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Prototyping and Evaluating Sensory Substitution Devices by Spatial Immersion in Virtual Environments

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Abstract: Various audio-vision Sensory Substitution Devices (SSDs) are in development to assist people without sight. They all convert optical information extracted from a camera, into sound parameters but are evaluated for different tasks in different contexts. The use of 3D environments is proposed here to compare the advantages and disadvantages of not only software (transcoding) solutions but also of hardware (component) specifics, in various situations and activities. By use of a motion capture system, the whole person, not just a guided avatar, was immersed in virtual places that were modelled and that could be replicated at will. We evaluated the ability to hear depth for various tasks: detecting and locating an open window, moving and crossing an open door. Participants directed the modelled depth-camera with a real pointing device that was either held in the hand or fastened on the head. Mixed effects on response delays were analyzed with a linear model to highlight the respective importance of the pointing device, the target specifics and the individual participants. Results are encouraging to further exploit our prototyping set-up and test many solutions by implementing e.g., environments, sensor devices, transcoding rules, and pointing devices including the use of an eye-tracker.

1 INTRODUCTION

1.1 Sensory Substitution

Sensory substitution consists in replacing an impaired sensory channel by another, functional, one. Most Sensory Substitution Devices (SSD) are used to compensate visual impairments by the auditory or tactile senses. They aim at assisting in different kinds of tasks like object finding and navigating (Stoll et al., 2015). Electronic SSDs rely on (fig. 1):

- a sensor such as a color camera or a depth camera (e.g. Kinect). It is fastened on the user or freely positionable by him/her,
- a transcoder which processes the information coming from the sensor to drive an actuator,
- an actuator which stimulates a functional sense of the user, for example hearing or touch.

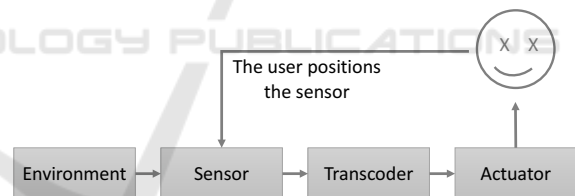


Figure 1: Electronic sensory substitution device principle.

Bach-y-Rita et al. carried out a pioneering work highlighting the importance of the action perception loop in these systems (Bach-Y-Rita et al., 1969). They showed that their Tactile Vision Substitution System (TVSS) which converts an image captured by a video camera into tactile stimuli, was much more efficient when users directed the video sensor themselves. Indeed, actions regulate perception and perception constantly directs actions. Therefore, it is essential for the user to be able to position the sensor (fig. 1) or a focal point in the scene. The efficiency of the scene pointing technique, e.g. by hand or with the head appears as an important issue.

The reader can refer to (Kristjánsson et al., 2016) for a state of the art on SSD.

1.2 Problematic

Evaluation or appropriation of an SSD in the real world raises the following problems:

1. it can only be done after a complete prototype has been built, which may be long and tedious,
2. the scene to immerse the user may be either a complex natural scene which makes difficult the adjustment and evaluation of the transcoding laws, or a simplified real laboratory scene specifically constructed for the tests which is always time-consuming to set up and hard to replicate.

To address some of these problems, recent works have been based on moving an avatar in a 3D virtual environment. These avatars are steered using a video game controller with a tactile feedback (Khoo et al., 2012), the Phantom device with haptic and sonic feedbacks (Lahav et al., 2015), or keyboard keys (Maidenbaum et al., 2016) with sonic feedback generated with the EyeMusic SSD (Abboud et al., 2014). These works highlight the benefits of using 3D virtual environments to test and to practice on SSD. However, in such set-ups, the user's sensory feedbacks are limited to those generated according to the positioning of the avatar.

We constructed an experimental set-up model (section 2) in order to get closer to real-life sensory and motor experience than through an avatar. We used a motion capture system to immerse the whole user's body in the virtual 3D environment that s/he perceives through a SSD. This situation was closer to an ecological context as it preserved most of the natural action perception loops.

Thus our set-up model aimed at combining both the agility advantages of virtual worlds that can be designed, changed and replicated at will for situations and tasks, and incarnation in the real-world where the human body can experience natural sensations and gestures. We tested it on blind-folded users (section 3). It allowed to compare performances in object search and navigation tasks depending on two pointing techniques: by moving one's hand or one's head.

We also adapted the setup to a more original way of manipulating the sensor device (section 4), based on (blind) gaze movements. Although it has not been tested on a significant sample of participants, it showed operational enough to be presented as another example of adaptability of the prototyping /evaluation set-up model and opens up on large perspectives.

2 CONNECTING SSD INTO A VIRTUAL ENVIRONMENT

2.1 Principle

While the general principle of SSD (fig. 1) remains the same, the real world environment and the hardware sensor are both replaced by a virtual scene and a virtual camera controlled by the user (fig. 2).

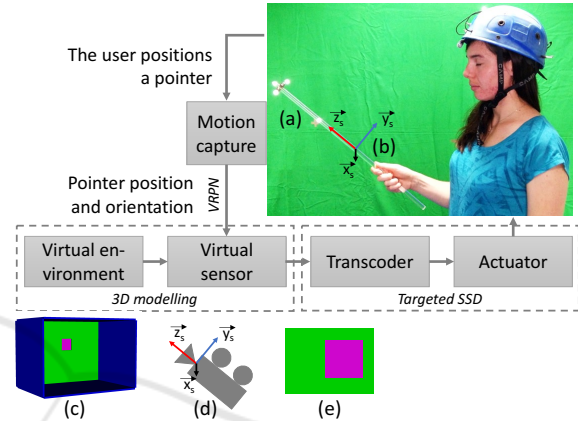


Figure 2: Designed experimental set-up principle.

(a) real stick equipped with 4 markers reflecting IR light

(b) real stick position and orientation

(c) virtual environment example

(d) virtual sensor positioned and oriented as the real stick

(e) image produced by the virtual sensor

Modeling the Virtual Environment. We used a 3D modelling library to describe the environment. fig. 2(c) shows a virtual environment example: a wall in a room is pierced by a square window.

Virtual Environment Capture. The virtual environment is captured by a virtual sensor, the scene camera, as shown in fig. 2(d).

Matching Real and Virtual. To realize the immersion, i.e. to link the real and virtual spaces, the user must be able to manipulate the virtual sensor from the real world. We used a motion capture system to extract a real object's (fig. 2(a)) position and orientation (fig. 2(b)). This position and orientation are replicated on the virtual sensor (fig. 2(d)).

Interfacing with the Transcoder. To generate a perceptual feedback of the virtual scene through the targeted SSD, we extracted information from the virtual sensor compatible with its transcoder. As an example, fig. 2(e) represents the colour image acquired from the viewpoint of the virtual sensor. This portion of the background wall with the window is sent to the transcoder of a SSD working on colour images.

The following subsections detail the technical solutions we used to implement this principle.

2.2 Motion Capture

To acquire the position and the orientation of objects (sensors) in space and interact with a virtual world, we used a VICON motion capture system. Based on a passive optical technology, it consists of a set of 12 infra-red T40s cameras, distributed around the volume to capture. Around each camera's lens, a circular array of infra-red projectors is placed to illuminate the scene, and especially 8-mm spherical reflecting markers that were fixed on the objects to track. The images captured by the infra-red cameras reveal the position of the markers reflecting the infra-red from different view angles. Based on a prior calibration, the position of each marker is calculated by a triangulation-type algorithm. From the relative position of markers placed on a solid object, the VICON system delivers its position and orientation in space, in a user-defined referential. Fig. 2(a) shows the 4 markers placed on the stick. Our room allowed the user to move in a $W \times L \times H = 3 \times 3 \times 2$ m real volume. As we will see in section 3 this is enough to carry out experiments on mobility. However, the virtual environment can be extended beyond this limit, even if the user cannot physically visit it. The spatial accuracy of the VICON system we used is in the order of a millimetre, and its operating frequency is 515 Hz.

2.3 3D Modelling

A 3D modelling library or a 3D video game engine is required to design a 3D virtual environment, for immersing the user. We chose the OpenSceneGraph (OSG) 3D library because it is free, cross-platform and C++ programmable. Moreover it can be easily interfaced with the VICON system. Its low-level nature allows us to create simple scenes quickly. The realistic aspect of the scenes is not a priority for our experiments. If more realism were needed, a video game engine such as Unity 3D could have been used.

2.4 Interfacing the Motion Capture System and the 3D Modelling

The VICON Tracker software thus provides the spatial configuration of the markers of objects to track and it calibrates the system, and it also behaves as a Virtual-Reality Peripheral Network (VRPN) server. VRPN is a broadly-used device and network-independent protocol for retrieving information from virtual reality peripherals, such as motion capture systems or joysticks. By using a VRPN client, a simple program can obtain the position and orientation of an object quite easily from the VICON system. The

client just has to indicate the name of the object to track to the server.

We used the osgVRPN plugin to interface OSG with the VICON system. osgVRPN behaves as a VRPN client which positions and orients a scene camera. For example, it allows to position and orient the scene camera presented in fig. 2(d) according to the position and orientation of the stick manipulated by the user (fig. 2(a)).

2.5 Targeted SSD

SSDs transcoders use different kinds of inputs. For example, some retrieve depth information from focused depth sensors (such as a laser beam), others work on color images from standard cameras, or depth maps from Kinect-like cameras. The following subsection describes how to get these different types of information from the OSG scene camera.

2.6 Interfacing the 3D Modelling with the Targeted SSD

The OSG intersector mechanism can be used to retrieve focused depth information: it returns the list of objects intersected by a ray coming from a given pixel of the image captured by the scene camera. The distance between each of these objects and the scene camera is also given.

Thanks to callbacks on the rendering of the scene camera, it is also possible to get back from the Graphical Processing Unit (GPU) memory the color image and the zbuffer corresponding to the camera's point of view. The zbuffer is used during graphic rendering to determine which triangles of the scene are visible from a given point of view. It can be considered as a greyscale image whose levels represent the distance that separates the visible objects from the camera. The zbuffer can be used as a depth map and thus feed the SSDs transcoders using Kinect like sensors. However, we would like to draw the reader's attention on the fact that the zbuffer's $z' \in [0; 1]$ values are related to the actual distances $z \in [z_n; z_f]$ (with z_n the distance to the nearest visible point, n for "near" and z_f at the farthest visible point, f for "far") by equation (1).

$$z' = A \frac{1}{z} + B \text{ where } A = \frac{z_n z_f}{z_f - z_n} \text{ and } B = \frac{z_f}{z_f - z_n} \quad (1)$$

Thus, transformation on the zbuffer is necessary to feed a transcoder waiting for a depth map in a given distance unit, in millimetres for example.

3 EXPERIMENTS

Human participants with normal vision were immersed in a virtual environment they only perceived through sound feedback coming from a SSD, for two experiments. In the first one, participants used the pointer to locate a virtual target while sitting on a chair; in the second one, they used the pointer to find an open door to walk from one virtual room to another. The purpose of these experiments was to test and compare two different pointing devices: a stick held by the hand and a headset. To minimize response variability due to training or strategy changes along trials, participants learned to use the SSD with the two pointing devices before starting the actual tests. In this training phase lasting around 30 minutes, they could open and close their eyes at will. During the actual tests, partitioned into blocks of eight or six trials, they kept their eyes closed. Participants had to alternate pointer after each next block.

3.1 First Experiment: Detecting an Open Window on a Virtual Wall

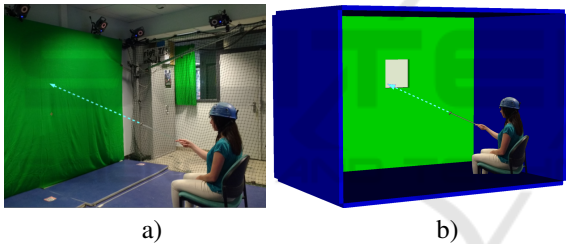


Figure 3: First experiment a) participant in real environment b) participant immersed in virtual environment.

The task was a partial replica of a real-world test used as proof of concept for an original SSD (Twardon et al. 2013). One woman and six men (Age: mean = 21.8 years-old, SD = 0.4) were successfully immersed in a virtual closed room (WxLxH=3x3x2m). They sat 1.5m in front of a 3x2m wall. Their task was to locate an open window on this wall (fig. 3). The window could be in four different positions (top right, top left, bottom right and bottom left quadrants), and two different sizes, large (75x75cm) or small (50x50cm). The SSD delivered a 220Hz-sound when the pointer was directed to the open window, contrasting with the continuous 110Hz-sound emitted when it was directed to the rest of the room (i.e. one octave less). Tests were organized in eight blocks of eight trials. Each block comprised the eight different combinations of window position and size, randomly ordered. At each trial, a starting signal was vocally given to initiate the search. The participant told the

window position as soon as detected. The delay between starting signal and response was timed manually and measured in seconds.

Results. The pointing device seems not to affect the delays (fig. 4). However the change of window's size and position may contribute to variability in the measures, as well as individual differences between participants and interactions between these variables. To test these factors, a conventional ANOVA or a Fisher test were discarded because repeated measures were obtained from the same participants. In addition, a Shapiro test discarded normality within each pointer devices' sample. Therefore, a linear model with mixed effects was preferred, with fixed variables common to all participants, and individual participants' effect as a random variable.

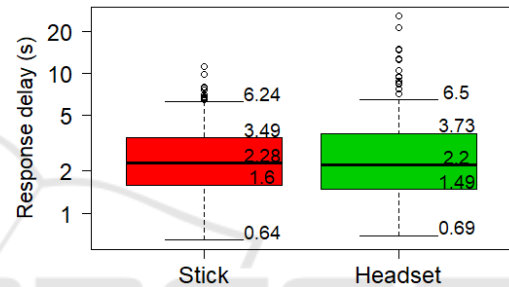


Figure 4: Distribution of the first experiment response delay (in sec.) for all participants according to the pointer used (red: stick, green: headset).

We used the lme4 package to perform our mixed effect model analysis in R (Bates et al., 2015). The model is defined as follows:

$$Y_{pt,siz,pos,par} = \mu + \alpha_{pt} + \beta_{siz} + \gamma_{pos} + \tau_{par} + \epsilon + I_2(\alpha_{pt}, \beta_{siz}, \gamma_{pos}) + I_3(\alpha_{pt}, \beta_{siz}, \gamma_{pos}) \quad (2)$$

with $Y_{pt,siz,pos,par}$ being the response delay (the log transform of the delay in second), μ the mean delay, α_{pt} , β_{siz} , γ_{pos} the fixed effects respectively due to the pointing device, the window's size and the window's position, τ_{par} the random effect due to the individual participant, ϵ the error component (or uncontrolled random effect) with $\epsilon \hookrightarrow N(0, \sigma_1^2)$, and $I_2(\alpha_{pt}, \beta_{siz}, \gamma_{pos})$, $I_3(\alpha_{pt}, \beta_{siz}, \gamma_{pos})$ respectively the 2nd and 3rd order interaction effect.

Following a parsimonious and simplified process, the strongest p-value variable was successively withdrawn from the model until the remaining p-value variable is larger than 5%. The resulting model issued from equation (2) was thus simplified as:

$$Y_{pt,siz,pos,par} = \mu + \beta_{siz} + \gamma_{pos} + \tau_{par} + \epsilon \quad (3)$$

Thus, the response delay does not depend on the pointer used. It strongly depends on the window's

size and the participant. Window's position also participated to the response delay variability but to a lesser extent. We used a multiple comparison test (Hothorn et al., 2008) to study every effect significance.

The multiple comparison test shows a very significant effect of the window's size ($p = .0003 < 5\%$) on the response delay, small window's response delays being longer than big window's ones. Some window's positions shows slightly significant effects on the response delay. Windows in position n°3 (at the bottom left) are somewhat longer to find than those in position n°1 and 2 (top right and top left with respectively $p = .0095$ and $p = .0072$).

Conclusions. Results show that big windows are faster to locate than small ones, with significant differences between individual participants. By contrast, the pointing devices can be considered as equivalent in this task. However, directing the beam of the SSD with the head may be uncomfortable when scanning on a longer term.

3.2 Second Experiment: Walking through an Open Door Separating Virtual Rooms

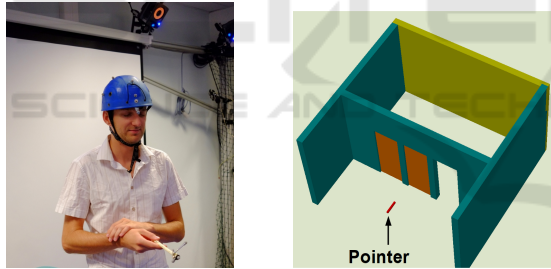


Figure 5: (left) Participant navigating and moving the pointer in the real environment; (right) pointer (red stick) moving in the virtual environment.

Five young male participants, (Age: mean = 22.4 years-old, SD = 0.4), participated in this experiment. Four of them had already done the first experiment.

They were immersed in a virtual environment mimicking two rooms (LxW=5x3m) separated by a partition wall (LxH=5x3m) that comprised three doors, (LxH=0.8x2.0m), one of which was randomly open at each trial (fig.5). The task of the participant starting from the front room was to locate the open door and walk through it into the back room.

The sound pitch f in Hz delivered by the SSD was a monotonous function of depth d , i.e., distance from the end of the pointing device to the next virtual surface point in its direction. The function used, replicated a preceding SSD (Twardon et al., 2013), is de-

fined by equation 4:

$$f = f_0 \cdot 2^{(d_{max} + d_{min} - 2d)/(d_{max} - d_{min})} \quad (4)$$

where f_0 is the reference frequency to be heard half-way between d_{min} and d_{max} , d_{max} and d_{min} being the upper and lower limits of d ; they are related to z_f and z_n in equation (1). We used $f_0 = 220Hz$, $d_{min} = 0.5m$ and $d_{max} = 4.5m$.

Tests were organized in six blocks of six trials. Each block comprised twice the three different door positions. Each trial started with the onset of the sound feedback, the participant standing 1.5m in front of the center door. The sound was continuous but when the pointer collided with a virtual wall, the sound was interrupted for two seconds. When the door was crossed and passed 1.0 m further, the sound finally switched off and the participant returned to the starting point. The response delay for the trial was the time in seconds separating sound onset and final sound offset.

Results. As well as for the first experiment, we used a linear model with mixed effects to study the used pointer, the door position and individual participant effects on the crossing delay. The model is defined as follows:

$$Y_{pt,pos,par} = \mu + \alpha_{pt} + \beta_{pos} + \tau_{par} + \alpha_{pt}\beta_{pos} + \epsilon \quad (5)$$

with $Y_{pt,pos,par}$ being the response delay (the log transform of the delay in seconds), μ the mean delay, α_{pt} and β_{pos} the fixed effects respectively due to the pointing device and the door position, τ_{par} the random effect due to the individual participant, $\alpha_{pt}\beta_{pos}$ the 2nd order interaction term and ϵ the error component (or uncontrolled random effect) with $\epsilon \hookrightarrow N(0, \sigma_\epsilon^2)$.

Following a parsimonious and simplified process of insignificant effects backward elimination, the model defined in (5) can be simplified as follows:

$$Y_{pt,pos,par} = \mu + \beta_{pos} + \tau_{par} + \epsilon \quad (6)$$

Thus, the door crossing delay only depends on the door position and the participant and not on the pointer used.

Conclusions. Multiple comparison tests shows that the door position has a significant effect on door crossing delay, the door at the center being faster to cross than the doors beside, with significant differences between individual participants. As for the first experiment, pointing devices can be considered as equivalent.

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