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Spatialized Vibrotactile Feedback Improves Goal-Directed Movements in Cluttered Virtual Environments

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ABSTRACT

Spatial awareness in virtual reality (VR) is a dominant research topic. It plays an essential role in the assessment of human operators' behavior in simulated tasks, notably for the evaluation of the feasibility of manual maintenance tasks in cluttered industrial settings. In such contexts, it is decisive to evaluate the spatial and temporal correspondence between the operator's movement kinematics and that of his/her virtual avatar in the virtual environment (VE). Often, in a cluttered VE, direct kinesthetic (force) feedback is limited or absent. We tested whether vibrotactile (cutaneous) feedback would increase visuo-proprioceptive consistency, spatial awareness, and thus the validity of VR studies, by augmenting the perception of the operator's contact(s) with virtual objects. We present experimental results obtained using a head-mounted display (HMD) during a goal-directed task in a cluttered VE. Results suggest the contribution of spatialized vibrotactile feedback to visuo-proprioceptive consistency.

Introduction

When designing complex industrial settings, as we encounter at the French Atomic Energy Agency (CEA) in the Institute for Magnetic Fusion Research (IRFM) during the development of fusion plants, assembly and maintenance issues must be considered in the early stage, due to the huge impact that they might have on the overall layout. The components designed have to be remotely handled and/or to be maintained by operators. That process involves taking into account the human factor to assess the feasibility of assembly or maintenance processes. The operator's accessibility and protection: ergonomic postures and gestures must be guaranteed, in order to derive valid conclusions with regard to the real situation. Virtual Reality (VR) provides tools to optimize such developments. Focusing on the human factor, spatial awareness in virtual environments (VE) is a topic of major interest. Sometimes the operator must work in a confined environment and pay attention to the position of his/her whole body, relative to the position of various objects (Figure 1). In this context, visuo-proprioceptive consistency is a key aspect for the scenario validation using VR technology.

We use the term visuo-proprioceptive consistency to refer to the spatio-temporal coherence between the operator's and avatar's kinematics. This concept can be linked to the concept of kinematic symmetry proposed by McMahan (McMahan, 2011). Spatio-temporal coherence describes a bi-directional link of interaction. The avatar must adopt the same posture as the user, being co-localized with the user. Conversely, the user must integrate the posture limitations imposed on the avatar by the VE.

In this context, the lack of haptic feedback (tactile and kinesthetic, for example due to technical constraints) results in incomplete sensorial feedback, as soon as the subject interacts with virtual objects. Multimodal feedback, including proprioceptive and tactile modalities, is crucial in constructing a spatial mental model of the world (Berthoz, 2000; Kammermeier, Buss, & Schmidt, 2001). In typical VE collisions of the body with virtual objects do not typically result in proprioceptive and tactile feedback; nothing is actually present to stop the subject's movement. This deficiency might lead to a lack of the user's presence in the VE, and be one reason for inappropriate behavior, with respect to reality, resulting in visuo-proprioceptive inconsistency.

To address these limitations, vibrotactile (cutaneous) stimulation appears as a good candidate to substitute force feedback (Lindeman, Page, Yanagida, & Sibert, 2004). We hypothesize that vibrotactile feedback, positioned on the operator's skin, will enhance spatial awareness of elements in the VE. Vibrators are light, wearable, and constitute an unobtrusive interface that can be directly mapped onto body coordinates. They also have the advantage of involving a sense (touch) that is often under-exploited in VR as an informative channel, and that avoids overload the visual and audio perceptual channels.

Finally, a large spectrum of data can be displayed using different amplitude and frequency vibration patterns. Vibrotactile interfaces thus appear to be a good candidate to partially substitute kinesthetic information and make users aware of impending or actual collisions, in highly constrained spaces.

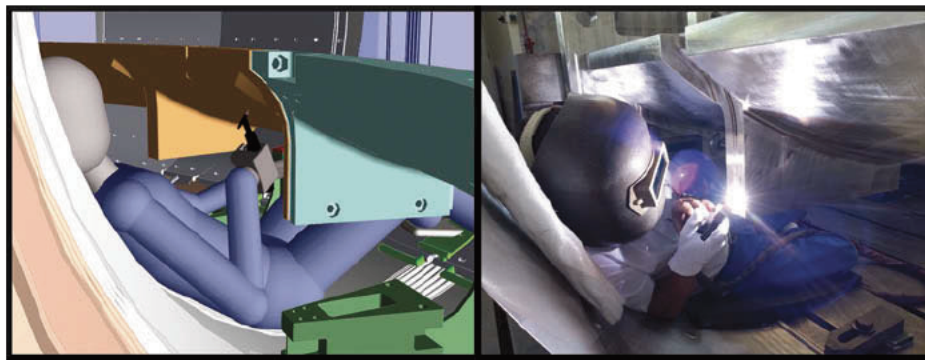


Figure 1. Welding task simulation in Virtual Reality (left) and with a real mock up (right).

In this article, we present an experimental study exploring the contribution of multi-localized vibrators to visuo-proprioceptive consistency during goal-directed movements in a cluttered VE. The article is structured as follows: First, a short literature review of the use of vibrotactile stimulation in spatial behavior is provided (Sec. 2). The experimental procedure is then described (Sec. 3) and the results are presented and discussed (Secs. 4 and 5). To finish, conclusions and perspectives are presented (Sec. 6).

Related work and background

Vibrotactile stimulation

Haptic perception combines two types of perceptual information. The kinesthetic perception delivers information on both the relative positions and movements of body parts and muscular effort. Tactile perception enables the feeling of different types of stimulus on the skin, such as thermal properties, vibration, pressure, and pain. Touch has been used to substitute other perceptions (visual, auditory) or as an extra information medium. Three main transducer types are used for tactile display of spatial patterns on the skin: static tactile, electrotactile, and vibrotactile (Kaczmarek & Bach-y-Rita, 1995).

Vibration has long been used as an informational medium in different applications. Although the historical application of vibrotactile stimulation was to assist visually impaired users (Bach-Y-Rita, Collins, Saunders, White, & Scadden, 1969; Goldish & Taylor, 1974), vibrotactile stimulation is not limited to this purpose. In particular, it can be used in human-machine interfaces for VR. Vibrotactile feedback can be divided into three main application areas (Choi & Kuchenbecker, 2013):

Multimedia and entertainment

Vibrotactile-based feedback is frequently used in the gaming industry. First implemented in the “rumble packs” for the Nintendo 64 and Sega Dreamcast controllers, the incorporation of vibrotactile feedback into controllers is now common use and is a topic of ongoing research (Israr & Poupyrev, 2011). Also, with the emergence of 4-D films and VR games, various new devices using vibrotactile feedback have been released.

Abstract information

This domain has been studied for more than a decade. Communication and guidance are the main objectives. As outlined above, the most traditional purpose of vibrotactile stimulation use is the development of communication devices for people with sensory impairments (Bach-Y-Rita et al., 1969; Gemperle, Ota, & Siewiorek, 2001; Goldish & Taylor, 1974). Vibrotactile devices have also been exploited for guidance: movement guidance (e.g. for the teaching of good posture and bowing technique to novice violin players (Van Der Linden et al., 2011), training Ryukyu Kempo (Bloomfield & Badler, 2008)...) and spatial guidance (Flores et al., 2015; J. B. Van Erp, Van Veen, Jansen, & Dobbins, 2005). Vibrotactile feedback has also been used to display information: mobile user interface (e.g. feedback when typing), attention and warning information (e.g. in a car driving with warnings against hazardous driving or dangerous situations (Meng, Gray, Ho, Ahtamad, & Spence, 2014)).

Physical information

Physical information can be displayed using vibrotactile interfaces. In this case, the interface provides vibration in response to a motion or an action performed by the user in the VE. This area can be divided into two topics: conveying properties of physical objects (e.g. material Properties) (Romano & Kuchenbecker, 2012) and contact location. One of the objectives of providing physical information is to improve spatial awareness.

Spatial awareness

In the field of human operators’ simulation, the use of vibrotactile devices for enhancing spatial awareness has gained a lot of attention. Weber et al. (2011) outlined the main reasons for this. Firstly, the tactile channel is less overloaded than the visual or acoustical channels in complex scenarios. Secondly, vibrotactile stimulation can be unobtrusive and inform the operator without disturbing other users. Finally, the stimulation is localized on the user’s skin. It triggers an intuitive form of spatialized feedback. Moreover, vibrotactile interfaces are light and wearable. Therefore, vibrotactile feedback is a good candidate to partially substitute the kinesthetic stimulation sense and to make users aware of impending or actual collisions in highly constrained

spaces. While obtaining a force feedback is relatively straightforward when using a haptic (active) force device, force feedback cannot be applied to all types of scenarios. In particular, it is not satisfactory when interact with a complex VE when the whole-body posture is involved. The technology used to generate force-feedback stimulation is typically cumbersome, costly, and has a limited range of motion (Lindeman, Yanagida, Hosaka, & Abe, 2006). They are well adapted to some applications, for example remote handling simulations, but they are not suitable to deliver whole arm force feedback. To allow a “whole-body” feedback, complex devices such as an exoskeleton are needed. They are generally very costly and complex to implement. Another interaction metaphor that might be studied to “replace” haptic perception is a tangible interface. This consists of adding physical elements within the user’s workspace, to create a mixed reality (Hoffmann, 1998; Milgram & Kishino, 1994). This is beyond the scope of this article.

Recent studies have successfully investigated the effect of vibrotactile stimulation while interacting with virtual objects, to determine whether vibrotactile stimulation might act as an effective substitute for haptic kinesthetic stimulation and enhance spatial awareness. Results showed that tactile cues are effective for imparting collision stimuli to the user’s body. In particular, Bloomfield and Badler (Bloomfield & Badler, 2008) consider the case of a constrained environment and propose to render collisions with localized vibrotactile feedback. They show an improvement in performance (completion time) with vibrotactile feedback, as compared to pure visual feedback. Lindeman et al. studied vibrotactile feedback in several contexts. In one of their studies, they used a jacket with multiple vibrators to improve the feeling of collisions when navigating in a VE (Lindeman et al., 2004). Ryu and Kim were also interested in simulating contact with the environment during navigation. They showed an improvement of the presence feeling when using a whole-body vibrotactile system (Ryu & Kim, 2004). The present experiment is in the continuation of studies we previously carried out with vibrotactile feedback. In the previous experimentations, we validated the developed vibrotactile device and we studied spatial perception in a navigation task. We showed that representation of one’s own-body (avatar) and vibrotactile feedback improve distance perception by helping to calibrate the body/environment relationships (Louison, Ferlay, Keller, & Mestre, 2015; Mestre, Louison, & Ferlay, 2016). Based on these experimentations, we decided to study further the effect of localized vibrotactile feedback in a context closer to the study case encountered on assembly and maintenance tasks. More precisely, we focused on reaching manual tasks and studied the contribution of spatialized contact feedback in a constrained environment from the angle of visuo-proprioceptive consistency.

Spatial acuity

The spatial acuity of tactile stimuli is an important parameter when studying tactile feedback. It is necessary to have an idea of how many actuators are needed and where to put them to correctly “feel” the environment.

The tactile spatial resolution for pressure or static stimulation has been widely studied (Vierodt, 1870; Weber, 1834; Weinstein, 1968). A precise mapping of the spatial acuity has been established over the body (Lederman, 1991; Weinstein, 1968). It has only recently been studied with respect to vibrotactile stimuli ((Cholewiak, Brill, & Schwab, 2004; Cholewiak, Collins, & Brill, 2001; Sofia & Jones, 2013; J. B. F. Van Erp, 2007) ...). Due to the propagation of the vibration through the skin, the resolution is lower regarding the resolution of pressure stimulation.

When using vibrotactile stimuli, it has been shown that the several parameters play a role: position over the body, frequency, skin temperature, age, to mention a few. Jones et al. (Jones, Nakamura, & Lockyer, 2004) have, in preliminary tests, established that the optimal stimulation frequency (i.e. where the sensitivity is greatest) is between 120–250 Hz for the torso. In this study, we focus on manual assembly and maintenance tasks, so we are particularly interested in the upper limb. Cholewiak and Collins (Cholewiak & Collins, 2003) demonstrated that a physical separation of 25 mm on the forearm was insufficient to provide very accurate identification. On the arm/forearm, a distance superior to 50 mm is needed for a percent of correct identification of the location superior to 65% (Cholewiak & Collins, 2003; Sofia & Jones, 2013).

The funneling effect

A particularly interesting aspect of vibrotactile stimuli is the existence of several perceptual illusions arising from the configuration of vibrators. These illusions occur when the spatial and temporal patterns of vibrotactile stimuli lead to specific perceptual interpretations (Flores et al., 2015). Several effects of simultaneous and/or successive stimulations of two points (on the skin) were discovered, one of which being that they can create “phantom” movement sensations. These illusions enable the use of a linear array of actuators to induce vibrotactile sensations that continuously move on the body. There are several well-known sensorial effects. In the “sensory saltation” or “cutaneous rabbit” illusion, a series of three short pulses applied successively to three aligned loci create a sensation of movement on the skin (Geldard, 1982; Geldard & Sherrick, 1972). It is also possible to perceive an apparent tactile motion by controlling the start and stop timings of successively activated actuators. Yet another of these perceptual phenomena is called the “funneling illusion” (Alles, 1970; Békésy, 1958). This illusion corresponds to phantom sensations of stimulation position between two actual stimulation positions. Moreover, the position of the phantom sensation can be controlled by modulating the amplitude of the two stimulations (Figure 2) (Cha, Rahal, & El Saddik, 2008).

This modulation can be realized using a linear model, but a loss of intensity of the phantom sensation can be felt in the middle (Figure 3). Alles (Alles, 1970) proposed using a logarithmic rather than linear variation, to keep the same perceived intensity, no matter where the phantom sensation is. Seo and Choi (Seo & Choi, 2010) showed that the logarithmic model is better for the prediction of the felt intensity of the phantom sensation, while the linear modulation is better for the prediction of the position of the phantom

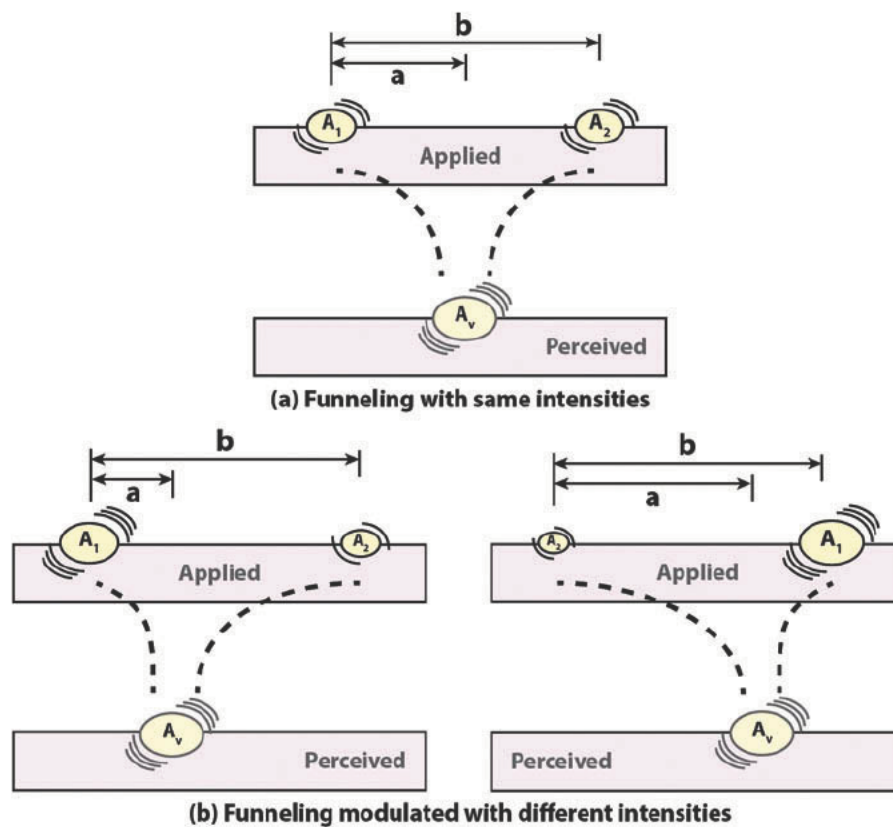


Figure 2. Illustration of the funneling illusion. The two stimuli are perceived as a unique stimulus, whose location can be changed by modulating the amplitude of the two stimuli. Adapted from Cha et al. (2008) and Israr and Poupyrev (2011).

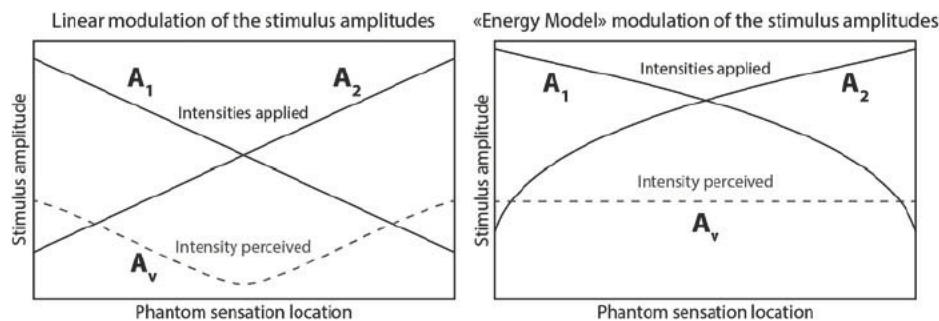


Figure 3. A linear modulation of the stimuli amplitude causes a loss of the intensity felt in the middle. A logarithmic or an “energy model” modulation allows a constant perception. Adapted from Alles (1970).

sensation. Israr and Poupyrev (Israr & Poupyrev, 2011) proposed an “energy model”, which allows a better control of the intensity and the localization of the phantom sensation (Figure 3). The distance between the two actuators/stimuli has to be in a range between 40 and 80 mm (Cha et al., 2008).

Material and methods

In the continuation of previous results we formulated a first hypothesis: adding vibrotactile feedback to give contact information offers better collision awareness. The tactile stimulation (vibration) should replace the missing proprioceptive information and thus help the subject to build a calibrated spatial representation of the VR environment, thus increasing spatial

awareness. We also proposed to focus on the study of the coherence between visual and proprioceptive information. From previous studies, we proposed that a co-localized avatar and tactile stimulation (signaling contacts between the avatar and virtual objects) would increase visuo-proprioceptive coherence and the construction of an efficient spatial representation for the success of a reaching task in a cluttered environment.

The second hypothesis specifically addressed the question of the spatialization of contact information. The use of a custom-made vibrotactile stimulation system using several vibrators, delivering localized contact should information allow a more precise perception of the spatial localization of the contact points. As a consequence, spatialized information should to improved body-scaled spatial representation and to optimized behavior in the VE.

The simple task chosen in this experimentation is intrinsically linked to some of the studies done to test accessibility or maintenance feasibility in complex and/or confined environment. During the design of the ToreSupra/WEST facility (a fusion reactor at CEA, France), many studies of accessibility close to this case study has been required (Bernard et al., 2017; Ferlay et al., 2015; Keller et al., 2015). We think that vibrotactile feedback use should be adapted to the task. This study involves a manual task, so we focus on the upper limb.

Subjects

Twenty-eight subjects (eight female) voluntarily took part in this experiment. They have been chosen among university students and staff, with ages between 20 and 34 years (mean = 23.6; SD = 3.4). The volunteers were in majority right-handed (3 left-handed), but no differences were found concerning handedness. All participants gave written informed consent prior to the study, in accordance with the 1964 Declaration of Helsinki. The study was approved by the local institutional review board of the Institute of Movement Sciences.

Subjects were naïve as concerns the purpose of the experiment. All subjects reported normal vision and sense of touch and were free from any locomotor or postural disorder. Their stereoscopic acuity was tested using the Randot® Graded Circles test (Stereo Optical Company Inc, Chicago, IL, USA). Their inter-pupillary distance (IPD) was measured using the Oculus configuration utility software. IPD ranged from 60.6 to 67.9mm (mean = 64.1; SD = 2.2), and was used to adjust stereoscopic rendering to each individual. The subjects were not selected regarding their stature. Their standing height ranged from 163 to 190 cm (mean = 177.6; SD = 7.1).

Apparatus

The experiment was conducted in a square area (3 × 3 meters), being the inside of a CAVE (Cruz-Neira, Sandin, & DeFanti, 1993) setup at CRVM (www.crvm.eu). Subjects were equipped with an Oculus Rift DK2 device. This *head-mounted display* (HMD) allows stereoscopic 3D rendering of VEs, with a 960 × 1080 pixel resolution per eye. It uses a combination of 3-axis gyros, accelerometers, and magnetometers, which allows precise head orientation tracking. Positional tracking of the HMD was performed using an external infrared tracking sensor, tracking a known constellation of infrared light-emitting diodes on the HMD. The subject's head tracking was used to update stereoscopic images relative to the subject's point of view. The HMD was connected by wire to the graphics PC, running an application developed with Unity software. The wire came from the top and was long enough to minimally disturb the subject's movements (Figure 4).

The CAVE tracking system (ArtTrack from Advanced Realtime Tracking GmbH) with eight cameras, using recognition of passive markers reflecting infrared light, was used to monitor the subject's full-body posture. Passive markers (17) placed all over the subject's body (feet, legs, thighs, waist, chest, hands, arms, forearms, shoulders, and head), were used to acquire the subject's movements (Figure 4). The ART-Human® software was used to reconstruct the subject's skeleton from the tracked markers' positions. It automatically calibrated the bone lengths of a human body model and used advanced inverse kinematics to reconstruct and visualize, in real time, the human body posture. This body reconstruction was used to calculate a real-time and co-localized virtual representation of the subject's body in the Unity application (Figure 7, left). The real-time VR system operated at 60 Hz.

Moreover, visual feedback (VE and self-avatar) could be augmented by vibrotactile feedback. The vibrotactile device was developed previously (Figure 5) (Louison et al., 2015).



Figure 4. A subject in the experimental setup. He wears the HMD, with the external infrared tracking sensor in front of him. He also wears an ART full body capture set.

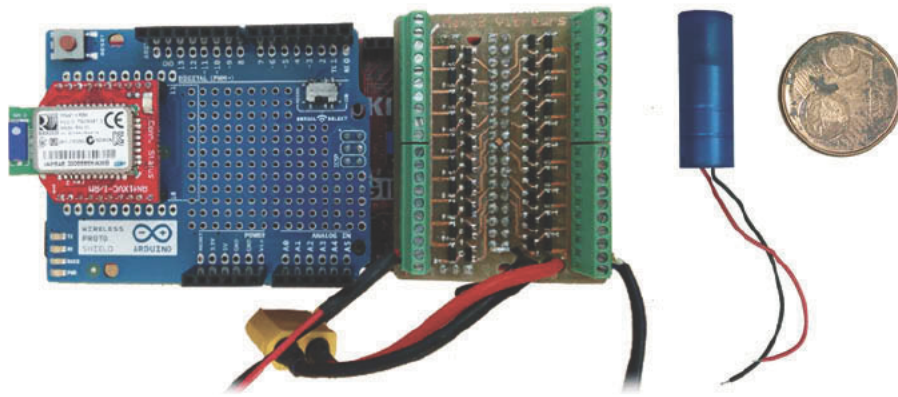


Figure 5. Vibrotactile controller prototype and a vibrator.

The prototype has been realized by merging the different solution proposed in the literature (Gemperle et al., 2001; Lindeman & Cutler, 2003; Martínez, García, Oliver, Molina, & González, 2014; Regenbrecht, Hauber, Schoenfelder, & Maegerlein, 2005). The vibrotactile device was based on an Arduino-like microcontroller (ChipKit Max32™), equipped with a Bluetooth module for communicating with the PC on which the simulation was running. The controller can address up to 20 vibrators using the daughter board that we made. Vibrators can be activated with 101 levels of intensity (from 0% to 100% of the maximal vibration) and two vibration patterns (continuous or discontinuous). The intensity levels have been obtained using a pulse-width modulation (PWM) with 10 ms cycle. The PWM allowed us to have an average value of voltage by turning the switch between supply and load on and off at a fast rate. The longer the switch is on, as compared to the off periods, the higher the total power

supplied to the load. For example, the intensity level '25' is equivalent to a PWM duty cycle of 25%. The controller activates vibrators: DC motor with an eccentric mass (12,000 tr/min 3 V CC — from Parallax Inc. ref. 28822), connected by wires. The controller is powered by two rechargeable batteries. One is used for the board power supply and the other for the vibrators' supply.

In the present experiment, ten actuators were used. They were positioned on the subject's arm with a special jacket we designed (Figure 6). The jacket was available in different sizes (from S to XL) to best fit each subject's morphology. The vibrators were aligned and spaced at a maximum of 8 cm from each other along the limb, with the exception of vibrators n° 6 and n° 7 spaced about 16 cm. The reason for the larger space is that the inner side of the upper arm was less likely to be in contact with an object in this scenario, so we decide to put only one vibrator at this position. At a distance

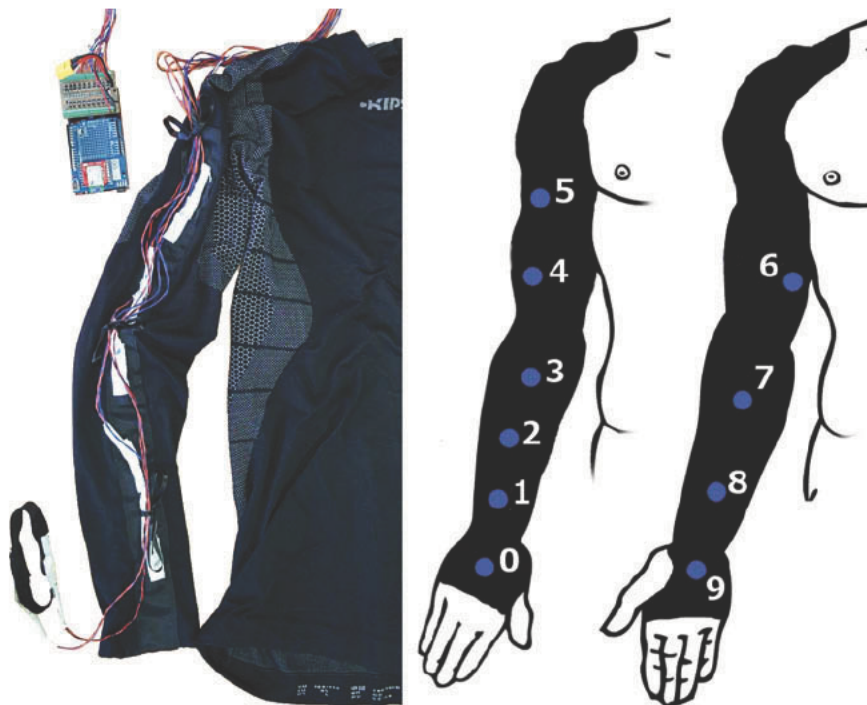


Figure 6. Vibrotactile suit with the vibrotactile controller and position of the ten actuators along the arm.

of 10 cm the motor mechanical noise was 50 dB max. The noise generated by the vibrators attach to the jacket was negligible and should not be considered as an extra auditory clue to the vibrotactile condition.

The VR loop (motion capture to sensorial rendering) was controlled by a PC. The experimental application was built with Unity3D, to allow experimental control, data recording and all scenario actions. The XDE physical engine developed by CEA LIST (<http://www-list.cea.fr/en/>), integrated to Unity3D, allowed realistic and real-time physical simulation and human control from ARTHuman data.

Due to the use of bluetooth wireless connection between vibrotactile device and the main PC, there was a delay between the moment when the vibration instruction was sent and the moment when the vibration occurred. The delay has been estimated with a special setup using a 240 Hz video camera. The global delay was measured from the trigger action (sending the command via bluetooth) until the start of the vibration. We repeated the measurement 55 times and obtained a delay around 80 ms ($M = 80.7\text{ms}$; $SD = 10.5$). However, this delay was never reported by participants.

Vibration modes

The XDE physical engine allows the computation of contact points between rigid bodies. The position of the contact, the normal and the force applied is computed for each contact point. From this computation we know the contact location between the VE and the avatar's arm. The physical engine does not allow interpenetration between two rigid bodies. For example, if a subject tries to walk through a wall in the VE, the avatar will be stopped by the wall even though it does not exist in the real world. To simplify, a spring is created between the subject's tracked body and the avatar when the avatar is in contact with an object. This allows to compute the exerted force and to regain its position when the obstacle's conflict no longer exists. The contact information (position and force) is used to compute which vibrator is activated to represent the contact on the subject's arm and the amplitude of the vibration. The computation needs to know the position of the contact regarding to the position of the location of the actuators. The vibrators were virtually placed on the avatar limb (but invisible to the user). The calibration was manually executed before the experimentation by having the real vibrators spatially coincident with the virtual vibrators.

In this experimentation, three different conditions (modes) of vibration were used. Each mode had a specific algorithm to select the amplitude of vibrators during a contact.

Single: In this mode, only one actuator was used to represent the existence of a contact between the avatar and the VE, regardless of the position of the contact on the avatar's arm. The selected vibrator was always the same (actuator 0 on [Figure 6](#), right). The vibration amplitude was computed according to the force of the contact (see after). If there was more than one contact at the same time (e.g. two contacts in different places on the arm), the amplitude was the maximum value of all contact forces.

Nearest: In this mode we selected the nearest vibrator to the contact position on the avatar's arm. The amplitude was

related to the force of contact (see after). If more than one contact had to be represented by the same vibrator (e.g. two contacts localized on the arm near the same vibrator), the vibration amplitude was the maximum value of the force of these contacts. Several contacts could be represented at the same time by different actuators.

Funneling: The funneling effect, as previously introduced, is a psychophysical phenomenon that allows to create a felt perception of a phantom location between two points of stimulation. We decided to use this effect to create the sensation of a contact position that would be closest to the "actual" contact point. The goal of the funneling algorithm was to find, if possible, a pair of close vibrators such as the contact point was between the positions of the two vibrators. The algorithm has a list of vibrators pairs that cannot be used for the funneling effect. This is the case for vibrators that are not on the same side of the limb, e.g. between vibrators 0 and 9 (although it might be interesting to study). It is also the case for vibrators that are too far apart (e.g. between vibrators 6 and 7). If no pair of vibrators could be found, then we applied the "Nearest" algorithm. If a pair of vibrators was found, we applied the energy model proposed by Israr and Poupyrev (Israr & Poupyrev, 2011) to calculate the amplitude of both vibrators, according to the position of the contact point and the contact force. When more than one contact had to be represented by a vibrator or a pair of vibrators (e.g. two contacts localized in the same area), the contact with the highest force had the priority.

Let A_1 and A_2 be the intensities of the two physical actuators selected and the phantom intensity A_v . The formula to compute the amplitude of both vibrators A_1 and A_2 is as follows:

$$A_1 = \sqrt{(1 - \beta) \cdot A_v} \text{ and } A_2 = \sqrt{\beta \cdot A_v} \quad (1)$$

where β is the ratio of the distances a to b (see [Figure 2](#)) of the phantom location between the two actuators.

The intensity of the vibration (or phantom intensity A_v in the funneling condition) is mapped from the contact force computed by the physical engine. The value returned by the engine is a real number, corresponding to the normal force of the contact force in Newton. During a session, the max value of contacts force is recorded. The intensity of vibration of a current contact is the percentage of the current normal force in relation to the maximum recorded force during the session. This mapping allows one to use the full range of the vibrator power and adapted to the subject. When brushing past an object in the environment the vibration will be very weak (e.g. under 20% of the intensity) and an attempt of penetration of the VE will deliver a strong vibration (around 100% of the intensity of the vibrator). The algorithm behavior has been tested during pretest and has shown good rendering.

Virtual environments

The experimentation setup consisted in two VEs, one for the training session and one for the experimental session itself. The



Figure 7. Training environment with the avatar is in the initial position (before adjustment to the participant).

training environment was made from Unity primitives and involved a simple 3D model designed using Blender[®] 3D modeling software. This VE was composed of a 1.015 m height table and a box with a transparent wall and an aperture in front of the subject (Figure 7). Four targets (blue spheres 7 cm in diameter) were positioned inside this box, they could be switched on and off at will. This table was positioned in a 3 × 3 m room (the actual size of the physical space in the CAVE). The size congruence between the VE and the “real” physical space was meant to enable real walking of the subject in the experiment, which appears to be an effective way to get rid of locomotion interfaces and cybersickness, and to favor presence (Lepecq, Bringoux, Pergandi, Coyle, & Mestre, 2009).

The experimental environment was designed using CATIA[®] Computer-aided design software, imported into Unity3D. This environment represents a part of a

ToreSupra/WEST facility, a fusion reactor at the Alternative Energies and Atomic Energy Commission (CEA, France). The VE was composed of a platform to access the back of a heating antenna that is made of a support beam, pipes, etc. Four targets (blue spheres, same size as in the training session) were positioned in this environment, in the middle of the pipe forest. These targets were positioned within arm’s reach (Figure 8), distributed on the top, bottom, right, and left sides. The size of targets was selected during pre-tests, such that the task was comfortable. They could be switched on and off. The four targets were positioned between 1 m and 1.6 m height as follows: target 1 to the center down (around 1m height), target 2 to the right, target 3 to the top center and the target 4 to the left. This distribution was chosen to diversify the movements from trial to trial.

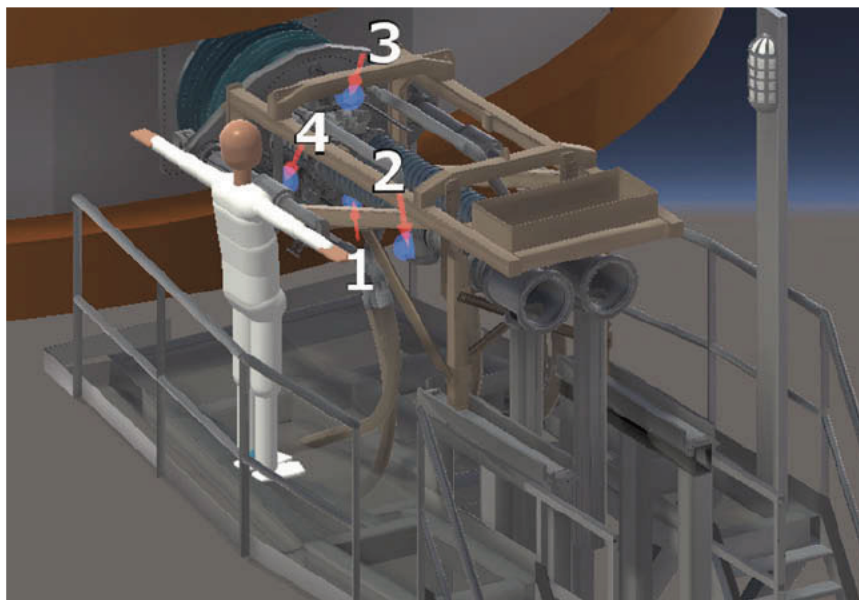


Figure 8. Experimental environment with the four targets.

Experimental conditions

The independent variable was the type of collision feedback, with 4 conditions. It could be *only visual* or augmented with vibrotactile stimulation. The vibrotactile feedback was used to represent any contact between the right arm and the environment. There were three different conditions of vibrotactile feedback. The first one used the ten vibrators distributed all along the arm to render localized contact by activating the *nearest* vibrator to the contact point (see “nearest” algorithm). The second one also used the ten vibrators, but took advantage of the psychophysical phenomenon called “funneling illusion” to render more precisely localized contacts (see “funneling” algorithm). The last one used a *single* vibrator (vibrator n° 0, on the top of the hand, see Figure 6) to represent any contact on the right upper limb (see “single” algorithm) with the VE. When the subject’s virtual arm came into contact with a virtual object, a continuous vibration was sent to the vibration device. The stronger is the force applied by the subject to an object, the more intense is the vibration. These three modes offer different levels of collisions rendering spatial accuracy. The experimentation was divided into four consecutive, counterbalanced between subjects, sessions. During a session the subject experimented one of the experimental conditions. The subjects were divided into different session order groups. No visual metaphor (e.g. contact arrows) was added in the four conditions to indicate collisions. The only visual indicator was the targets (blue spheres) that change of color when users reached them. The collision detection was realized by the XDE physical engine. The system continuously computed collision detection regardless of whether the vibrotactile controller was activated or not. All the contacts with the environment were recorded during the experiment. For each vibrator, the level of vibration amplitude was recorded from 1 to 100, 0 meaning no detection.

Procedure

After being recruited for the experiment and having basic measurements taken (see Sec. 3.1), the subject was equipped with tracking markers (seventeen targets made of passive markers) and with the vibrotactile device. The ten vibrotactile actuators were placed on the right arm, forearm and the hand, with a special suit (Figure 6). Once equipped, the subject was taken to the experimental area and equipped with the HMD.

A calibration step was required to build a biomechanical model of the subject using the ART-Human* software. To do this calibration, the subject had to stand in a “T” posture at start. After that, the subject had to move all limbs and rotate joints in all possible axes in order to calibrate the bone lengths and target positions. A configuration file with the bone lengths was generated and used by the XDE engine to create a morphological avatar of the subject in the VE. The virtual avatar was made of simple primitives (cylinders) (Figure 9). Even if it has been shown that users prefer a representation with high fidelity (Pusch, 2008), it has been shown that abstract avatars do not reduce the illusion of virtual body ownership (Lugrin, Latt, & Latoschik, 2015) and they are easier to use for the physical engine computation.

After this calibration phase, the real experimentation phase started. The experimentation was divided into four sessions, one for each experimental condition. A session was composed of two steps: training, followed by the recorded trials. The initial training VE was displayed to the subject with an avatar in a T pose in front of the table. Different adjustments and configuration steps were made; they had to be done at the beginning of each session and environment. The initial Oculus field of view was calibrated to match the tracking system reference. The Bluetooth connection between the PC and the vibrotactile device was established and tested by activating all the vibrators one by one, and the subject was asked whether they could feel them. The morphological avatar was then “attached” to the user’s movements. At the end of this setup, the avatar was optimally co-localized with the subject’s own body, reproducing the subject’s movements in real-time. The subject was seeing the avatar’s body as his own from a first-person subjective view (Figure 9, right).

The subject was next presented with a training session. The task in this training phase was the same as during the experimental phase. He was required to reach with the right hand different interest points (targets) within the VE, then to maintain the reached position for one second to validate it. These points were represented by blue spheres, changing in color intensity when the hand was in the target’s acceptance zone, and disappearing when validated. The subject was asked to reach the target with the most fluid and natural movement, like they would do in the real world. No specific information was given concerning the behavior to be adopted in case of contact with the VE; they were just informed that a vibration means a contact. During the session with the “Single”

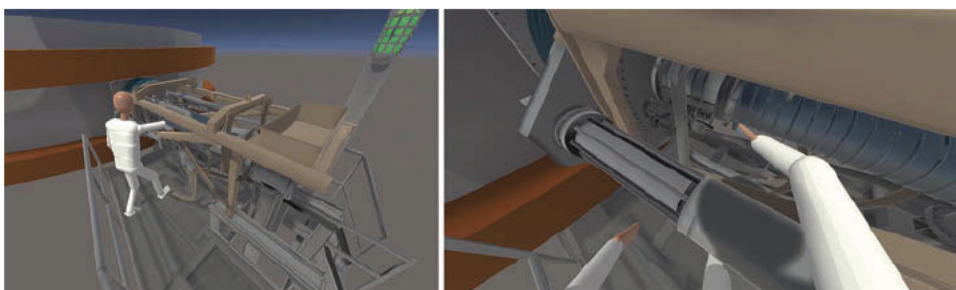


Figure 9. Left. Global view of the experimental virtual environment with the avatar doing the task. The recording of full body movements was used to build a co-localized avatar. Right. First person subjective view inside the HMD.

condition, we explained them that a contact with the right arm of the arm will be represented by the unique vibrator, and during the two spatialized feedback condition that the ten vibrators will be used to represent contact. During the visual only condition we explained them that no vibrators will be used. During this training phase, they could get familiar with the task, with the virtual body and, depending on the condition, with the eventual vibrotactile feedback. They could test the feedback as long as they wanted.

After these training sessions, the second environment was displayed; the adjustment and configuration steps were repeated. When the subject was ready, the first target was displayed and the first trial could begin. The task was the same as in the training environment. One trial consisted of the following sequence: the subject was standing with arms along the body, and, on the experimenter input, a new target appeared. Following a beep, the subject had to reach the target and maintain the final position to validate it. When validated, another beep was played and the target disappeared. The subject had to take the initial position before another trial could start. Participants were allowed to have a short rest before starting the next trial, to avoid physical exhaustion.

Each subject carried out four sessions: one for each of the four conditions: without activation of the actuators (visual), with just one vibrator (single), with ten vibrators using the “nearest” algorithm and with ten using the “funneling” algorithm.

The experiment was interrupted by a short break between each session. During these breaks, the subject could rest and had to fill three questionnaires about cybersickness (SSQ (Kennedy, Lane, Berbaum, & Lilienthal, 1993)), a NASA-TLX questionnaire (Hart & Staveland, 1988) in order to measure perceived workload and a SUS questionnaire (Brooke, 1996). Each session consisted of twenty trials. Each trial corresponded to one of four target positions. Each target position condition was repeated five times. Within a given session, the targets succession order was randomized across subjects.

The subjects were split into four groups. Subjects were randomly assigned to one group, each group having a different succession order of the four experimental conditions to control for potential order or time effects (fatigue, learning, etc.). After having finished all four experimental sessions, participants were asked to complete a post-experimental IPQ

questionnaire and some questions were asked by the experimenter about their feeling about immersion, the avatar and the vibrotactile feedback.

Data analysis

During the experiment, several behavioral indicators and events were recorded and analyzed. They consisted of the 3D positions of the right upper limb markers, as a function of time, with respect to the 3D positions of environmental elements. These positions came from the ART-Human software. Recorded data also included the 3D positions of the three segments of the right upper limb (hand, arm and forearm) of the avatar. Both sets of positions (markers and avatar) had the same spatial frame of reference and were measured at the center of segments/bones. Simultaneously, the amount of contact points detected by the physical engine was recorded at any moment during a trial.

In order to reduce noise in the data, some data sets were truncated. In some cases, the subjects tried to follow a path before they realized that they could not reach the target using that path. In these cases, they returned to a position close to the initial position (outside the structure) before attempting another trajectory, until they found a way to reach the target and validate the trial. The data corresponding to failed attempt trajectory portions were deleted. Only the final (successful) reaching movement was kept for each trial (from a position outside the environment, until validation). The Figure 10 shows the full trajectories of the Avatar hand movement for one subject (left) and the same trajectories without the part of the trajectories corresponding to path that do not lead to the target (right).

The main metrics that we wanted to focus on were related to the concept of visuo-proprioceptive consistency. We propose qualifying this consistency by the difference between user’s and avatar’s posture. To analyze that, we computed first the Root Mean Square (RMS) of the distance between the real subject position (obtained from the tracking system) and the avatar’s position. We call it thereafter the co-localized error (RMSE):

$$RMSE = \sqrt{\sum_{t=1}^n (\text{error}(P_{avatar,t}, P_{user,t}))^2}$$

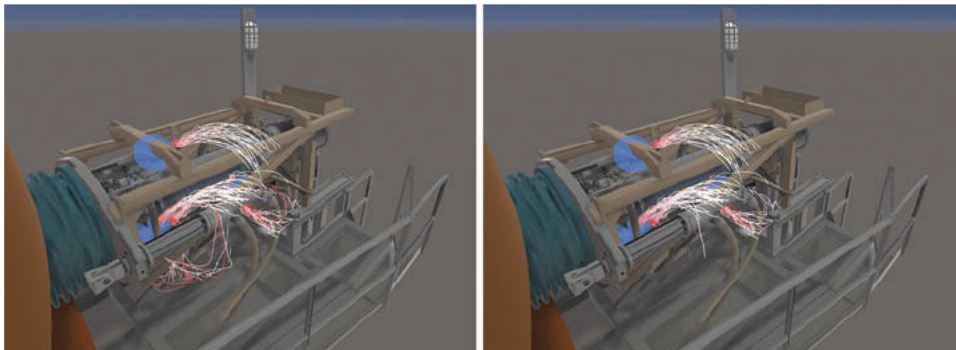


Figure 10. Left: Representation of the full trajectories of the Avatar hand movement of one subject. Right: Same trajectories but without the initial failed attempts.

Where the function *error* is the distance between an avatar and a user position (from the tracking system) at a given moment. We combined the error of the three segments (hand, arm, and forearm) together.

Then we analyzed the RMS of the angular deviation between the avatar and user trajectory direction by segments. We call it thereafter the co-localized deviation (RMSD):

$$RMSD = \sqrt{\sum_{t=1}^n (\text{deviation}(\vec{v}_{avatar,t}, \vec{v}_{user,t}))^2}$$

where the function *deviation* is the angle (rad) between an avatar and the user movement direction vector at a given moment. The vectors are created between each consecutive point of the trajectory (see Figure 11). We combined the deviation of the three segments (hand, arm, and forearm) together.

These metrics give us a direct indication about the subject behavior regarding physical objects in the environment. In other words, we wanted to evaluate the continuous co-localization between the subject's arm and the avatar arm during the reaching movement. The interest of studying visuo-proprioceptive consistency using these metrics is to show how the limits of the VE are integrated in the subject behavior.

Then as global performance index, we computed trial duration. We next computed the number of contact points during the movement, the ratio between the time spent in contact (with environmental objects) and total trial duration, and the mean contact time during a trial. These indicators were meant to analyze how subjects dealt with the occurrence of contacts, as a function of experimental conditions.

The statistical analyses were conducted using repeated measures analysis of variance (ANOVA). We then used post hoc analyses with Bonferroni adjustment and Planned Comparison tests.

Results

Co-localization error (RMSE)

We computed the co-localization Root Mean Square Error (RMSE). The error of co-localization refers to the distance between the real subject position (position of the ART targets from the tracking system) and the corresponding avatar positions. We computed RMS for the right (reaching) upper arm (which includes three segments: arm, forearm and hand). Repeated measures ANOVA with the experimental conditions as within factor revealed a significant effect ($F(3, 81) = 7.5127; p = .00017$). Subsequent post hoc analyses with Bonferroni adjustment showed that RMSE values in the three vibrotactile conditions were lower than in the "visual only" condition ($p < .005$), and these three conditions were not statistically different from each other (see Figure 12). This result suggests that visuo-proprioceptive consistency was improved by the vibration feedback. However, they did not show that a spatialized feedback (funneling or nearest conditions) has a significant effect, as compared to a single vibrator (located on the hand, whatever the contact position). Next, we analyzed another metric link to co-localization with the trajectories of the movement.

Co-localization deviation (RMSD)

We computed the direction trajectories Root Mean Square Deviation (RMSD). The error refers to the deviation between subject's actual trajectory direction (obtained from the position of the ART targets from the tracking system) and the corresponding avatar trajectory direction. We computed RMSD for the right (reaching) upper arm (which includes three segments: arm, forearm, and hand). Repeated measures ANOVA with the experimental conditions as a within factor revealed a significant effect ($F(3, 81) = 11.020; p = .000004$). We observed a more linear tendency effect, as compared to the result on RMSE above (Figure 13). Subsequent post hoc analyses with Bonferroni adjustment showed that RMS values in the three vibrotactile conditions were lower than in the

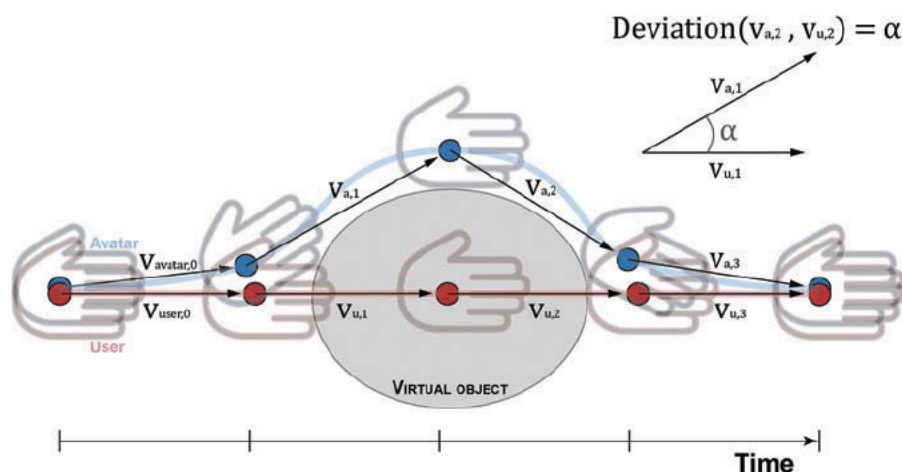


Figure 11. Example of the trajectory of the avatar's hand (blue) and user's hand (red) and computation of the co localized deviation.

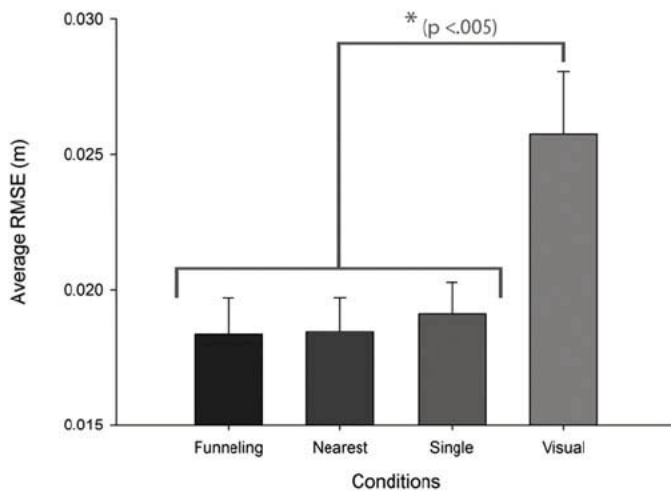


Figure 12. Average values (with standard error) of RMS error, as a function of experimental conditions.

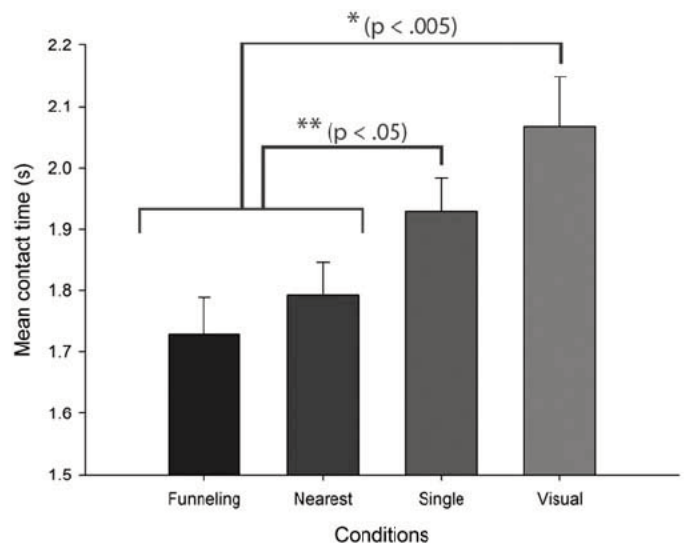


Figure 14. Average values (with standard error) of the mean contact time in a single trial, as a function of experimental conditions.

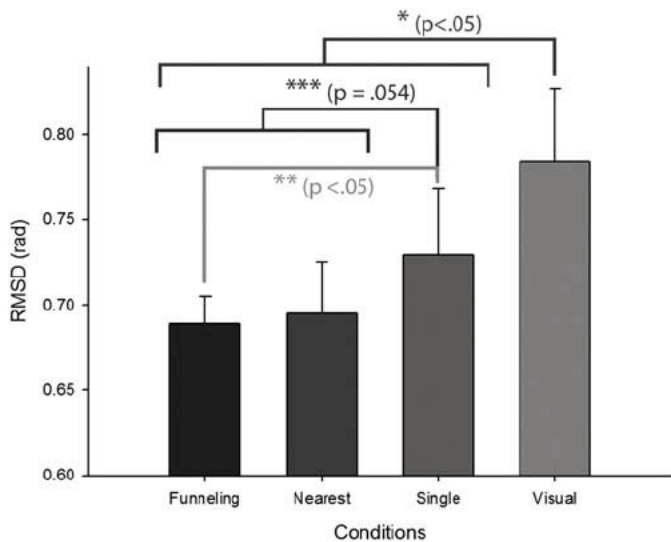


Figure 13. Average values (with standard error) of RMS deviation, as a function of experimental conditions.

“visual only” condition ($p < .05$). The “funneling” and “nearest” conditions did not differ statistically ($p > .50$). Planned Comparisons tests revealed that the “single” condition was statistically different from the “funneling” condition ($p < .05$). We also found a tendency effect between “single” and the group {“nearest”, “funneling”} ($P = .054$). Like in the previous results on RMSE, this suggests that visuo-proprioceptive consistency was globally improved by the vibration feedback. Moreover, analyses show a partial effect of the spatialized feedback, as compared to a single vibrator. We continued our analysis by considering how subjects reacted when a collision was detected.

Mean contact time

We analyzed the reaction time when a contact was detected with the mean of contact time during a single trial. We measured contact time from the moment when a contact point was

detected along the upper arm until there were no more contact points detected. A significant effect of experimental conditions was found ($F(3, 81) = 7.2249; p < .001$). We observed, as for the RMSD analyze, a tendency for a linear effect (Figure 14). Post hoc analysis (Bonferroni) showed that the “single” condition was not statistically different from the “visual” condition ($p = .49$). However, both “funneling” and “nearest” conditions gave significantly lower values of mean contact time as compared to the “visual” condition ($p < .005$). The “funneling” and “nearest” conditions did not differ statistically significantly ($p > .50$). Finally, Planned Comparisons tests revealed that the “Single” condition was statistically different from the group {“nearest”, “funneling”} ($p < .05$). This pattern of results suggests that the “single”, non-localized vibrator informs the subjects about the occurrence of a contact, but that subjects still have to “search/identify” where the contact location is (they just have a global information), as in the “visual” condition. In that case, localized vibration (funneling or nearest) directly gives an indication about the contact location, the information of the contacts localization allow a faster correction of movements, thus reducing contact time.

Next, we analyzed different aspects of subjects’ behavior, trying to understand better these first effects.

Trial duration

A significant effect of our experimental conditions on individual trial duration was found ($F(3, 81) = 11.186; p < .001$). The duration was shorter in the “visual only” condition, as compared to “vibration” conditions (Figure 15). Subsequent post hoc analyses with Bonferroni adjustment showed that trial duration in the three vibrotactile conditions were higher than in the “visual only” condition ($p < .05$), and these three conditions were not statistically different from one another (see Figure 15). This result suggests a faster execution of the task without vibrotactile feedback. This effect might seem to be in contradiction with the RMSE results (above). However, it might be explained by the fact that, in the visual-only condition,

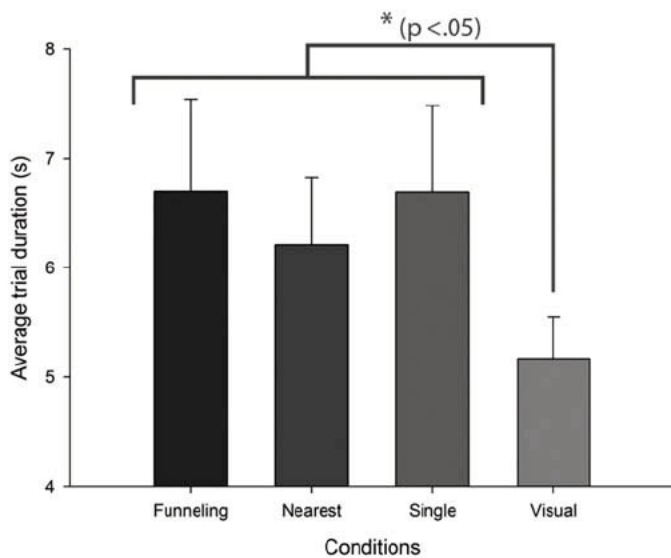


Figure 15. Average values (with standard error) of trial duration, as a function of experimental conditions.

subjects spent less time taking into account collisions with environmental objects. This leads to decrease the realism of the interaction. We next considered different aspects of the subjects' reaction to collision events during a trial.

Contact time ratio

We next computed, for each trial, the ratio between total contact duration and total trial duration. We found that the experimental conditions had a significant effect on this ratio ($F(3, 81) = 10.432$; $p < .001$). Despite the fact that trial duration was shorter in the "visual" condition (Figure 15), subjects spent proportionally more time colliding with environmental objects in that condition; as compared to "vibrotactile" conditions (Figure 16). With the vibrotactile conditions the contact time ratio was lower than with the Visual condition. Funneling: $M = 0.559$; $SD = 0.083$ ($p < .005$), nearest:

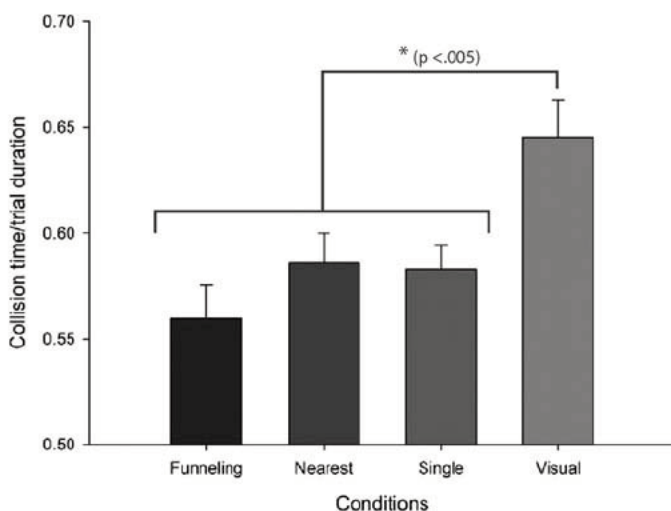


Figure 16. Average values (with standard error) of the ratio between contact time and total trial duration in a single trial, as a function of experimental conditions.

$M = 0.585$; $SD = 0.0740$ ($p < .005$), single: $M = 0.582$; $SD = 0.0610$ ($p < .005$) than with the visual condition ($M = 0.645$; $SD = 0.093155$). No significant difference was found between the three vibrotactile conditions.

Average number of contact points

The average count of contact points, all along the upper arm during a trial, was analyzed. As expected, confirming the previous analyses, a significant effect of experimental conditions was found ($F(3, 81) = 13.744$; $p < .001$). The number of contact points was higher in the "visual only" conditions (see Figure 17).

These data suggest that, as compared to pure visual feedback, vibrotactile stimulation increased spatial awareness in the subjects, enabling them to avoid contact with environmental objects. The fact that we found only little evidence for a difference between a single (non-localized) vibrator and localized vibrators suggests that vibrotactile feedback tends to act as a warning signal, enhancing spatial awareness.

Questionnaires

The global score of the questionnaires about workload (Nasa-TLX) and usability (SUS) was analyzed. There was no statistical difference between for both scores (Table 1). Moreover, the usability scores are above the average (Bangor, Kortum, & Miller, 2009) and the workload score should be considered as low regarding general workload score observed (Grier, 2015).

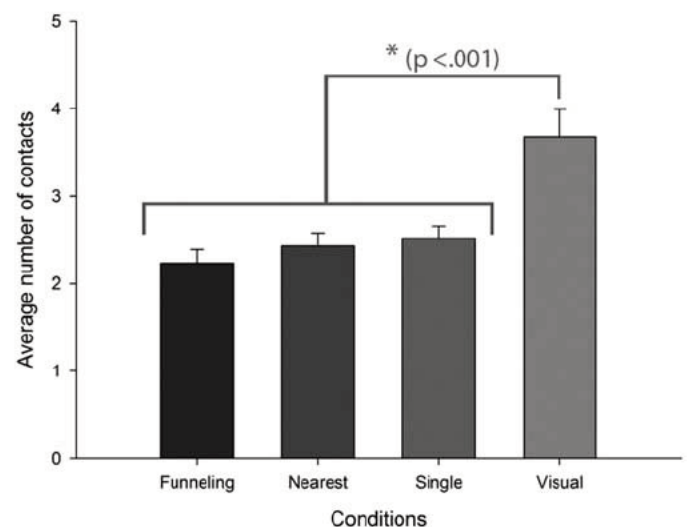


Figure 17. Average values (with standard error) of the mean number of contacts in a single trial, as a function of experimental conditions.

Table 1. Means (SD) of the SUS scores and the Nasa TLX scores as a function of experimental conditions.

Condition	Funneling	Nearest	Single	Visual
SUS Score	70.53 (2.78)	70.71 (2.28)	67.77 (2.56)	69.91 (2.55)
Nasa TLX Score	23.43 (2.10)	24.78 (2.46)	25.68 (2.74)	22.82 (2.50)

The global setting and the vibrotactile information don't seem to have a negative impact on usability and workload.

Discussion

In the present study, we investigated several conditions of vibrotactile feedback during goal-directed movements in a cluttered environment, while our subjects wore a HMD. Compared to pure visual feedback of a co-localized arm avatar, this feedback was meant to enhance the detection of collisions. Specifically, we compared two spatialized vibrotactile feedback with ten vibrators along the upper limb using Funneling or Nearest Algorithms, one non-spatialized vibrotactile feedback with a single vibrator and a condition without any vibrotactile feedback (default visual condition). Participants had to reach targets with their right hand in a cluttered VE, without force feedback. They were instructed to try to adopt the most fluid and natural movement as possible. No time performance was specifically requested.

We evaluated the different vibrotactile conditions by using several metrics: Error and Deviation of co-localization, contact time trial duration, contact time/trail duration ratios and number of contacts. We found evidence that individuals make less error of co-localization and less contact when having a vibrotactile feedback.

First of all, subjects with vibrotactile stimulation showed a lower co-localization RMSE and RMSD. This positive effect can be explained by the fact that a vibrotactile feedback increases spatial awareness and so the visuo-proprioceptive consistency, thus helping the subjects to maintain the spatio-temporal co-localization between their real arm and the virtual arm.

Secondly, subjects had a proportional duration of contact shorter and had fewer contacts with the vibrotactile feedback. This helps us to understand how the vibrotactile feedback information is used. Regarding the reduction of contact points and the contact time ratio, the vibrotactile information warns subjects and they react by correcting their position, resulting in spatio-temporal co-localization improvement.

Here, we tested the situation where the subjects used a HMD. As a consequence, they did not see their real arm. This is certainly why vibrotactile information played such a significant role in perceiving (or not) the distance between the real and virtual arm. This situation is certainly different from an augmented reality situation, such that studied by Pusch (Pusch, 2008), in which the operator could see his/her own arm, adding a visuo-visual factor (between the real and virtual arms) to visuo-proprioceptive consistency. It would be interesting to test our experimental setup in a CAVE system for instance; where the subject has direct vision of his/her real arm (we have ongoing work in that direction). However, the "CAVE" setup could pose serious problems such as the fact that objects become transparent when your real arm penetrates them, jeopardizing presence. Comparing CAVE and HMD setups remains a topic of interest for future work.

We only found a small difference between the different conditions of vibrotactile feedback. This suggests that, before

localized information, vibrators deliver "warning" information using the somesthetic modality. This is simple information that is already able to increase spatial awareness and overall spatial behavior.

More detailed analyses of reaching behavior would certainly be useful to investigate further the contribution of localized vibrations. However, we found evidence that subjects with the multi-localized vibrotactile feedback made shorter contact time than with the single actuator or without vibrotactile feedback. It appears that the reaction to a contact is faster with localized information. The differences are small but represent a meaningful difference in motor control. It could be explained by the fact that the multi-localized vibrotactile feedback allows fast localization of a contact point without visual search and a faster reaction to it. This is supported by subjective data (post hoc open interview). Subjects generally reported that the extra information given by the multi-localized vibrotactile device was relevant to find the location of contact points. Moreover, subject obtain a better dynamic behavior regarding the direction of the movement as shown by the RMSD analyze. We suppose that the localized information allows, thanks to a greater reactivity, a finer control of the trajectory regarding the environmental constraint. The proposed distribution and position of the vibrator have been chosen regarding the task and validated in preliminary tests. It's seemed important to adapt to each scenario the use of vibrotactile feedback; it's why the vibrotactile device must be versatile to be able to match with the need of the different cases of study.

Concerning questionnaires completed by the subjects between sessions, no significant effect was noticed regarding workload (Nasa-TLX) and usability (SUS) between conditions. The equipment and the vibrotactile information did not have a negative impact on usability and workload. This suggests that the use of the vibrotactile feedback was "transparent" to the user. It might also be explained by the fact that the user did not need any particular adaptation time to understand and integrate the extra information provided by the tactile stimulation. The feedback provided is relatively natural compare to what he could expect to feel, easy to understand and it uses the tactile modality.

Finally, no statistical difference was observed between the two multi-localized vibrotactile feedback conditions (funneling and nearest conditions). The fact that there is no difference between these two algorithms may indicate that an increase in the resolution of the spatialized feedback display is not necessary. It could also be due to the limitations of the vibrotactile device used in this experiment and to an insufficient configuration of the funneling algorithm. The sensitivity to vibrotactile stimuli varies considerably between subjects and body localization, and an individualized parameter setup might be necessary to make the funneling algorithm more efficient.

Conclusions and future work

Our approach involved both a dynamic and co-localized visual representation of the subject's body and a multi-localized vibrotactile feedback as a substitute for force

feedback. The results suggest that vibrotactile feedback enhances visuo-proprioceptive consistency. Moreover, a localized vibrotactile feedback allows faster localization of contact points without overloading the visual sense by reducing the need of a visual search and also favoring visuo-proprioceptive consistency.

It seems that using vibrotactile feedback to enhance the perception of collisions with virtual elements is a very promising approach to the improvement of spatial awareness of the operator in a cluttered environment. As such, it might be an important factor for the ecological validity of virtual experiments. It would also be interesting to compare vibrotactile and force feedback in encumbered VEs, in which haptic force systems can be intrusive.

A large amount of information can be displayed through the tactile modality, making use of perceptual phenomena such as the “funneling illusion”. Nevertheless, in the present study we failed to show that this phenomenon could have a significant effect. Future work will continue in that direction with two approaches. First, behavioral analysis has to be refined, and the task itself might be improved. In the present task we did not specifically ask subjects to precisely identify the position of a contact. The spatialized vibrotactile information is used to adapt their movements and as observed in the present task, a medium precision is sufficient to do these adaptations. The need for precise contact feedback spatialization (e.g. with funneling) should be studied in a more specific task requiring precise identification of the position of the contacts, which was not required in the current task. The funneling illusion might also be used with non-static environments. Secondly, the hardware implementation we used might have been limited in its capacity to render the funneling illusion. It has been shown that the Input-Output relation from the applied voltage to vibration magnitude perceived by the user is not transparent (Ryu, Jung, Kim, & Choi, 2007). Moreover, the amplitude perceived varies between people. Further work should implement more advanced rendering methods to assure a more precise rendering.

Finally, if vibrotactile stimulation is able to enhance spatial awareness and visuo-proprioceptive consistency, it cannot totally substitute kinesthetic feedback. One of the most striking examples is the case where the user needs the support of an object in the environment to accomplish their task. We think that mixing tangible interfaces and vibrotactile feedback is a promising approach to the study of complex accessibility and maintenance tasks in VR.

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