDAR, providing kinesthetic feedback through taut strings.

- Visual intrusiveness is a critical issue in CAVEs, as physical objects are visible. This may cause a critical reduction in immersion [7], with the usual results.
- Physical intrusiveness also needs to be minimized to fit ergonomics and accessibility requirements.
- All perceptual stimuli should be synchronized with the visible self to avoid any visuo-haptic conflict.
- Haptic modalities (textures, kinesthesia, visual feedbacks, etc.) must respond to the use-case requirements.
- Industrial requirements must also be considered, which can be gathered through *usability*. There exists several definitions of usability with many different criteria like effectiveness, efficiency, learnability, attractiveness, security, operability, etc. [8]. In this study, we consider efficiency, effectiveness, and satisfaction of subjects (ISO 9241-11).

Several systems can be suited for use in CAVEs. Large scale *SPIDARs* [9] (Fig. 1), haptic arms, haptic gloves, or even non-contact haptic systems [10], [11]. Unfortunately, none of these are compatible with our use-case, due to deficiencies in fidelity, ergonomics, flexibility, robustness or flexibility.

2.3 Passive Haptics

Passive haptics, also called *Augmented haptics* or *Pseudo-haptics* were also studied in many experiments. The idea is to oppose a tangible passive object, co-located with the virtual object, to the actions of the user [12], [13], [14]. The subject merges the real and virtual environments in a global one, with visual and haptic feedback, like in the experiment conducted by Hoffman [13]. Research showed that it significantly increases the sense of presence and global immersion [15], [16].

This method is affordable, safe, and does not need computation time. It provides a robust kinesthetic feedback as well as the appropriate cutaneous sensations, although it does not address every possible situation. Still, it is suited for a large number of use-cases, especially when it simulates simple shapes, and can render satisfactory kinesthetic feedback. Kinesthesia is the key to performance in eye-coordinated tasks whereas cutaneous feedbacks are more effective when rendering only simple alerts [17]. Some systems seek a compromise between several haptic modalities like textures, forms, compliance, temperature, inertia, friction, whereas focusing on a precise modality makes an efficient haptic system easier to attain.

Despite all of these strong advantages, there are a couple of drawbacks.

- One or many tangible objects need to be accurately adjusted, calibrated, or even built, for every change in the displayed scene, which decreases the flexibility of the virtual technologies. When using passive haptics, loading a simulation may take more time than launching a visual environment with a few clicks.
- Real objects cannot be overshadowed by any virtual object in CAVE-like displays. This causes unusual image overlap and corresponding distorted distance perception [18], thus only the foreground can render haptics.
- An accurate spatial calibration between real and virtual objects may be difficult to attain. This is mainly due to imprecisions in the virtual position of the eye, and unfortunately it causes great offsets between visual and haptic perception [19], [20], [21]. The position of the eye is difficult to take into account, as people have important morphologic disparities [22].

Passive haptics are implemented in Renault CAVE IRIS (Immersive Room and Interactive System) to allow the users to sit in a car and handle a steering wheel. However, the virtual parts are totally occulted by physical ones which cannot be modified easily. The physical parts need to be calibrated as accurately as possible and tracked with precision to match multiple environments, and these constraints rarely allow for a perfect visuo-haptic synchronization.

2.4 Sensory Substitution

Sensory substitution is a substitution to haptic feedbacks by other sensory information, such as visual or auditory. These lighter solutions were considered to add interactive functionalities to VEs without heavy haptic implementation. Several studies concluded that visual or auditory cues helped users to know if and when a virtual collision occurred [23], [24], [25], [26], [27], [28], especially realistic cues like shadows or inter-reflections. Nevertheless, cues must be optimized for their effect to be positive. According to Kitagawa et al. [27], auditory cues may become intrusive while continuous and they are not as precise as visual ones while discrete. On the other hand, continuous visual cues are proven effective, but need to be seen by users while auditory ones do not.

Several studies concluded that the more visual cues there are, the stronger the space perception [29] and the easier the interaction becomes, although too many cues may increase the cognitive load or intrusiveness [26]. There were also experiments conducted to investigate which visual cues could be used, and when. Sreng et al. [28] concluded that visual glyphs like arrows or spheres were appreciated in the perception of distances and effort, whereas light sources were more effective to perceive contact locations. In general terms, continuous visual cues can provide continuous feedback capabilities from software and thus allow subjects to gain precision and accuracy.

3 Context of the Work

The automotive industry investigates virtual technologies to avoid the production of physical prototypes which are expensive and time consuming, but haptic modalities are needed in VEs lacking interaction capabilities [7]. Three haptic systems are tested in this experiment to evaluate if they could be of interest for dashboard HMI engineering design.

This study is focused on flat HMIs like touchscreens to satisfy the need of testing new designs of car computer interfaces while being in the cockpit, in context, not necessarily while driving. Such a system would allow the designers to evaluate the integration of their software creations inside the car, and the usage of the HMI with the right posture. Nowadays, HMIs are only tested on classic computers before they are integrated in an expansive physical prototype, not always in the exact configuration of the car.

This context is compatible with haptic systems which render only flat objects. The implementation is thus simplified and three interactive methods are considered.

- A sensory substitution based, visual-only, interaction system.
- An additional passive haptic device made of a transparent glass subjectively calibrated.
- A classic tablet fixed on an articulated arm.

The systems are evaluated in accordance with three criteria.

- *Performance* should be sufficient to allow effective interactions and feelings of confidence.
- *System Usability Scale*—Industrial usage requires a tool to be accessible to a large panel of users, and compatible with a large panel of use-cases.
- *Relevance*. Each haptic modality can respond to additional use-cases which must fit the context.

Finally, this experiment is carried out to evaluate how a subjective visual calibration, quickly made by each subject before beginning the experiment, can improve the quality of the visual coherence between the real and virtual parts. To have an efficient haptic feedback able to give self-confidence to the engineers who use the tool, real and virtual objects need to be perceived precisely in the same place.

4 RESEARCH PLAN

4.1 Scientific Context

This research aims at studying the added value of haptic feedback in interacting in immersive VEs. It is focused on virtual touchscreen-like HMI design.

Three haptic modalities are evaluated. We dealt with different scientific barriers :

- *CAVE-related questions* like intrusiveness, visuo-haptic synchronization, and space perception. CAVEs cause specific issues that HMDs do not. Objects cannot be visually intrusive, physical and virtual parts are mixed within the environment (especially the body of the subject), space perception can be biased, anthropological parameters have an influence, etc.
- *Haptic system related questions*, specific to the modality (kinesthesia, cutaneous, sensory substitution, etc.) and the actual device implemented.

We also seek to study industry-compatible interaction systems, with every related additional constraint (ergonomics, robustness, accessibility).

4.2 Research Questions and Hypothesis

Our research questions are related to the added value of tangible interfaces in the context of a full visual immersive system (CAVE type):

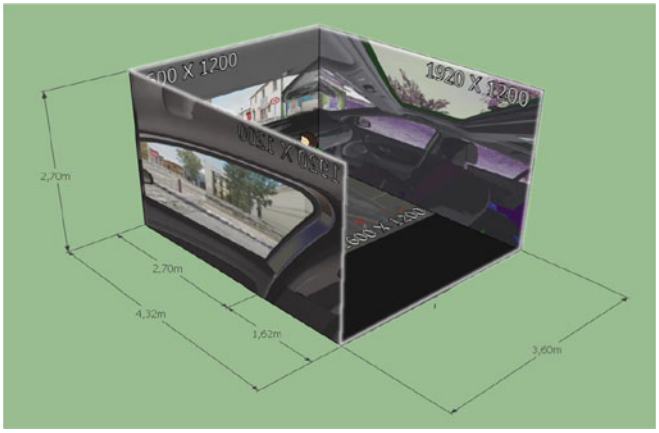

Fig. 2. P3I: Plate-forme d'Intégration immersive industrialisée.

- To which extent a tangible interface brings a better sense of interaction in virtual immersion?
- What is the precision of interaction in using a tangible interface?

It is expected that a tangible interface is an added value for precision as well as user's confidence in the interaction, thanks to the space calibration process done with kinesthesis and haptic feedback. Thus, our hypothesis are the following:

- The precision of the interaction is better when using tangible feedback.
- The tangible interface brings a better comfort to the user in his interaction.

The study aims to grow the knowledge on transparent passive haptic systems and find new ways to improve them.

5 EXPERIMENTAL STUDIES

5.1 Virtual Environment (VE)

This experiment took place at Renault, in the P3I (Plateforme d'Intégration Immersive Industrialisée) CAVE (Fig. 2). This CAVE is a 4-faced immersive room, with front, floor, and two side walls. It is 2.7 m high, 4.32 m deep, 3.6 m large and has high definition video projectors displaying every pixel in a 2.25 mm square.

Head tracking is provided by 8 ARTtrack infrared cameras, as well as hand and finger tracking using an active finger-tracking device (Fig. 6) with an alleged 1-millimeter precision.

The VE is computed and displayed by Oktal SCANeR Studio ©1.4, at a 60 Hz frame rate, working with Catia V5 via TechViz middleware. Renault's Megane 4 interior is displayed and the outside environment is a reproduction of Guyancourt, France (Fig. 3).

A tracked car seat, co-located with the virtual seat allows subjects to sit down just like they would in a real car.

5.2 Experimental Conditions

5.2.1 Interaction Systems

Three different haptic modes are tested during the 3 phases (described Fig. 4) called phase X, Y and Z.

- *Phase X - Sensory substitution*. Only the CAVE is used and no tangible haptic system is added. A green button, when pressed, would color itself into a darker

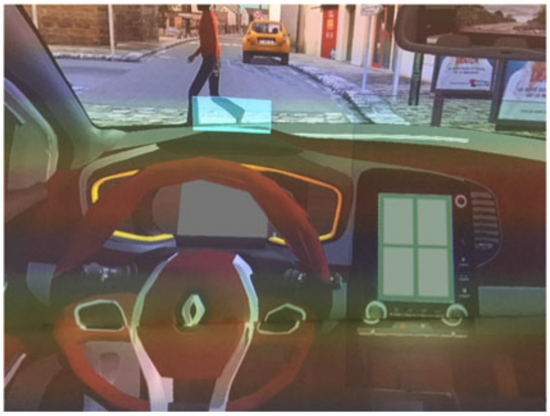

Fig. 3. The passive slate, nearly invisible in the environment during phase Y.

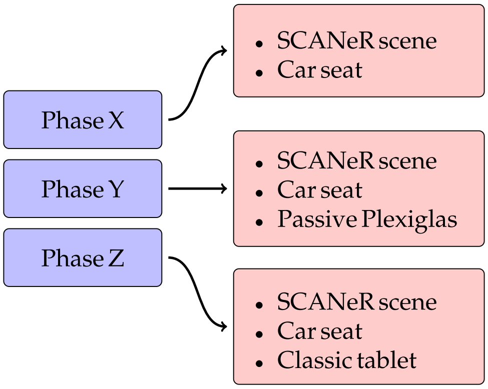

Fig. 4. Different haptic modes for different phases of the experiment. Phases are randomly ordered.

green, and then turn back to white when released. Although it does not provide any force feedback, it does offer a way of interacting.

- *Phase Y - Passive haptics*. A transparent glass subjectively calibrated is placed in the CAVE to provide a tangible contact and a robust depth marker to rely on. Plexiglas is chosen for its great transparency, we can see in Figs. 3 and 6 that the system is nearly invisible.
- *Phase Z - Classic tablet*. The tablet is fixed on an articulated arm. The exact same software is displayed on it, and the interaction system is the multi-touch screen instead of the finger tracking glove. The tablet used is a Samsung Galaxy A6 with more than sufficient specifications

5.2.2 Methodology

The 3 phases are randomly ordered to avoid a learning bias, and they are attempted in a row in order for the subjects to have fresh memories of what they felt in the previous test. The phases are separated by questionnaires : one questionnaire about the interaction implementation and one presence questionnaire (adapted from Witmer and Singer's [30]), for each interaction modality.

Within each phase, the subjects interact with the designated haptic mode as they would interact with the integrated touchscreen of a modern vehicle. The HMI is a simple 4-button interface, as illustrated in Fig. 5.

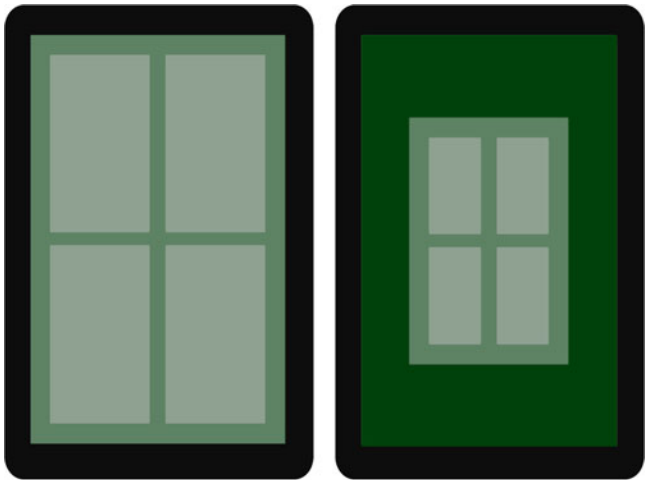

Fig. 5. There are only four buttons in the HMI, with two different scales.

Phases Sequencing. Each phase consists of 2 series, which are differentiated by the size of the buttons. The buttons of the first series are much bigger than the ones of the second series, as shown in Fig. 5.

A series consists of 20 successive interactions on the interface. To trigger every interaction, one of the 4 buttons on the interface turns green. The subject is tasked to touch the center of the button when this occurs. Once it is touched, the button turns grey again and the interface waits for a random duration before triggering the next interaction.

Subjects are instructed to touch precisely the center of the button, with a constant speed. They are also asked to put their hand on their knee between each interaction, to ensure regularity. The subjects are aware that their interaction durations are timed and their accuracy is being measured.

At the end of a series, we save the collected data : response duration, relative error of each interaction, and the subjects' comments verbatim.

5.2.3 Latency

In addition to the usual latencies produced by the CAVE, we face two specific delays during our experiment.

- Streaming latencies: the HMI is streamed to the CAVE from another computer through the network. The HMI is refreshed 100 ms late due to this configuration.
- Interaction latencies: the tracking system and its network flow causes a 50 ms latency.

These latencies occur only in virtual modes and not when subjects interact with the tablet. They are identical during both virtual modes as the tangible Plexiglas is only a passive object.

5.3 Subjective Calibration

For every haptic mode, subjective calibration is conducted instead of analytic calibration.

- The physical parts are adjusted by the subjects until they coincide with virtual parts to their own vision (when there are physical parts).

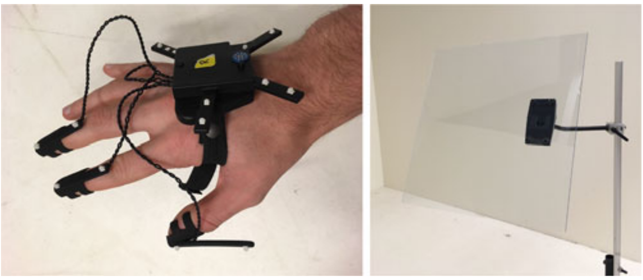

Fig. 6. A.R.T. Finger tracking device and the passive glass.

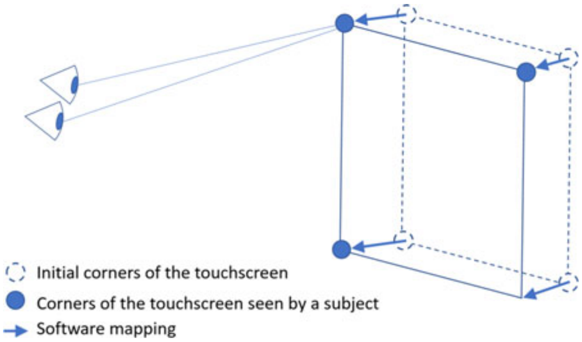

Fig. 7. The software maps the interaction system with the subjective calibration proceeded by the subject.

- The interaction engine is localized where the subjects can see it. They are asked to successively touch 3 corners of the virtual touchscreen (except when using the tablet), and the interaction system is mapped on this calibration, as represented in Fig. 7. Every action is theoretically taken into account 0.5 mm before the subject actually touches the glass to avoid erratic behavior.

In early experiments, analytic calibration (provided by measuring the interpupillary distance (IPD) of subjects and tracking the passive object) did not provide satisfactory accuracy. The subjects were complaining about a spatial offset between what they could see and what they could touch. Measuring the IPD obviously improves depth and scale perception, but is not always enough. It is measured to get a more accurate position of the eyes of the user, interpolated from his tracked 3D glasses, but there are other parameters influencing distance perception accuracy. Nose height and eye depth should be measured, as well as anything that has an influence on the location of the 3D glasses. The 3D glasses should also have sufficiently robust positioning on the subject, and be placed the same after a subject removes them and wears them again. When the location of the actual eye of the subject is not precisely known by the system, the vision frustrums cannot be computed accurately and this lead to spatial bias.

These constraints, in addition to the privacy issues caused by the company in the case that we collected and stored morphologic data, led us to consider a subjective calibration. It was found more accurate by early testers, but still not perfect. Further experiments should improve subjective calibration, perhaps combining it with analytic calibration, as it does not resolve all issues. Notably, the subjects should keep the same posture as during the calibration while interacting, and the same gaze direction (a straight forward gaze in our experiment) as well. If the subjective calibration is performed while looking straight forward, switching to lateral vision would corrupt it.

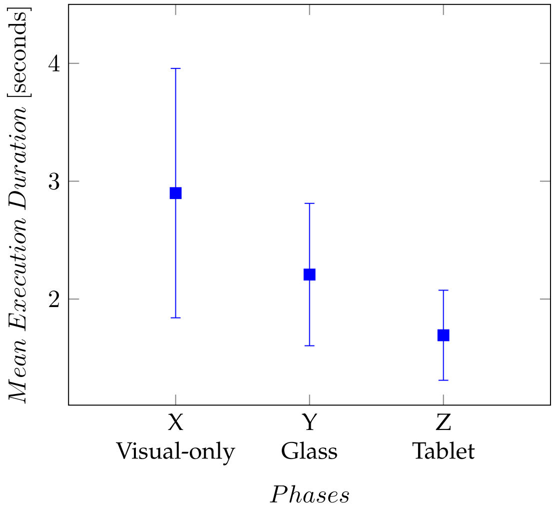

Fig. 8. Mean duration of interaction for each subject. Apart from a few points, we can see a global tendency where phase Z is faster than phase Y, which is faster than phase X.

5.4 Subject Panel

20 subjects took part in this experiment. To ensure confidentiality, each one of them is a Renault employee working in Guyancourt. Coming from various fields of work, half of them were totally VR-naive (they had never used a virtual reality immersive system before). The other half were experts. Males and females, most of them were between 25 and 50 years old. Their specificities were known by questionnaires, oral questions, and verbatim records. Their feelings were collected between each phase via our questionnaires.

Our numerical analysis is only based on 17 subjects, as there were subjects unable to succeed every phase or who provided aberrant results.

5.5 Measurements

Three indicators are used to evaluate the performance of the subjects. Every action is timed from the moment when a button turns green to when it is touched by the subject. Vertical and horizontal relative errors are measured by the software as the corresponding projection of the distance between the interaction and the actual center of the button. The third indicator is the questionnaire ratings. We also analyze verbatim records (Subjects are asked to comment each difficulty they encounter and to report whatever is crossing their mind) to complement these indicators.

The subjects were allowed to compare their different questionnaires when filling them out, and were all told that our interest is only in the differences between modes, not in the absolute values.

6 Results

6.1 Execution Duration

Data on execution duration can be observed in Fig. 8 . The Student's t-Test for paired samples was used for the comparison of two phases (the differences are normally distributed according to Shapiro-Wilk Normality Test). We found a significant difference ($p < 0.05$) of execution duration between haptic modes. The fastest mode was with the tablet (Z), with

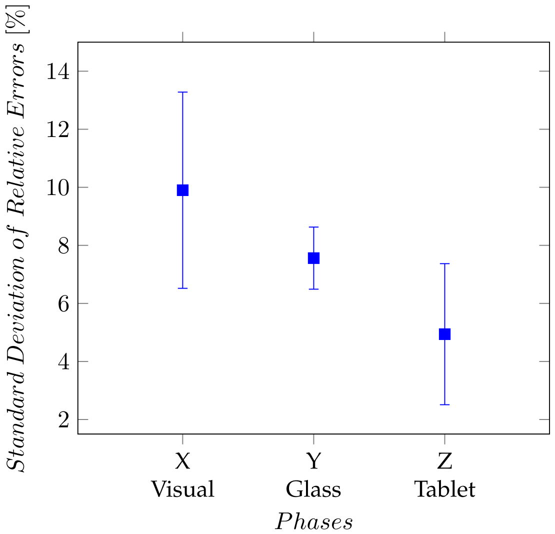

Fig. 9. Standard deviation of mean relative error for each subject. Again, a few users could be efficient with system X or Y, bust most of them lacked accuracy and regularity.

which the subjects' interaction took an average time of 1.5 seconds. Compared to this duration, both phase X (sensory substitution) and Y (Plexiglas) are slower. Phase X is also significantly slower than Y, twice the value of Z. However, this does not prove on its own that phase Z is superior. Lots of subjects did not appreciate it for the immersion experience, although every one of them emphasized that the tablet offered a more reliable interaction than any other system.

We identified two reasons for the poor performance in the virtual phases :

- *The reliability of perception* was a handicap for a few subjects whose spatial perception drifted over the course of the experiment. Some of them could not get to the end of the visual-only phase, and most of them sometimes had to try twice or more to achieve an action. This phenomenon also happened with the transparent glass, but was stronger and more frequent without it. The subjects would go deeper and deeper through the button, recalibrating their perception until they would not see the button on the same place than before. A perception recalibration and a one minute pause could often solve the problem, as discussed later. There were six recalibrations needed during phase X, and just one during phase Y.
- *Irresolution*, meaning the subjects slow their moves due to a lack of self-confidence, is also a major cause. Even when removing every interaction slowed by a reliability issue, the average duration of phase Y is longer than phase Z. The subjects are not as confident as they would be in real conditions and they slow their moves accordingly. This situation is worse during phase X, and there are greater disparities: standard deviation between means of subjects is almost twice as high as during phase Y and many subjects achieved a poor performance.

6.2 Relative Error

Relative error is analyzed and represented in Fig. 9. It was measured for each interaction and represents its position compared to the center of the button which was supposed to be touched. Although the A.R.T finger tracking device was found to be conclusive, we prefer to analyze repeatability to avoid any bias due to a constant shift in the tracking system. Once again, Student's t-Tests for paired samples were used to analyze differences among the modalities (the differences are normally distributed according to Shapiro-Wilk Normality Test).

While phase Y and Z have approximately the same mean standard deviation, phase X has a significantly higher value ($p < 0.05$). There are also more disparities between subjects, as the variance of variances is much higher. These differences are mainly due to perception uncertainty and shifts occuring during this phase. Different subjects reported that they felt the button was getting further and further away from them, until their interaction would not work anymore. On the computer, the operator could see their interactions progressively drifting to the left, because their move would intersect the virtual screen earlier than they thought. The software was designed to prevent them from realizing that they were shifting ; they only receive the information that they touched the button or not, not where they had touched it.

Finally, we can see on the graph that the standard deviation of standard deviations of relative errors is higher during phase Z. We assume that some subjects did not take phase Z as seriously as X and Y, as they all were familiar with tablets. Even though we specifically asked them many times to touch precisely the center of the buttons, the subjects were less focused during this phase.

6.3 Subjects Judgment

Each mode received specific recurrent reports from subjects.

6.3.1 *Sensory Substitution Mode*

This mode could be frustrating when the subjects thought they had touched the button but the system would not take it into account. When the calibration was correct, the subjects reported this mode as surprisingly pleasant to use, and the color cue was much appreciated. Several subjects reported that they enjoyed the fact that there were two color changes, one when they would press the button and one when they would release it.

6.3.2 *Passive Plexiglas Mode*

Being able to forget about depth issues and to lower the cognitive load and the uncertainty induced was much appreciated, but subjects sometimes had to put more pressure on the glass when the system would not react. Some subjects were especially happy with the glass placement, reporting that this precise calibration rendered a nice feeling. The system lacked a bit of robustness and rigidity and it can still be improved. The A.R.T glove structure could sometimes interfere between the glass and the skin, leading to a quality contact deterioration.

6.3.3 *Real Tablet Mode*

The tablet provided excellent interaction during phase Z, but impaired the VE due to contrast and brightness disparities. It caused a drastic reduction in immersion, and some subjects even wondered in which purpose the CAVE served. These subjects thought that the tablet experience

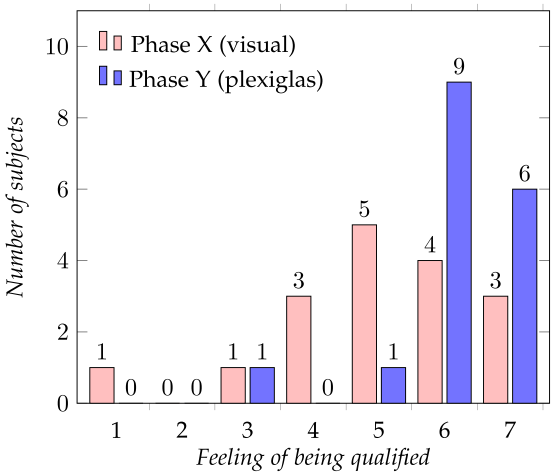

Fig. 10. The feeling of being skilled between phases X and Y.

would have been better without the CAVE, as the 3D glasses deteriorated the displayed image with their polarization. On the other hand, the subjects who were expecting an immersive experience reported that this phase was weird, easy to succeed but unpleasant and not necessarily an effective tool to work with.

6.4 Questionnaires

Concerning the questionnaires, phase Y obtained on average higher scores (nearly 50 percent) than phase X in the system specific category, while phase Z received even higher scores than phase Y. This questionnaire is mainly focused on the performance, with questions about self confidence in interaction, delay perception and global experience quality. Considering these results added to the corresponding performance, we assume that the glass helped people in their virtual interactions. The verbatim records confirm this assessment. Finally, several subjects reported that even so their performance felt better during phase Z, the very low immersion made it feel irrelevant to the use-case of virtual HMI design.

6.4.1 Delay Perception

Although latency is well known, we still asked subjects to rate the delay they perceived from 1 to 5, 1 being the best rate. We discovered that perceived latency is related to the performance of the subjects. The subjects who had difficulty interacting often blamed latency. For that reason, the mean rate of perceived latency obtained is a lot higher in sensory substitution mode (2.6) than in passive haptics mode (1.5). On the other hand, people who had no issue interacting reported that the latencies were detectable but low.

6.4.2 Confidence

In the presence questionnaire, we asked the subjects to rate their feeling of being qualified while using the current system from 1 to 7. We had significant results ($p < 0.01$ according to Wilcoxon signed rank test) showing that subjects felt much more qualified during phase Y than during phase X, as we can see in Fig. 10. Phase Z obtained heterogeneous grades, as subjects suffered from the lack of immersion : They may have felt confident in their interaction, but they did not in their evaluation of the vehicle HMI in context, which would be the real goal.

The remaining results of the presence questionnaire are less relevant, as phase Z obtains the same mean score than Y, only a little higher than X, whereas many subjects complained about the low quality of immersion while they were using the tablet. Witmer and Singer's questionnaire may not be appropriate for our research, as it contains only a few questions dedicated to haptics and interactions.

7 Discussion

7.1 Preferred System

In this experiment, none of the interaction modes were unanimously favored by all the subjects, regardless of the significant usability differences found in the results. They were asked to defend their point of view. Their arguments led us to conclude that when first seeing the system, every subject had his own idea of how it could serve specific use-cases, and these ideas ruled their expectations. Depending on what was their initial opinion about virtual technologies and if they were expert in HMIs development for car interiors, they nearly had chosen their system before beginning the experiment.

- Subjects who preferred phase X were mostly VR experts who expected an interactive system, not necessarily in this particular context. In their opinion, they were testing an interaction module to use with CAVEs in various applications.
- Subjects who preferred phase Y were VR naive and experts. They appreciated having a tangible and precise force feedback to oppose their moves and enhance their performance, in contrast with the sensory substitution mode which could lead to difficulties. In their opinion, they were testing a vehicle dashboard HMI in a realistic environment, just like if they were in a physical car, to simulate the car interior specificities.
- Subjects who preferred phase Z wondered why VR would be of any interest for dashboard HMI development. In this state of mind, they were not paying attention to the whole VE and they reported that they would have preferred being simply in their office with the tablet.

With this study, we emphasize that haptic modalities are use-case dependent and need to be implemented accordingly. There is also a performance factor, which granted phase Y better rates than other phases.

7.2 Application Area and Limitations

We observe that these haptic implementations would not fit the same application area.

- Sensory substitution can be implemented in most scenarios, as it just needs collision detection, but this flexibility has a price paid in usability.
- Transparent passive haptics, as we implemented it, only work in specific situations, like car flat tactile HMI design. Targets must be flat, static, and have simple shapes.

Improving the usability of sensory substitution may allow its use in a wider application area than passive haptics, but it is not conclusive for our use-case yet.

7.3 Recalibrations

Lots of subjects had their spatial perception shifted after a while during phase X, losing their references in the VE progressively. In the end, some of them would see the buttons in another place and their following interactions were all in error. Six subjects needed a perception recalibration during phase X and 4 subjects were able to take benefit from it. The recalibration consisted of asking them to look somewhere else on the scene, to look at themselves, to close their eyes for a few seconds. After those simple acts, they were once again able to interact.

These recalibrations were required only once during phase Y. We suppose that the tangible Plexiglas is a strong enough depth mark on which subjects' perception system can rely.

Discrete recalibration of subjects perceptions were studied in the past [31], and continuous recalibration may enhance the usability of fully visual modalities when perception robustness lacks.

7.4 Inter-Subject Disparities

Subjects adapted differently to phases X and Y, and more disparities were revealed during phase X. Both standard deviation of mean execution durations and standard deviation of standard deviations of relative errors are significantly lower during phase Y than during phase X. Additionally, there were more subjects failing phase X, or frustrated by it, than any other phase. This makes us assume that sensory substitution is more difficult to handle, and subjects with a lower level of adaptability were handicapped. As expected, people who were familiar with CAVEs and stereoscopy achieved a decent performance during phase X, whereas VR-naive subjects often could not. The added value provided by the passive transparent glass was more pronounced with these subjects who approached the performance attained by experts.

Finally, and once again, phase Z provided the lowest performance disparities, in spite of the subjects' overall opinion.

7.5 Learning in the Loop

A simple in-the-loop learning process was tested with a few subjects in sensory substitution mode. As the subject interacted, the operator informed them orally of their spatial error (long shift on the right, short shift on the top...). Results were impressive and subjects were able to be as accurate as during phase Z after only a few guided interactions and without additional information. A dedicated experiment with several different software-based in-the-loop learning cues would certainly be of interest, and would probably allow companies to find a reliable interactive modality which could be used in various work fields.

To synchronize the perception of the subjects with the visual and tracking system, we are not limited to the method of teaching users how to adapt their perception via visual or oral guidance. A strong self-correcting software could also be a solution which would need further study to be efficient and reliable.

7.6 Driving Simulation Situation

A simulated driving situation would introduce major differences, and thus require further studies.

- A moving environment continuously renews all spatial cues (depth, scales) and it may significantly reduce the perception shifts we encountered.
- Interacting with the HMI while driving is less important than safety. Users cannot keep their sight on the screen for too long, thus they will use either central vision for short durations or peripheral vision, which is not as efficient as central vision in many aspects [32], [33].
- The context itself also has influence over the haptic performance [34] and may influence the results as users would have a different focus.

8 Conclusion

In this article, we compared different haptic modes for tactile dashboard HMI design in a CAVE in order to measure the added value of tangible interfaces. We tested a simple sensory substitution system based on discrete visual cues, a passive haptic system made of a tangible transparent glass, and a classic tablet. The transparent passive haptic system allowed significant improvements in usability compared to sensory substitution. It enhanced usability through significant gain in accuracy, efficiency and self-confidence bringing a better user experience. We could thus show that the proposed tangible interface provides significantly more robust spatial haptic cues. Finally the tablet in spite of good performance was not well accepted as natural interface by subjects who reported a reduction in immersion.

Perspectives

In-the-Loop Learning. More multisensory cues could be added to continuously help users interact. In addition, software would take advantage of detecting theses shifts an adapt in real time.

Driving Simulation Context. Driving situations modify mental workload and performance while interacting with HMI. Future work will be carried out to study haptic modalities in driving situations.

Acknowledgments

This work was supported by a cooperation between the Renault Group and Arts et Métiers Engineering School. The authors would like to thank particularly the Renault Group for providing the materials and software we used in this experiment.

References

[1] F. P. Brooks, M. Ouh-Young, J. J. Batter, and P. Jerome Kilpatrick, "Project GROPE-HapticDisplays for scientific visualization," *ACM SIGGraph Comput. Graph.*, vol. 24, no. 4, pp. 177–185, Sep. 1990.

[2] M. Sato, "Space inteface device for artificial reality-SPIDAR," *Trans. Inst. Electron. Inf. Commun. Eng.*, vol. 74, no. 7, pp. 887–894, 1991.

[3] T. H. Massie and J. K. Salisbury, "The phantom haptic interface: A device for probing virtual objects," in *Proc. ASME Winter Annu. Meeting Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 1994, pp. 295–300.

[4] F. P. Brooks, "What's real about virtual reality?" *IEEE Comput. Graphics Appl.*, vol. 19, no. 6, pp. 16–27, Nov./Dec. 1999.

[5] G. Robles-De-La-Torre, "The importance of the sense of touch in virtual and real environments," *IEEE Multimedia*, vol. 13, no. 3, pp. 24–30, Jul. 2006.

[6] A. Kemeny, "From driving simulation to virtual reality," in *Proc. Virtual Reality Int. Conf..*, 2014, Art. no. 32.
[7] R. Scheibe, M. Moehring, and B. Froehlich, "Tactile feedback at the finger tips for improved direct interaction in immersive environments," in *Proc. IEEE Virtual Reality Conf.*, 2007. pp. 293–294.
[8] A. Assila, "An approach and a tool for subjective and objective evaluation of the usability of interactive systems: Application to passengers information assistance system," Theses, Université de Valenciennes et du Hainaut-Cambresis, Sep. 2016. [Online]. Available: https://tel.archives-ouvertes.fr/tel-01411235
[9] L. Buoguila, Y. Cai, and M. Sato, "New haptic device for human scale virtual environment Scaleable-SPIDAR," in *Proc. Int. Conf. Adv. Technol. Sci.*, 1997, pp. 93–98.
[10] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr, "AIREAL: Interactive tactile experiences in free air," *ACM Trans. Graph.*, vol. 32, no. 4, Jul. 2013. Art. no. 1.
[11] T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, "UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces," in *Proc. 26th Annu. ACM Symp. User Interface Softw. Technol.*, 2013, pp. 505–514.
[12] B. Bayart, "Réalité augmentée haptique: Théorie et applications," Ph.D. dissertation, 2007, thèse de doctorat dirigée par Kheddar, Abderrahmane Robotique Evry-Val d'Essonne, 2007EVRY0035, 2007.
[13] H. Hoffman, "Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments," in *Proc. IEEE Virtual Reality Annu. Int. Symp.*, 1998, pp. 59–63.
[14] A. Lecuyer, C. Andriot, and A. Crosnier, "Interfaces haptiques et pseudo-haptiques," in *Proc. Journées Nationales de la Recherche en Robotique*, 2003, pp. 43–4.
[15] B. E. Insko, "Passive haptics significantly enhances virtual environments," Ph.D. dissertation, Department of Computer Science, University of North Carolina at Chapel Hill, NC, USA, 2001.
[16] A. S. Carlin, H. G. Hoffman, and S. Weghorst, "Virtual reality and tactile augmentation in the treatment of spider phobia: A case report," *Behaviour Res. Therapy*, vol. 35, no. 2, pp. 153–158, Feb. 1997.
[17] K. Hale and K. Stanney, "Haptic rendering - beyond visual computing - Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations," *IEEE Comput. Graph. Appl.*, vol. 24, no. 2, pp. 33–39, Mar. 2004.
[18] P. Fuchs and G. Moreau, *Le Traité de la Réalité Virtuelle*, vol. 2, Cortlandt, NY, USA: Presses des MINES, 2006.
[19] J. P. Wann, S. Rushton, and M. Mon-Williams, "Natural problems for stereoscopic depth perception in virtual environments," *Vision Res.*, vol. 35, no. 19, pp. 2731–2736, Oct. 1995.
[20] K. B. Chen, R. A. Kimmel, A. Bartholomew, K. Ponto, M. L. Gleicher, and R. G. Radwin, "Manually locating physical and virtual reality objects," *Human Factors*, vol. 56, no. 6, pp. 1163–1176, Sep. 2014.
[21] R. V. Kenyon, D. Sandin, R. C. Smith, R. Pawlicki, and T. Defanti, "Size-Constancy in the CAVE," *Presence: Teleoperators Virtual Environ.*, vol. 16, no. 2, pp. 172–187, Apr. 2007. [Online]. Available: http://www.mitpressjournals.org/doi/abs/10.1162/pres.16.2.172
[22] N. A. Dodgson, "Variation and extrema of human interpupillary distance," in *Proc. SPIE*, vol. 5291, pp. 36–46, May 2004.
[23] L.-W. Chan, H.-S. Kao, M. Y. Chen, M.-S. Lee, J. Hsu, and Y.-P. Hung, "Touching the void: Direct-touch interaction for intangible displays," in *Proc. SIGCHI Conf. Human Factors Comput. Syst.*, 2010, pp. 2625–2634.
[24] H. H. Hu, A. A. Gooch, W. B. Thompson, B. E. Smits, J. J. Rieser, and P. Shirley, "Visual cues for imminent object contact in realistic virtual environment," in *Proc. Conf. Vis.*, 2000, pp. 179–185.
[25] C. Madison, W. Thompson, D. Kersten, P. Shirley, and B. Smits, "Use of interreflection and shadow for surface contact," *Perception Psychophysics*, vol. 63, no. 2, pp. 187–194, Feb. 2001.
[26] B. Petzold, et al., "A study on visual, auditory, and haptic feedback for assembly tasks," *Presence: Teleoperators Virtual Environ.*, vol. 13, no. 1, pp. 16–21, 2004.
[27] M. Kitagawa, D. Dokko, A. M. Okamura, B. T. Bethea, and D. D. Yuh, "Effect of sensory substitution on suture manipulation forces for surgical teleoperation," *Stud. Health Technol. Inform.*, vol. 98, pp. 157–163, 2004.
[28] J. Sreng, A. Lecuyer, C. Megard, and C. Andriot, "Using visual cues of contact to improve interactive manipulation of virtual objects in industrial assembly/maintenance simulations," *IEEE Trans. Vis. Comput. Graph.*, vol. 12, no. 5, pp. 1013–1020, Sep./Oct. 2006.
[29] M. O. Ernst and H. H. Bülthoff, "Merging the senses into a robust percept," *Trends Cognitive Sci.*, vol. 8, no. 4, pp. 162–169, Apr. 2004.
[30] B. G. Witmer and M. J. Singer, "Measuring presence in virtual environments: A presence questionnaire," *Presence: Teleoperators Virtual Environ.*, vol. 7, no. 3, pp. 225–240, Jun. 1998.
[31] J. E. Atkins, R. A. Jacobs, and D. C. Knill, "Experience-dependent visual cue recalibration based on discrepancies between visual and haptic percepts," *Vis. Res.*, vol. 43, no. 25, pp. 2603–2613, Nov. 2003.
[32] H. Strasburger, I. Rentschler, and M. Juttner, "Peripheral vision and pattern recognition: A review," *J. Vis.*, vol. 11, no. 5, p. 13, Dec. 2011.
[33] A. Soichiando, N. Kida, and S. Oda, "Central and peripheral visual reaction time of soccer players and athletes," *Perceptual Motor Skills*, vol. 92, no. 3, pp. 786–794, Jun. 2001.
[34] J. E. Atkins, J. Fiser, and R. A. Jacobs, "Experience-dependent visual cue integration based on consistencies between visual and haptic percepts," *Vis. Res.*, vol. 41, no. 4, pp. 449–461, Feb. 2001.

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