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Haptic Interfaces and Their Application on Computer-Mediated Tactile Communication

Thesis presented in partial fulfillment
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“Ich habe keine besondere Begabung,
sondern bin nur leidenschaftlich neugierig.”
— Sir Albert Einstein

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ABSTRACT

The sense of touch not only is a channel for acquiring information about the environment around us, it is also our most social sense. However, haptic interaction is usually implemented as a gimmick feature in modern interfaces. Although multimodal communication is commonplace in Virtual Environments, the most accessible Virtual Reality technologies do not even include the haptic component as a fundamental part. This thesis presents studies on perception, user performance, and user experience with vibrotactile communication devices built to support different interactive tasks in virtual and physical environments. We have assessed different haptic actuators, tactile display configurations, body sites, user profiles and methods to design a robust tactile platform. Such platform was finally built as a vibrotactile display to be worn around the head and to support spatial awareness and communication in both virtual and physical environments.

During our research, we particularly notice that the proactive use of touch for intercommunication is surprisingly neglected regardless of its importance for communication. Therefore, we have also directed our attention to elements present in speech articulation to introduce proactive haptic articulation as a novel approach for intercommunication. We propose that the ability to use a haptic interface as a tool for implicit communication can supplement communication and support near and remote collaborative tasks in different contexts. In addition, an articulatory interface can provide a direct and expressive way for communicating through tactile cues. To demonstrate that, our results were applied to the design of a vibrotactile head-mounted display especially made for interaction with immersive virtual environments. Such apparatus was shown not only to support guidance in 3D space but also to support intercommunication in collaborative virtual environments.

In addition to our technical contributions regarding the construction of a fully tested tactile display for multiple tasks and contexts, our main contribution is the conception and demonstration of a new paradigm for tactile interaction. Such paradigm focuses on providing simple and direct ways for individuals to express themselves through tactile cues in computer-mediated interaction with their environment and with others. Such paradigm embraces the final users and allows them to become interlocutors rather than just receivers of the haptic feedback.

Keywords: Human-computer interaction, haptic interaction, vibrotactile communication, haptic articulation, virtual reality, collaborative tasks.

Interfaces Hápticas e sua Aplicação em Comunicação Tátil Mediada por Computador

RESUMO

Além de um canal para adquirir informações sobre o ambiente ao nosso redor, o sentido do tato é também o nosso sentido mais social. No entanto, a interação háptica é geralmente implementada como chamariz nas interfaces modernas. Embora a comunicação multimodal seja comum em Ambientes Virtuais, as tecnologias de Realidade Virtual mais acessíveis nem sequer incluem o componente háptico como parte fundamental. Esta tese apresenta estudos sobre percepção, desempenho do usuário, e experiência do usuário com dispositivos de comunicação vibrotátil construídos para suportar diferentes tarefas interativas em ambientes virtuais e físicos. Foram avaliados diferentes atuadores hápticos, configurações de exibição tátil, locais do corpo, perfis de usuário, e métodos para se projetar uma plataforma tátil robusta. Tal plataforma foi finalmente construída como uma tela vibrotátil para ser usada ao redor da cabeça e para suportar tarefas de consciência espacial e comunicação em ambientes virtuais e físicos.

Durante a pesquisa foi observado que, apesar de sua importância para a comunicação, o uso proativo de háptica para intercomunicação é surpreendentemente negligenciado. Portanto, foi dada especial atenção aos elementos presentes na articulação da fala para introduzir a articulação háptica proativa como uma nova abordagem para intercomunicação. Foi proposto que a habilidade de usar uma interface háptica como uma ferramenta para comunicação implícita pode suplementar a comunicação e suportar tarefas colaborativas próximas e remotas em diferentes contextos. Além disso, uma interface articulatória pode fornecer um modo direto e expressivo de se comunicar através de sinais táteis. Para demonstrar isso, os resultados dessa pesquisa foram aplicados ao projeto de uma tela montada na cabeça com vibração, especialmente feita para interação com ambientes virtuais imersivos. Tal aparato mostrou-se útil não apenas para orientação no espaço 3D, mas também para intercomunicação em ambientes virtuais colaborativos.

Além de nossas contribuições técnicas em relação à construção de uma tela tátil totalmente testada para múltiplas tarefas e contextos, nossa principal contribuição é a concepção e demonstração de um novo paradigma de interação tátil. Tal paradigma se concentra em fornecer maneiras simples e diretas para que indivíduos se expressem através de sinais táteis em aplicações mediadas por computador para interair com seu ambiente e com outros indivíduos. Esse paradigma envolve os usuários finais e permite que eles se tornem interlocutores ao invés de meros receptores do *feedback* tátil.

Palavras-chave: Interação humano-computador, interação háptica, comunicação vibrotátil, articulação háptica, realidade virtual, tarefas colaborativas.

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LIST OF ABBREVIATIONS AND ACRONYMS

AR	Augmented Reality
CVE	Collaborative Virtual Environment
GUI	Graphical User Interface
HMD	Head-Mounted Display
NASA TLX	NASA Task Load Index
O&M	Orientation and Mobility
SEQ	Single Easy Question
STAI	State-Trait Anxiety Inventory
SUS	System Usability Scale
VE	Virtual Environment
VR	Virtual Reality

CONTENTS

1 INTRODUCTION

The sense of touch is more complex than vision and hearing. Field (2001) even points out that touch is ten times stronger than verbal or emotional contact. People use it as a means to convey nonverbal expressions that extend our communication skills. For this reason, Gallace and Spence (2010) affirm that the experience of users of communication devices will be truly complete and immersive only when touch will be fully integrated with virtual reality environments and internet technologies. For Van Erp and Toet (2015), there are two ways for information and communications technology systems to employ the sense of touch: for information processing, and for social or affective communication.

When it comes to haptic intercommunication, a wide range of systems have been developed to mechanically simulate interpersonal touch, such as hugs, pleasant strokes, and kisses (EID; CHA; EL SADDIK, 2008; HUISMAN et al., 2016; SAADATIAN et al., 2014). They also apply force-feedback and cutaneous stimulation to support presence in virtual environments, collaborative manipulation of virtual objects, remote training and even for interpersonal entertainment (CHEBBI et al., 2005; FOGG et al., 1998; HASHIMOTO; ISHIBASHI, 2006; IGLESIAS et al., 2007; KNOERLEIN; SZÉKELY; HARDERS, 2007; SALLNÄS; RASSMUS-GRÖHN; SJÖSTRÖM, 2000). The 'Taptic' interface of the recent Apple watch (2016) is a more commercial example of such technology. Apple Watch wearers can get someone's attention with a gentle tap and even send personal haptic signals to each other (e.g a heartbeat signal). In the mentioned systems, touch is applied for affective communication rather than information processing. Thus, the tactile cues are designed not to create any more cognitive load than a real touch (VAN ERP; TOET, 2013).

Van Erp and Toet (2015) affirm that our sense of touch, although often underestimated, is very well able to process large amounts of abstract information as well. This encouraged us to focus, in our work, on using touch to communicate more complex meanings, such as information about objects, warnings, actions and nonverbal cues. While other previous works also approached the use of tactile feedback as a way to convey information (BRAVE; NASS; SIRINIAN, 2001; OAKLEY; BREWSTER; GRAY, 2001; SEKIGUCHI; INAMI; TACHI, 2001), our regard lays mostly on the expressiveness of the set of haptic icons (i.e. the tactile vocabulary). In such context, the way the tactile vocabulary is presented to and processed by the users is a challenge to the design of systems for tactile communication (SHERRICK, 2013). However, even if a number of techniques have been proposed for creating tactile vocabularies, most of this process is fairly *ad hoc*.

In this thesis, our proposal is to use the sense of touch for communication. Therefore, our main **research question** is: How to design effective tactile interfaces to let users be informed by the system and to communicate with others, all through tactile feedback?

1.1 Motivation and Objectives

Haptic cues are usually rendered reactively by informative haptic interfaces. The system acquires the information about the environment (through sensors or predefined algorithms) and triggers the tactile feedback. However, an important part of social interaction is to perceive the others' needs and intentions and *proactively* act on these perceptions (CRAMER et al., 2009). Thus, in virtual environments as in real life, touch should be rendered proactively as well. Some affective haptic interfaces allow users to proactively exchange simple tactile cues to express emotions, but such cues do not support exchanging informative content. Even in informative tactile systems, interlocutors should be able to express themselves trough tactile cues.

Therefore, as our utterances are related to our control over our vocal apparatus, we propose that *haptic articulation*, analogously, be related to our control over haptic parameters. Moreover, the possibility to access different sets of haptic parameters gives the user the ability to articulate the tactons proactively in any manner they want to. In such a way, the tactile intercommunication should not only be proactive but expressive, dynamic, and straightforward such as speech articulation.

The **general goal** of this research then was: To study and to develop *effective tactile interfaces* for communication, taking into account their use for *intercommunication between individuals* and elements related to the *proactive articulation* of tactile signals.

The ability to articulate mechanical haptic signals should provide a way for individuals to express themselves through haptics in computer-mediated scenarios. In addition to learning a given haptic vocabulary and only perceive it passively during a task, users can also act on their environment using the haptic channel, by applying or even modifying the given haptic vocabulary. Thus, the contributions of a research on haptic articulation should be applied to a number of applications. Among the possible applications, we can mention the use of haptic articulation for:

- **An alternative channel for communication**: Depending on user profile or the context of use, the haptic channel may be the only one available for intercommunication. A conversational flow provided by the ability to articulate haptic signals in computer-mediated applications could be an alternative for speech processing interfaces for deaf-blind users, for instance (ZHAO et al., 2018). Moreover, in noisy and dark environments such as underground mines, burning buildings, or conflict areas, for instance, professionals and military forces could use the haptic channel for interacting and exchanging information. Users can also articulate haptic signals to exchange information with peers from the distance or if a discrete or private channel is needed (e.g. encoded haptic signals in the battlefield).

- **A supplementary sense during communication**: The haptic channel can be used for communication in addition to vision and hearing to reinforce or complement these other channels. The complementary use of haptics can improve communication mainly in virtual applications which inherently impose sensory limitations. For instance, spatial awareness, data visualization, and social interactions in virtual applications could benefit from the use of haptic feedback to reinforce other cues.

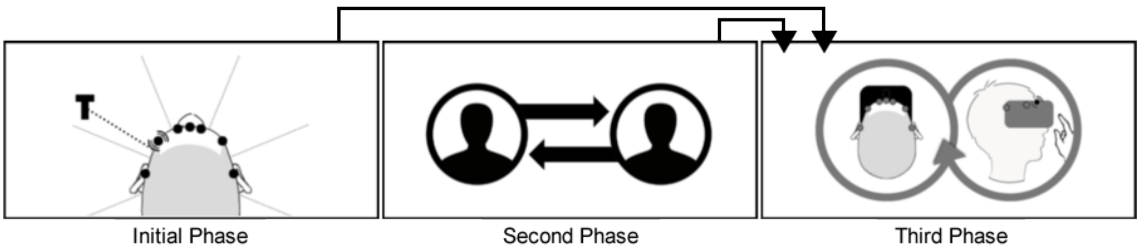
- **User-centered haptic vocabulary design**: The possibility to access different sets of haptic parameters gives the user the ability to articulate the tactons proactively in any manner they want to. It also allows the user to adapt the given vocabulary according to the user's preferences and needs. Such characteristic is present in speech articulation and language development as well. The ability to shape a language by using it could be applied during the design phase as well, by engaging users in the haptic vocabulary design process.

1.2 Approach

To develop this thesis, we have focused on an experiment-guided study aiming at converging to effective tactile interfaces and approaches for tactile communication and intercommunication in physical and virtual environments. We will see, along with the next chapters, that such study was made in three incremental phases (see Figure 1.1).

In an *Initial Phase*, a multi-purpose tactile interface is designed for tactile communication. Such interface has to take into consideration the perceptual constraints of the stimulated body site as well as its application to support different tasks, such as guidance, spatial awareness, and expressive communication in computer-mediated interaction. Thus, perceptual and psychophysical experiments, as well as performance experiments, are made to support the assessment of different applications, contexts, tasks, and analyses of different user profiles, actuators, and body sites. In a *Second Phase*, the interaction between multiple individuals is assessed to design a new approach for tactile communication. Such approach takes into consideration the proactive use of haptics and assesses how subjects apply tactile cues for computer-mediated intercommunication. Finally, in a *Third Phase*, the findings from the previous phases are incorporated into the design and assessment of a final tactile interface designed for both tactile communication and intercommunication. Such interface is designed and assessed with a focus on its application to immersive virtual environments.

Figure 1.1 - Incremental development phases



Source: the author.

1.3 Organization of this Thesis

The structure of this document follows the methodology employed in the development of this work. Chapter 2 presents the background and related work on tactile interfaces and applications; Chapter 3 describes our preliminary research on tactile interaction; Then, Chapters 4, 5, and 6 present the three phases of our research, respectively: the study and design of a multi-purpose tactile display; the proposal of a novel approach for tactile intercommunication; and the study and design of an interface for tactile communication and intercommunication in immersive virtual environments. Finally, Chapter 7 presents a summary of the contributions of this work.

2 BACKGROUND AND RELATED WORK

2.1 Haptic Devices and Interfaces

The sense of touch is basically divided between two other sub-senses: kinesthetic and cutaneous. The term "kinaesthesia" usually refers to the ability to sense the position and movement of our limbs and trunk. It includes the sense of proprioception which is provided by joints and muscle receptors. Cutaneous stimuli, on the other hand, are sensed through mechanoreceptors in the skin layers. These receptors allow us to sense different types of stimuli, such as thermal properties, pressure, pain and vibration of varying frequencies (LINDEMAN et al., 2006). Cutaneous stimuli have been explored for the development and improvement of techniques for simulation of texture and other tactile sensations. It also have been applied to the development of tools to enable tactile communication. This work focuses on tactile communication, which means to build mechanisms that support information of complex meanings, images, spatial information, as well as expressions and arbitrary signs. The greatest challenge in this area was well described by Sherrick (2013) as the discovery of a set of tactile patterns that, as speech sounds or letters, are clearly discriminated, rapidly processed and easily learned.

Many tactile devices have been built for human-computer interfaces. A great advantage in the construction of haptic devices is that tactile displays can be placed on different parts of the body (CHOLEWIAK; BRILL; SCHWAB, 2004). The hardware can be designed to be wearable and to deliver passive touch cues directly to the user's skin. Another advantage is that the tactile display can be used by users with different profiles. Formerly, many applications aimed at replacing the senses, thinking about tactile devices as a good alternative for deaf and blind people. However, several other applications focus on complementing senses instead (CHANG et al., 2002). The haptic feedback as a complementary modality is generally suggested when other senses are already loaded, implying multitasking and disruptions. Therefore, issues related to attention, memorizing and processing of tactile sequences also have to be considered for haptic interaction design.

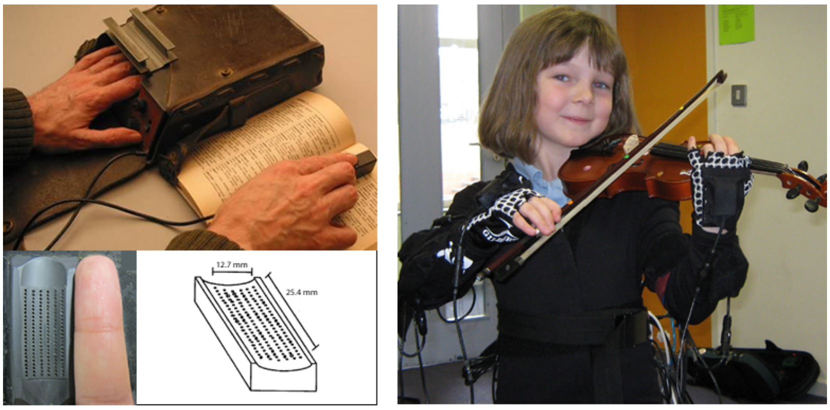
2.1.1 Tactile Displays

The first devices designed to transmit information via cutaneous stimulation have been developed in the form of an array of actuators (display), usually vibrating motors and contactors. Gault (1924), already in the 1920s, proposed the creation of a tactile display for communicating with deaf children by transmitting the acoustical energy from speech into vibrations delivered to the hand. A similar approach was used by Kirman (1973) who developed a 15x15 matrix of actuators to display correlates of a speech stream on the palm of the hand.

Among the early tactile displays, some followed an approach of reproducing or translating the alphabet letters to tactile patterns. Geldard (1957) designed a vibrotactile language called “Vibratese” that generated patterns corresponding to letters of the alphabet using a braille-like vibratory code. Then, he designed another application called “Optohapt” which converted printed letters to complex vibration patterns distributed over nine positions on the body (GELDARD, 1966). Bliss (1974) developed a small reading device as the Optohapt and called it Optacon. The Optacon, however, displayed the information through a 6x24 matrix of actuators located on the reader’s finger. Nowadays, it is possible to find new versions of those same tactile displays.

To be wearable and able to be placed in different parts of the body is a great advantage of the construction of tactile devices. Nowadays, there are several tactile applications made for different purposes, such as support posture correction (MIAW; RASKAR, 2009), learning dance steps (ROSENTHAL et al., 2011), alerting (MATSCHEKO et al., 2010), motion learning (SCHöNAUER et al., 2012) and even musical instrument teaching (LINDEN et al., 2011). All these tactile displays make use of simple or informative tactile signals rather than alphabet-like or braille-like vibratory codes (Figure 2.1).

Figure 2.1 - Examples of tactile displays: (left) The Optacon, as many early tactile displays, converted printed words into tactual stimuli; (right) MusicJacket deliver tactile signals on different parts of the body



Sources: Adapted from Bliss (1974) and Perez (2011).

2.1.2 Expressive Capacity

Braille readers must actively pass their fingers over the patterns made by the raised dots, so it is considered an active form of touch. Tactile feedback is generally used as an aid in multitasking environments further than for assistive devices. In such multitasking environments, the user’s primary attention and hands are engaged in another task. Therefore, the tactile cues are delivered passively by tactile displays to the user’s skin. To accomplish that, tactile devices basically make use of two sorts of tactile patterns: simple signals and more informative signals. Each one should be adopted under specific conditions and they have their own expressive capacity and limitations.

Usually, the design of tactile interfaces follows a “tap-on-shoulders” approach (HAO; SONG, 2010). This approach can be exemplified by a tactile sensation printed on the side of the user’s body that is facing a particular target or object. It adds an iconic factor on the tactile language because the sensation directly evokes the behavior (ERP; WERKHOVEN, 2006); such as the rooting reflex in newborns that means to a baby to turn their head in the direction of a stroke on the cheek. Those simple signals are limited in terms of expressiveness. Hence, simple signals are mostly adopted when there are limitations of either hardware or context of use. They are also applied to deliver alert signals and other limited information that do not demand a cognitive component in the response (MACLEAN; HAYWARD, 2008).

Early research has applied tactile stimuli to present complex data in order to reduce visual and auditory data overload (JONES; SARTER, 2008). In such circumstances, it is necessary for the tactile signal to be more informative. In such case, the tactile icon (tacton) can be designed metaphorically (symbolic) or more arbitrarily (abstract) (MACLEAN; HAYWARD, 2008); each design approach have its pros and cons. The construction of tactile icons involves cognitive and perceptual factors that must be taken into consideration in order to design signals that are easy to learn, memorize and process during the task. There are several studies that make use of arbitrary tactile patterns as a way to enhance the vocabulary expressiveness (ENRIQUEZ; MACLEAN; CHITA, 2006; ENRIQUEZ; MACLEAN, 2008; TERNES; MACLEAN, 2008). The present work focuses on the use of prefixation signals to construct tactile vocabularies that can be either expressive and easy to learn and process. In this context, vibrating stimuli is the most adopted (HAYWARD; MACLEAN, 2007). The capacity to manipulate vibration parameters such as burst/interburst duration and frequency makes the display able to rapidly produce different patterns in the user's skin. Varying vibrotactile parameters make it possible to encode additional meaning to the same signal (or tactile icon).

2.1.3 Tactile Icons

According to Brewster and Brown (2004), a Tactile Icon is a structured, abstract message that can be used to communicate complex concepts to users non-visually. The word Tacton is an agglutination of "Tactile Icon". Following the definition of an icon as "an image, picture or symbol representing a concept", a Tacton is a way to represent concepts succinctly. As a graphical icon, which can substitute a complete word or expression and speed up the interaction, a Tacton can convey tactile information in a smaller amount of space and time than Braille, for example. Graphical and aural icons are broadly used in user interfaces. The aural icons, also called Earcons, are similar to tactile icons.

Some earcons have a clear meaning, as the sound of a paper being crushed that usually indicates a computer file being deleted. However, there are more abstract concepts and Earcons with no intrinsic meaning, whose meaning has to be learned. There are researches that study the perception of different musical parameters, as timbre, frequency, and amplitude to create abstract earcons that are easier to learn and remember. At this point, the creation of tactile icons can be compared to earcons. In general, both earcons and tactons are sequential in time. Furthermore, tactons are also created by encoding information using parameters like frequency, amplitude, and so on. The perception of different stimuli, however, must be studied to better understand how to relate a pattern to some kind of information making it as easy to learn as possible (MACLEAN; ENRIQUEZ, 2003).

Similarly to the construction of Earcons, different parameters are used to transmit different kinds of information in a tactile device. Defining which parameters will be used and how they are related to the set of messages is a great portion of the construction of tactons. Fortunately, regardless of the specific tactor technology (electromechanical, piezoelectric, etc.), the tactile hardware will likely have some basic capabilities to manipulate parameters such as burst duration and frequency (RIDDLE; CHAPMAN, 2012). Brewster and Brown (2004) list the parameters and other variables that can be used to construct tactons.

The basic parameters used in the creation of earcons can also be used to create tactons. These parameters are frequency, amplitude, waveform, duration and rhythm. In the tactile language design methodology presented by Riddle and Chapman (2012) there are some examples of which information each parameter can better represent (this methodology will be further discussed later). Frequency and amplitude, as for earcons, offer a great range of variation. However, sensibility to these features is not well understood and neither has great results for the entire range. Brewster and Brown (2004) affirm that only nine different frequency levels should be used and only four in amplitude. They also discuss that changes in amplitude influence the perception of frequency. Thus, there are conditions for variation of both parameters in the same pattern.

The variations of timbre in sound can be better differentiated than waveform variations in tactons, so this variable became less important in tactile language design. Duration is a parameter easy to control whatever the hardware controller is. Modulation of burst duration can be used to express proximity to an object (increasing burst duration) or differentiate an attack (short bursts), for instance. Groups of bursts with different durations can compose rhythmic units. Rhythm can address groups of events in the same area of the skin and it is good to inform temporal characteristics as proximity changes and pace velocity, for example. When each parameter in a Tacton addresses a different meaning, it corresponds to a transformational approach (TERNES; MACLEAN, 2008). In addition, the whole Tacton can be used to modify a tactile expression, which corresponds to an affixation approach (JESUS OLIVEIRA; MACIEL, 2014a).

In addition to hardware features and the type of information conveyed, spatiotemporal factors should be taken into consideration in the design process. The position and area of the body where the tactile patterns are printed, and also the relative position of a tactor in a tactile display affect the quality of discrimination, memorization, and learning of a tactile language.

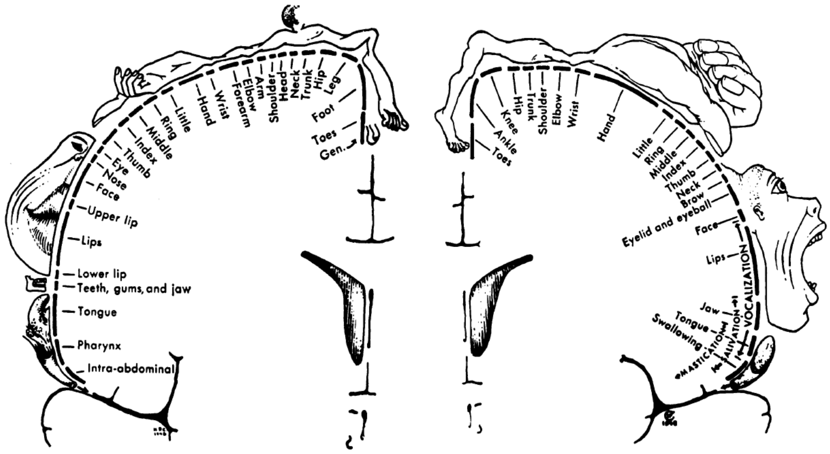
2.2 Human Factors in Haptization

A structured form of communication can not be successful in conveying information via touch if its design does not contemplate the neurological and physiological factors related to the sense of touch. The physiological properties of the mechanoreceptors and how they report to tactile perception can be found in numerous reviews, with names like Cholewiak, Collins, and Sherrick in front of important work and significant contributions in this area (CONWAY, 2001).

Just a glance at the Homunculus (Figure 2.2), initially proposed by Penfield as a representation of the relationship between parts of the cerebral cortex and the sensory and motor systems, confirms the importance of proprioception in tactile communication. Figure 2.2 is a version of the illustration used by Penfield in his work called “The cerebral cortex of man” and consists of a diagram of a cross-section of the cerebral hemispheres. In this diagram, solid bars were drawn at the periphery of the hemispheres and the length of the bars give an indication of the relative cortical areas from which the corresponding responses were elicited (SCHOTT, 1993).

The homunculus can be considered as some form of “map” of human cortical representation, being more or less precise in relation to actual brain areas identified at surgery. In this representation, it is possible to notice a large sensory area devoted to hands, as well as to feet and vocal tract. This is one of the reasons why many devices are built as displays for printing patterns on the palm of the user, for example. Furthermore, the

Figure 2.2 - The motor and sensory homunculus



Source: Penfield and Rasmussen (1950).

glabrous skin on the human body has different types of mechanoreceptors in contrast to hairy body sites, like torso and arms (JONES; SARTER, 2008; CHOLEWIAK, 1999).

2.2.1 Influences of Body Site and Space

Many experiments have been conducted to determine the sensitivity of various areas of the skin, the pattern-detecting ability of the skin, and other psychophysical attributes. The first known psychophysical research on spatial acuity was undertaken in the nineteenth century by Weber (WEBER; DE PULSU, 1834). After that, in another remarkable study, Weinstein (WEINSTEIN, 1968) measured thresholds of two-point discrimination and tactile point localization on several body loci in considerable detail.

For testing vibrotactile pattern recognition and discrimination at several body sites, Cholewiak and Craig (1984) employed similar patterns and techniques to compare processing across loci. In these studies, subjects judged comparable sets of spatial patterns presented in the same way to the finger, palm, and thigh in tests of recognition, discrimination, and masking [1]. The acuity of several body parts was tested in processing tactile patterns. Among them: arm, forearm, the abdomen and finger by generating stimuli in different settings to identify the influence of body parts according to display size, arrangement of actuators, age of users and stimulus time (CHOLEWIAK; COLLINS, 2000; SHERRICK; CHOLEWIAK; COLLINS, 1990; GOBLE; COLLINS; CHOLEWIAK, 1996; BARGHOUT et al., 2009; OAKLEY et al., 2006).

The use of two-point limen as a measure of spatial acuity has been questioned along the years (CHOLEWIAK; COLLINS, 2003). Johnson and Phillips (1981) introduced alternative methods (gap detection and discrimination of grating orientation) and applied them to the fingertips, finding that the ability of subjects to discriminate stimuli is much finer than what is indicated by classical studies (VAN ERP, 2005). Overall, most acuity measures were taken with pressure stimuli, while most applications nowadays use vibrotactile stimuli. Because these two types of stimuli are partly processed by different mechanoreceptors in the skin (JONES; SARTER, 2008; LEDERMAN; KLATZKY, 2009; SOFIA; JONES, 2013), the acuity for vibrotactile stimuli is still being investigated (VAN ERP, 2005; KERDEGARI et al., 2014).

[1] Masking is related to the phenomena of one stimulus (visual, auditory, or tactile) affecting the detection of another

Tactor position in the matrix is also an important factor. For instance, if two objects touch us simultaneously, we perceive their (suprathreshold) spatial separation and their arrangement more distinctly if they are oriented along the transverse rather than the longitudinal axis of the body (CHOLEWIAK, 1999). We also have considered that in our experiments where we relied on perceptual profiling of the head to better support tactor positioning on a vibrotactile display.

2.2.2 Temporal Processing of Tactile Sequences

Tactile sequences may represent a perceptual issue on a task. The limitations of temporal processing on different parts of the body is not completely known (GALLACE; TAN; SPENCE, 2007). In fact, several studies have demonstrated that attention dwells on a stimulus (visual, aural or tactile) for several hundreds of milliseconds. Therefore, it is common a person to wrongly report the existence or position of the second target of two targets displayed in sequence (Attentional Blindness) (HILLSTROM; SHAPIRO; SPENCE, 2002). Furthermore, Cholewiak and Craig (1984) found that the level of performance across sites depended, to different degrees, on duration.

The temporal processing of tactile sequences is directly related to the processing and memorizing of tactile patterns and therefore learning. Hirsh and Sherrick (1961) suggested that temporal processing can be broken down into two processes: the ability to correctly perceive that two events occurred (i.e. two strokes); and the ability to accurately judge which of two events occurred first. Thus, we know that at least two main issues are present in the tactile processing: the processing of multiple stimuli at a time; and the processing of a sequence of stimuli.

The perception of tactile sequences can be affected during multisensory interaction and attentional blindness might be a factor (HILLSTROM; SHAPIRO; SPENCE, 2002). Attention may dwell on a stimulus (visual, aural or tactile) for several hundreds of milliseconds. Therefore, a person may wrongly report the existence or position of a second target of two targets displayed in sequence. We could notice such effect when comparing different vibrotactile vocabularies in our preliminary studies. In our studies, users felt that the patterns in sequence were the most difficult to understand during navigation.

2.2.3 Learning and Memorizing Tactile Sequences

Learning is strongly linked to memorizing. Gilson and Baddeley (1969) as well as Sullivan and Turvey (1972) showed that short-term memory for the tactile stimuli locations is best for the first 5 or 10 seconds after memorizing a tactile sequence. Also, memory for touch start decreasing after training is stopped (CONWAY, 2001).

The way in which the stimuli are presented is important for constructing a mental representation and memorizing tactile sequences. Its relevance was evidenced in studies by Watkins and Watkins (1974). They noted that the way the information is encoded for storage is important. Asking the user to memorize a sequence of touch associating each tactor to a numerical index is different to accomplish the same task by asking the user to associate each tactor to a cardinal point. The user experiments we present later in this work were based on metaphors to better support identification and memorization as well.

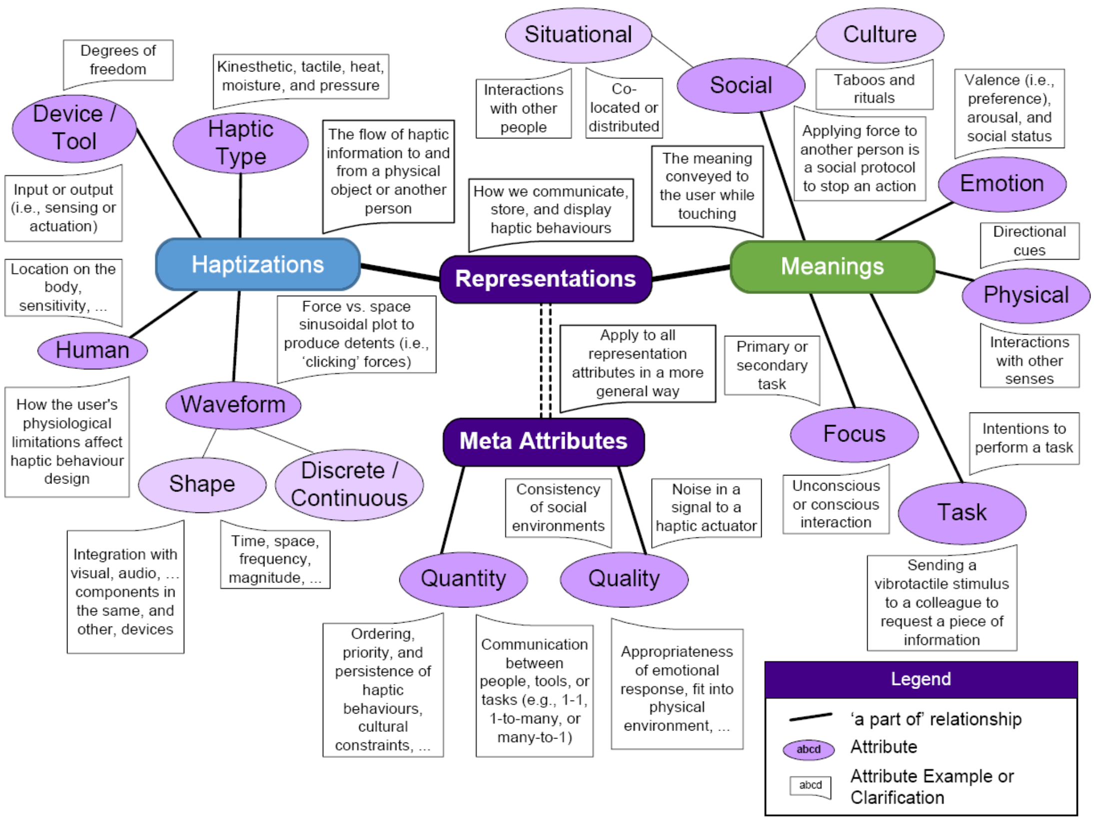
A multisensory reinforcement training is advantageous even when the stimulus will later be invoked purely through the tactile channel (MACLEAN; HAYWARD, 2008). Furthermore, the use of metaphors assists identification and memorization of tactile patterns. It is a conventional approach to design tactile icons based on metaphors. The metaphors chosen by the designer can be taught to the user. So, it would simplify the association between meaning and the arbitrary tactile pattern. Those associations are commonly established by the designer. However, some studies present good results showing that users can also choose the stimulus-meaning associations themselves (ENRIQUEZ; MACLEAN; CHITA, 2006; ENRIQUEZ; MACLEAN, 2008). In this work, the metaphors and associations were chosen by the designer.

2.3 Methods and Tools for Tactile Interaction Design

A tactile interface design must be centered on the user. The interaction design must look at the supported activities, the user profile, and the use context in order to be usable. It is common for the people who work with haptics to become more concerned about mechanics and automation. However, the problems are better solved by looking closely at the user's need. Thereby, to design suitable solutions it is necessary to watch and listen to people and notice where they struggle. Working together with people who have different backgrounds and training can also be productive. It is important for the teamwork to be multidisciplinary (ROGERS; SHARP; PREECE, 2002; MACLEAN; HAYWARD, 2008).

Design interfaces to render such unfamiliar sensations has some challenges. People are not habituated to processing abstract haptic representations and there is no predefined tactile vocabulary to describe such representations. According to MacLean (2008) "our subjects have been using vision for the kinds of tasks we test since early childhood, and they have been using the tactile version for perhaps a 3-30 min training period". Figure 2.3 shows a design space of haptic components that can be used to aid the design of haptic representations (SWINDELLS; SMITH; MACLEAN, 2005).

Figure 2.3 - Possible Design Space of Haptic Components

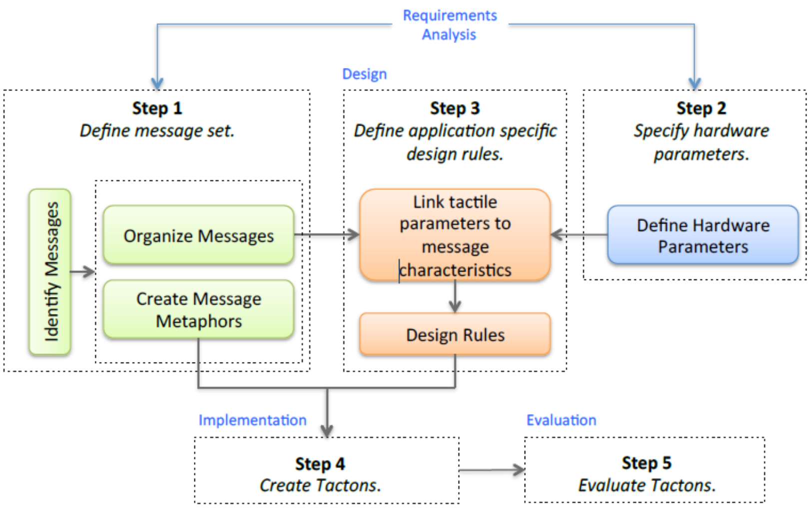


Source: Swindells, Smith and MacLean (2005).

The process of interaction design involves four basic activities: the identification of the needs and requirements; design; prototyping; and evaluation (ROGERS; SHARP; PREECE, 2002). Evaluating is very important and focuses on ensuring that the product is usable. So, it usually seeks to involve users throughout the design process. The evaluation process must include perceptual and interaction questions. It has to contemplate how information is interpreted and remembered (meanings), as well as characteristics of the development and use of physical haptic signals (haptizations).

The construction of tactons depends on the capabilities of the hardware that will be used and the type of information to be transmitted. The type of information will determine what kind of metaphors can be used to design the tactile representation. Also, the hardware capabilities delimit the possibilities of combining different parameters and consequently how many different signals may be constructed. Chapman and Riddle (2012) presented a method for building tactile patterns. This methodology provides a five steps flow for building tactile signals (see Figure 2.4).

Figure 2.4 - Tactile Language Design Methodology



Source: Riddle and Chapman (2012).

Step 1 is about defining the message set. The scope of the message set may vary given the purpose of the haptic interface. Usually, tactile languages are made *adhoc*. Defining the message set comprises the identification of the concepts to be communicated and the metaphors that will be used. Designing tactile signals with metaphors makes them more comprehensible (MACLEAN; HAYWARD, 2008). *Step 2* concerns specify the tactile hardware parameters. Understanding the capabilities and constraints of the system is important in determining the parameters available for manipulation.

Step 3 is to define application-specific design rules. Design rules are intended to facilitate standardized construction. Literature suggests that tactile parameters can already have some implied meanings (BREWSTER; BROWN, 2004). If those meanings can be linked to the inherent meaning of messages within the message set, a mapping can be derived between tactile parameters and messages (see Figure 2.5).

The *Step 4* is the creation of tactons. The previous steps were taken to enhance the intuitiveness of the tactile messages. Now the tactons are composed for making complex messages. Complex tactons and complex messages are made up by the addition of qualifiers to other simple tactons. The qualifier gives details about the message. So, if

Figure 2.5 - Table with linkage of perceptual characteristics of message with tactile parameter (partial message list)

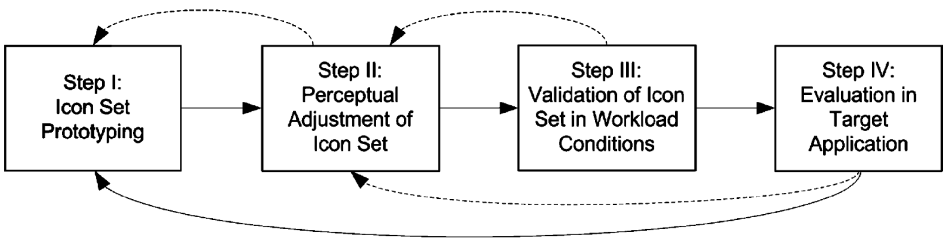
Example Message	***Perceptual Characteristic***	***Tactile parameters associated with characteristic***
Direction (e.g., N, S, E, W)	***Geospatial***	*Tactor location*
Proximity to point	***Geospatial***	*Burst Duration*
Geographical markers (e.g., waypoint)	***Categorical/ Type***	*Spatiotemporal pattern; shape*
Pace (e.g., fast, slow)	***Temporal***	*Rhythm – burst/interburst duration*

Source: Riddle and Chapman (2012).

the message is about navigation, the qualifier gives descriptive information about direction, distance, and pace, for example. This composition can be done by following any approach to syntax development (BREWSTER; BROWN, 2004). There are also editors made to support the design of vibrotactile effects that use graphical representations to edit either waveforms or profiles of dynamic parameters (SCHNEIDER; ISRAR; MACLEAN, 2015; SCHNEIDER; MACLEAN, 2016). Finally, *Step 5* of the tactile language design is the evaluation. After constructing the tactons, they should be evaluated to validate their design and performance.

For Chan (2008), when designing haptic icons, it is desirable to maximize memorable icon set-size. Additionally, it is necessary to observe at least four variables: easiness of association of the stimulus with target meaning, individual stimulus salience, discernibility of items in the set, and maintenance of desired salience level under a cognitive workload. Therefore, Chan proposes an iterative and user-centered four-step process to encompass those variables (Figure 2.6).

Figure 2.6 - A process for developing haptic icons. Solid lines are standard progression, and dotted lines indicate iterations that might be needed



Source: Chan, MacLean and McGrenere (2008).

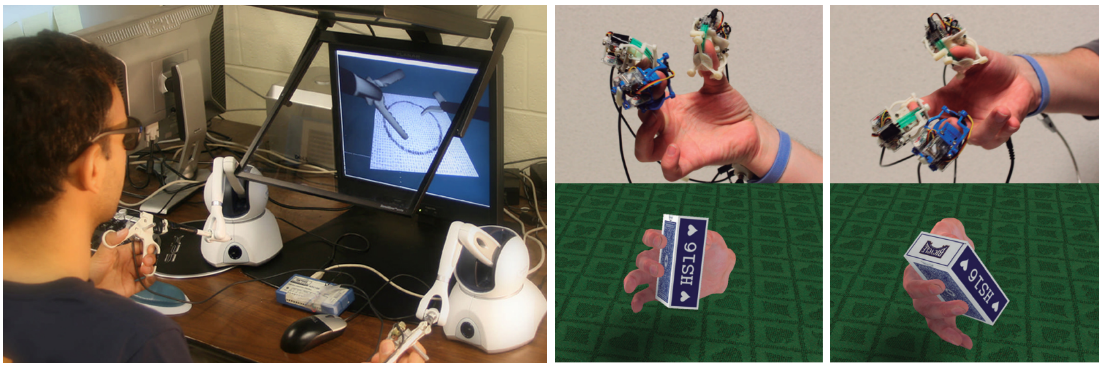
Step I concerns the icon set prototyping. While Chan (2008) designed his icons based on his own observations and insights from past work, the Riddle's method could be used to systematize this step. The progressive refining of the tactile icons is the main advantage of Chan's methodology. In Step II a perceptual adjustment is made in order to guarantee that the families of stimuli are related and yet distinguishable. The remaining steps are related to evaluation; Step III concerns the validation of the icons in workload context and Step IV is the application trial. As for the different design methods, the user participates mostly of the steps concerning evaluation rather than the initial steps.

2.4 Haptics in VR and Collaborative Virtual Environments

According to Srinivasan and Basdogan (1997), the ability to touch, feel, and manipulate objects in a virtual environment provides a sense of immersion that is not possible to have only with vision and hearing. Both proprioceptive and cutaneous feedback have been applied to various applications of virtual reality and teleoperation, such as surgical simulators for medical training, manipulation of micro and macro robots for minimally invasive surgery, rehabilitation, virtual art exhibits, video games and simulators that enable the user to manipulate virtual objects and to touch virtual humans (see Figure 2.7 left), and so on (MACIEL et al., 2008; ZIAT et al., 2014; MEDELLÍN-CASTILLO et al., 2015; PIGGOTT; WAGNER; ZIAT, 2016; TREMBLAY et al., 2016).

Most haptic devices used for manipulation of virtual objects are designed to provide kinesthetic feedback to the user, such as the Omega or the Phantom devices. However, kinesthetic feedback is usually provided by desktop haptic interfaces. Thus, there are studies that explore the use of body-grounded force-feedback devices and wearable tactile displays instead (PEREZ et al., 2016; BOUZIT et al., 2002; GABARDI et al., 2016) (see Figure 2.7 right). That increases the user mobility and autonomy in the virtual setup.

Figure 2.7 - Table- and body-grounded kinesthetic haptic devices for virtual reality



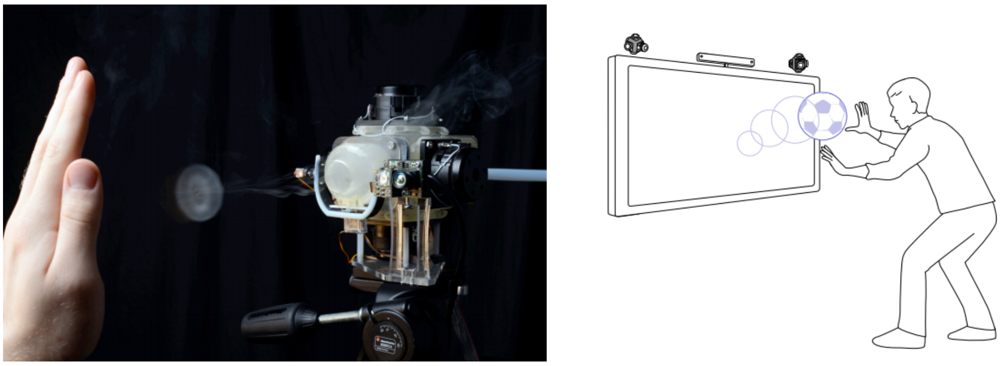
Source: Maciel et al. (2008) and Perez (2016).

There are other devices that go even further, producing a mid-air sensation using air jets (SODHI et al., 2013) and acoustic radiation via ultrasonic waves (SUBRAMANIAN et al., 2016; DZIDEK et al., 2018) (see Figure 2.8). These touchless sensing devices provide haptic feedback without in anyway instrumenting the user.

When it comes to collaboration in a virtual environment, Sarmiento et al. (2014) describe it as complex, requiring suitable interaction artifacts and sufficient level of immersion. The main characteristic of a Collaborative Virtual Environment (CVE) corresponds to the process through which an individual work evolves into collaborative work. Such process is supported by sharing artifacts, which are elements of interaction that facilitate the sense of awareness of the shared context and of the others. There are studies that apply Haptic feedback to improve awareness in CVEs. For instance, haptic feedback is applied to support presence in virtual environments, remote assistance, collaborative manipulation of virtual objects, and so on (BASDOGAN et al., 2000; BAILENSON; YEE, 2008; CHELLALI; DUMAS; MILLEVILLE-PENNEL, 2011) (see Figure 2.9).

Media richness is an important factor to be considered in the design of applications for intercommunication. Haans and Ijsselsteijn (2006) exemplify media richness as the extent to which a communication medium facilitates immediate feedback, multiple channels, and contextual and nonverbal cues. Thus, to produce (or to reproduce) tactile messages

Figure 2.8 - (left) The AIREAL device emits a ring of air called a vortex, which can impart physical forces a user can feel in free air. (right) Multiple AIREAL devices can be used to provide free air tactile sensations while interacting with virtual objects



Source: Sodhi et al. (2013).

Figure 2.9 - A VR setup that enables two people, at remote locations, to interact with each other through visual and haptic displays

Source: Basdogan et al. (2000).

should be as straightforward and simple as talking. Only a handful of previous works apply touch in a way that teams can use expressive tactile signals to intercommunicate. Users can either proactively trigger tactile cues by pressing buttons (CHAN; MACLEAN; MCGRENERE, 2008), performing specific gestures (BROWN; WILLIAMSON, 2007; CHANG et al., 2002; ROVERS; ESSEN, 2004), or even selecting graphical icons on a display (ISRAR; ZHAO; SCHNEIDER, 2015). The articulation of force-feedback is often more direct and simple. That is because the manipulandum of receivers moves as senders move their own manipulandum (SMITH; MACLEAN, 2007; ULLAH et al., 2011). However, it lacks expressiveness since such applications are not made for information processing. Regarding virtual environments, we need interfaces that are powerful, yet non-obstructive (BURDEA, 1999).

In our quest to design a tactile language for intercommunication, we need to rely on a tactile display that provides both expressiveness and autonomy. Thus, in this work, we focused on allowing users to articulate vibrotactile patterns proactively to interact with their partners. Such approach provided a way for users to not only use the predefined set of patterns to intercommunicate, but also to adapt it dynamically to attend their needs during the task.

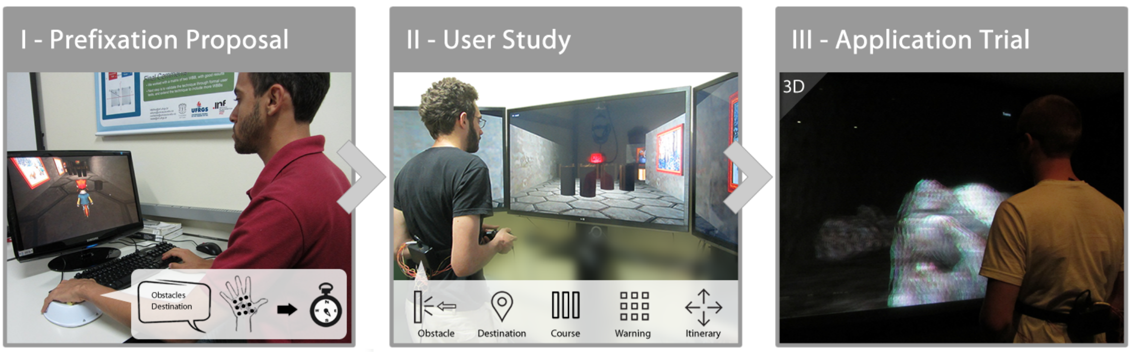
3 INITIAL RESEARCH

In this section, we present a summary of our initial studies and findings concerning vibrotactile communication and multisensory interaction. In these preliminary studies, we had considered tactile perception, user experience, and user performance on different tasks, contexts, and for different user profiles. Our main focus was to study the components of tactile communication, and to make contributions to the development of tactile vocabularies and devices for interaction in both virtual and physical environments.

When it comes to vibration, different kinds of information can be expressed by the use of different parameters. The meaning for each parameter (or combination of parameters) is assigned by the designer according to certain metaphors and methods. Such encoding may increase the complexity of the language, but also allows the transmission of a greater amount of information compared to a conventional tap-on-shoulders approach. We hypothesized that it would be possible to produce tactile vocabularies with fewer signals to recall by reusing tactile parameters or tactile patterns. We explored design approaches for tactile languages and proposed a *novel approach for prefixation*.

The proposed technique was used to design vibrotactile patterns to support navigation tasks and it was tested in different virtual scenarios. The development of our tactile vocabularies and the research on vibrotactile prefixation was conducted through an iterative and incremental process (see Figure 3.1). Thus, we present our findings from the perspective of a cyclic set of steps of (re)design, prototyping, user experiments and analysis of different tactile vocabulary designs.

Figure 3.1 - Our research on vibrotactile prefixation was conducted accross three phases



Source: the author.

3.1 Introducing the Modifier Tactile Pattern

In our first study, we designed a vibrotactile display to increase the user experience in a virtual environment (see Figure 3.2). The tactile feedback was used to support orientation and locomotion by transmitting information about position of obstacles and destination.

Figure 3.2 - The tactile display was made with nine actuators arranged in a 3x3 grid. Eight vibrating motors positioned at the cardinal and ordinal directions were used to convey spatial information while the central motor helped to distinguish whether the information concerned obstacles to be avoided or the direction of the destination point

Source: the author.

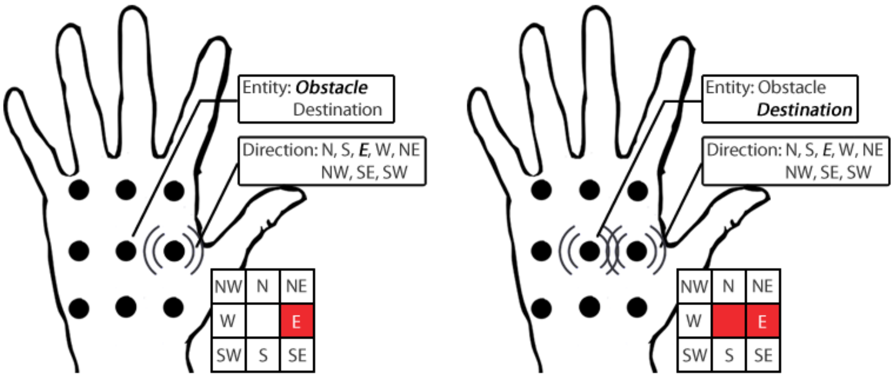
As presented in Section 2.3, haptic representations have a component concerning its haptization and another concerning its meaning. When it comes to language, Saussure (SAUSSURE, 2006) affirms that a sign is also divided into two components: the signifier (an "acoustic image" in speech) and the signified (the "concept" related to the sign). The acoustic image linked to an idea (or signifier) concerns phonetic execution. We can then assume it is related to the haptization component of a haptic representation. Accordingly, Enriquez and Maclean (ENRIQUEZ; MACLEAN; CHITA, 2006) define haptic phonemes as the smallest unit of a constructed haptic signal. In our study, however, we focused on meaning aspect (signified) to define haptic morphemes as the minimal *meaningful* unit of a haptic representation.

Haptic morphemes, such as for general linguistics, can also be classified as free or bound. That means that there are elements in the construction of a tacton that have a meaning themselves, but such meaning is only expressed when the element is printed with another pattern. The construction of our first vibrotactile display focused on demonstrating the evidence of a pattern that works as a bound morpheme, or a modifier. Figure 3.3 shows two examples of tactile patterns in our initial vocabulary.

We have defined the concept of *Modifier Tactile Pattern* as a tactile signal that modifies the interpretation of the remaining signals on a Tacton or tactile sequence. The concept of Modifier Tactile Pattern is subject to some of the same rules that govern the use of modifier signs in Braille. The Modifier can be composed by more than one pattern. It can change the meaning of the current Tacton or the meaning of the next Tacton. It can also change the meaning of an entire tactile sequence (JESUS OLIVEIRA; MACIEL, 2014a). The modifiers should enhance the vocabulary expressiveness keeping it easy to learn.

We assessed the perception of vibration patterns rendered by our tactile display, its interpretation as tactons, and its use for navigating virtual scenes with different light conditions: completely dark, and variable lighting. Even in the completely dark condition, user could find a obstacle-free way towards the target.

Figure 3.3 - (left) Example of a tacton made to convey the existence of an obstacle towards east and (right) one to inform the direction of the destination towards east



Source: the author.

Our initial results inspired new strategies to optimize the displaying of the tactile icons on the hand. The hand, although a sensitive loci, was less effective in receiving large amount of vibration from our device. However, we noted that the division of focus on the different elements of the tactile pattern, provided by the Modifier pattern, helped users to better discriminate the information conveyed by the tactile signals. We also noted that, as the users move mostly forward on navigation, they use to keep their attention on the frontal motors. So, by turning the rear motors off automatically during the navigation we could mitigate masking effects and enhance the interaction.

3.2 Assessment of Tactile Vocabularies

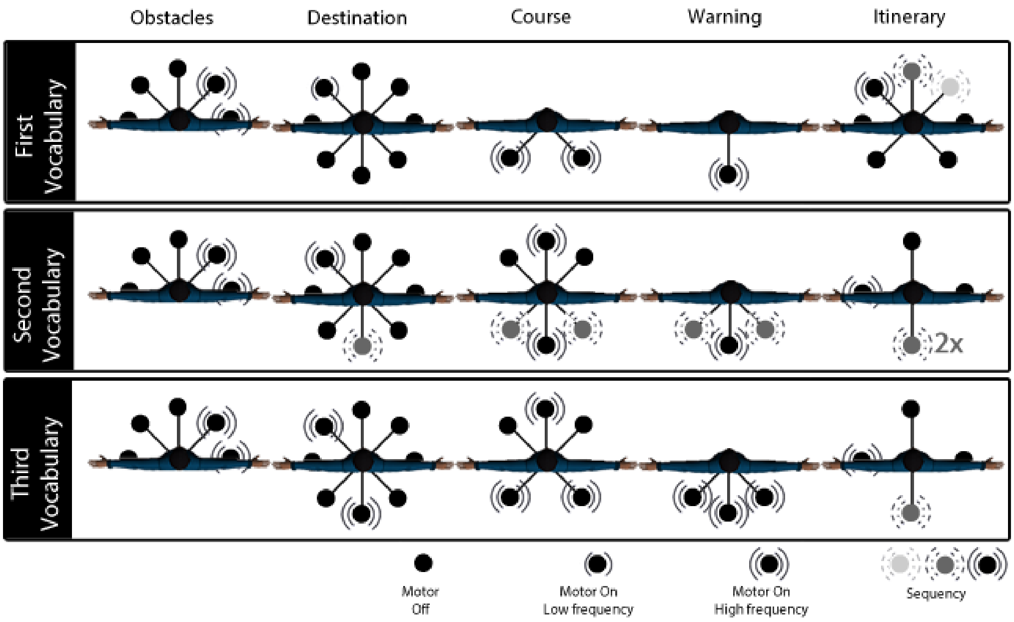
We proceed to explore means to construct vocabularies with modifiers and analyzing how their design affects the user perception and the user performance in navigation. This time, we wanted the tactile display to be wearable while providing tactile cues from an egocentric perspective. Even though the hand is very sensitive to vibrations, the perception we have about the location of our own body in the three-dimensional space is often referenced to the orientation and location of the relatively stable trunk of the body. Thus, we have changed our tactile display into a belt (see Figure 3.4).

Figure 3.4 - The vibrotactile belt

Source: the author.

We have studied three different choices in the design of a tactile language for 3D navigation: a conventional non-prefixed vocabulary and two Modifier-based vocabularies (one prefixed by juxtaposition and other by superposition) (JESUS OLIVEIRA; MACIEL, 2014b). All those three vocabularies were designed to convey five kinds of information: Destination, Obstacle, Course, Warning and Itinerary (see Figure 3.5).

Figure 3.5 - Example of tactons in each vocabulary

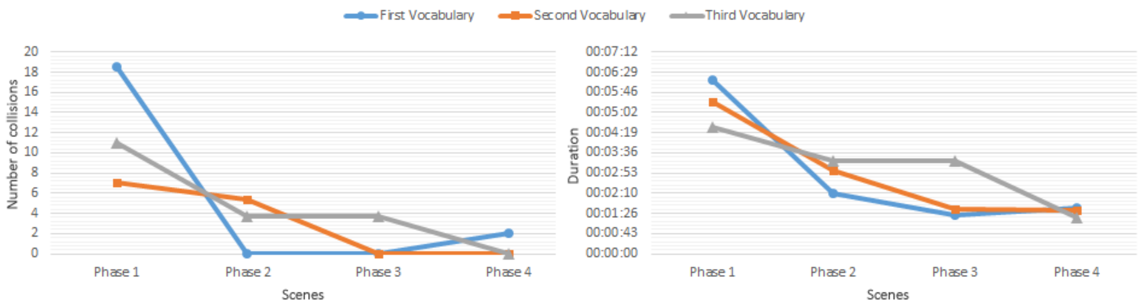


Source: the author.

In a perception test, many occurrences have been left unanswered for those patterns that were exhibited in sets of two and three motors. One-way ANOVA showed that there is an effect of the amount of motors that compose the tactile pattern on the perception of the pattern ($F(3.88)=27.99$, $p<0.00003$). As the number of actuators increase, so does the misperception of the tactile signal.

Then, each subject had to navigate through four different scenarios using the tactile belt. It is possible to observe the improvement of the three groups along the levels as their times and number of collisions decrease (see Figure 3.6 left). With all vocabularies, users go faster at each subsequent level (see Figure 3.6 right). However, we found no effect of the tactile vocabulary modality on user performance.

Figure 3.6 - User performance. Left: number of collisions in each level/scenario. Right: duration of the navigation in each level/scenario



Source: the author.

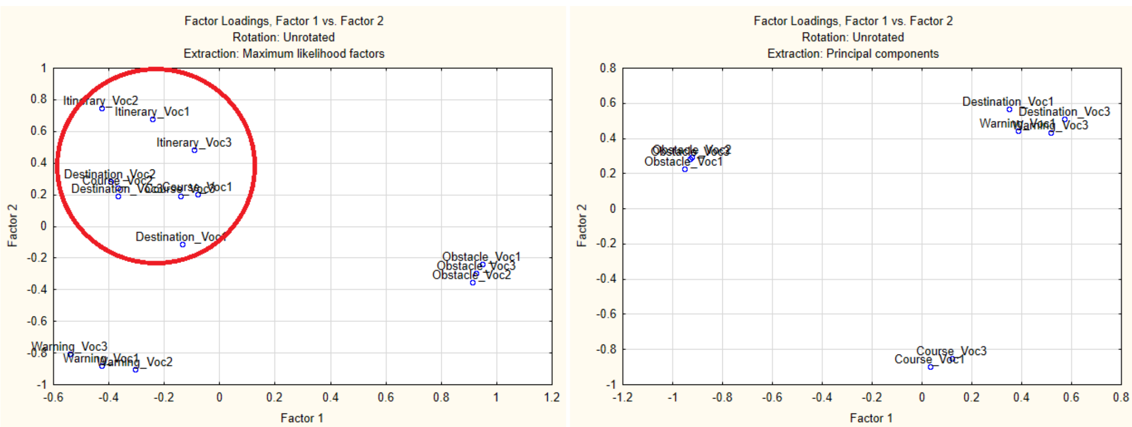
The modifier-based vocabularies were reported as affording a better experience. However, the difference between the performances of the subjects in the three conditions did not yield significant differences.

3.3 Tactile Guidance in Underground Mines

In a final iteration, we performed a perceptual adjustment of the dozen tactile patterns we have tested in the previous iteration. We have followed the method presented by Chan (2008) (mentioned before at Chapter 2.3) which takes into account at least four variables in the design of the vocabulary: easiness of association of stimulus with target meaning, individual stimulus salience, discernibility of items in the set, and maintenance of desired salience level under cognitive workload. However, instead of testing the perception of the tactile icons under the influence of arbitrary visual and auditory distractors, we tested its perception and workload during the actual navigation.

We performed different factorial analysis with the results for perception and interpretation of the tactons used in the previous iteration. The first analysis reveals groups of correlated icons concerning its *meaning*. As highlighted in Figure 3.7 (left), the icons used to convey information about Course, Destination and Itinerary were grouped together. To avoid ambiguity, only Itinerary was kept in the final design.

Figure 3.7 - (left) Factorial analysis of the created vocabularies. Factors are related to the interpretation of the tactile signals. The signals used to convey information about Course, Destination and Itinerary were grouped together and are highlighted on the graph. (right) Factorial analysis of the remaining icons. Factors are related to the way that the patterns were made. Tactile icons displayed as sequences were excluded of the analysis due its performance on navigation task

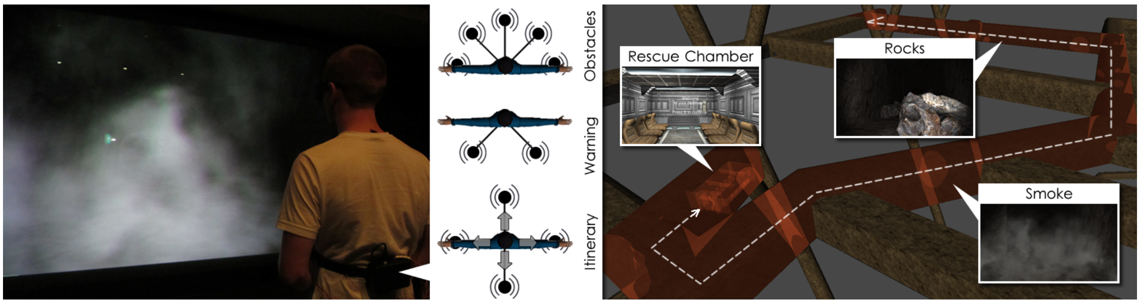


Source: the author.

Then, to guarantee the individual stimulus salience, we performed another factorial analysis related to the *construction of the patterns*. Figure 3.7 (right) shows the result of the analysis. We chose the icons that were positioned more distant from each other on the graph to select those that would compose the final vocabulary for navigation. This final vocabulary was applied for navigation in a virtual underground mine (JESUS OLIVEIRA et al., 2014) (see Figure 3.8).

Underground mines have large areas that are not enlightened and many times the miners count only with the light from their mining helmet. Due to the use of explosives,

Figure 3.8 - (left) The tactile vocabulary conveyed information about itinerary, obstacle proximity and warnings in a virtual underground mine. (right) fumes gradually increase the need for the haptic display to avoid the obstacles



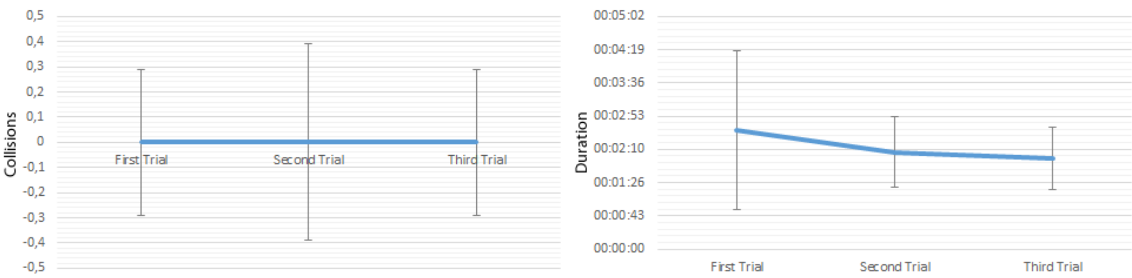
Source: the author.

underground slips, and the mineral exploration, the mine galleries can contain smoke and powder fumes that can difficult the vision. In the underground environment the noise is also frequent. Therefore, the tactile feedback seems to be suitable to aid the mine workers in their tasks. To test this, we designed a virtual representation of a mine and simulated a risk situation wherein the user should navigate in the mine to reach a rescue chamber just by following our tactile vocabulary. The perceptual adjustment of our tactile vocabulary increased its usability as well as the memorization of its signals (see Table 3.1 and Figure 3.8).

Table 3.1 Final Vocabulary Interpretation Confusion Matrix, N = 3

Information	Response (%)				
	"Itinerary"	"Obstacle"	"Warning"	"Don't get it"	" "
Itinerary	**91.11**	4.44	0.00	0.00	4.44
Obstacle	2.22	**91.11**	2.22	2.22	2.22
Warning	0.00	3.33	**96.66**	0.00	0.00

Figure 3.9 - (left) Number of collisions in each trial. (right) Mean time to complete the navigation task in each trial



Source: the author.

3.4 Summary

Through an iterative and incremental process, we did a large review on the research about vibrotactile communication and assessed a dozen families of tactile icons. More than eighty subjects participated in our experiments in different virtual setups. That helped us to shape the concept of Modifier Tactile Pattern, to understand spatiotemporal constraints in the design of vibrotactile representations, and to construct a usable vocabulary for navigation.

In this process, we have prototyped tactile displays for different body sites covering glabrous skin (hand) and hairy skin (waist), always using ERM motors to render the vibrotactile cues. We also addressed the effects of multisensory stimuli and sensory substitution in our experiments through the navigation on completely dark scenarios and enlightened ones, but we did not perform experiments with diverse user profiles, such as with blind subjects. Our study on tactile communication was also focused mostly on navigation and the use of a tactile feedback that was produced by the system and not for communication between different users in a shared virtual or physical environment. That motivated us to continue exploring different technologies for tactile actuation, user profiles, contexts of use, and methods to support building more effective and dynamic tactile interfaces.

4 STUDY AND DESIGN OF A HEAD-MOUNTED TACTILE DISPLAY

The research described in this chapter was meant to build on our previous results (Chapter 3). At this phase, we continued exploring different variables concerning the design of haptic representations to design a more versatile tactile interface. We started by assessing vibration pleasantness and comfortability across head, neck, and trunk as alternatives for directional cueing from an egocentric perspective in a pre-test (unpublished). We confirmed that tactile location around the neck is difficult to perform, as reported by Morrow et al. (2016). However, we perceived that the head could be a suitable alternative for egocentric navigation along with the trunk. The skin on the head is known to be one of the regions of the human body most sensitive to mechanical stimulation. There are studies wherein vibrating actuators are attached to glasses, helmets, and headbands to be used as tactile Head-Mounted Displays (HMDs) (RASH et al., 2009; NUKARINEN et al., 2015; KERDEGARI; KIM; PRESCOTT, 2015). Thus, head stimulation is an alternative, especially for virtual setups that use VR headsets in which the interaction is mostly driven by the head movements.

However, the skin on the head is far from being homogeneous. The glabrous skin of the forehead, for instance, offers much more acuity than the hairy occipital and temporal regions (MYLES; KALB, 2010). Therefore, studies exploring vibrotactile localization around the head recommend the use of lower density arrays, composed by four or five tactors (DOBRZYNSKI et al., 2012; GILLILAND; SCHLEGEL, 1994). Unfortunately, lower density tactile arrays are less informative and there might be cases in which more tactors could provide better performance and usability (HAWES et al., 2005; TSUKADA; YASUMURA, 2004). Thus, we have performed a comprehensive set of experiments to support the design of vibrotactile HMDs for applications linked to spatial awareness, navigation, and guidance in physical and virtual environments.

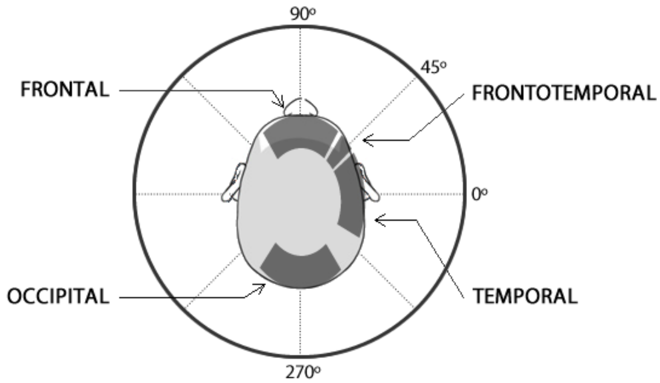
In the remainder of this chapter, in Section 4.1 we present the psychophysical assessment of the spatial acuity on the head. In Section 4.2, we present the assessment of the trade-off between actuator density and precision by comparing three kinds of directional cues delivered on the head. Finally, in Section 4.3, we apply our tactile display as an anti-veering device to assist blind individuals to walk straight from a point to another.

4.1 Spatial Discrimination of Vibrotactile Stimuli Around the Head

Although the existing literature on head stimulation reinforces the feasibility and advantages of Tactile HMDs (RASH et al., 2009), little research had explored the head by the time of this research. Moreover, although tactile acuity has been extensively investigated for pressure stimuli, *vibrotactile* resolution of the skin has not (VAN ERP, 2005; CHOLEWIAK; COLLINS, 2003). Fundamental knowledge on the spatial acuity of the head, as well as subjective factors, e.g. pleasantness and workload, are required to design optimal tactile displays that can provide good performance and yet comfortability for interactive tasks on a daily basis.

Therefore, we have performed a psychophysical assessment of the spatial acuity on the head, as well as the analysis of the reaction times, the task workload and the pleasantness of vibrating stimuli as a function of the stimulus location. Our study focused on four regions around the head: three main regions, consisting of Frontal, Temporal, and Occipital, and one intermediate Frontotemporal position (see Figure 4.1).

Figure 4.1 - Regions around the head where vibrating stimuli are displayed



Source: the author.

4.1.1 Materials and Methods

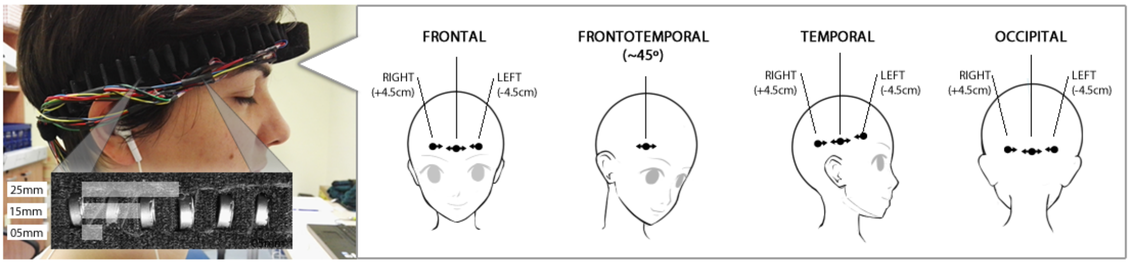
4.1.1.1 Subjects

Twelve subjects participated voluntarily in the study (six males and six females). They were not involved in the research project. Their ages ranged from 27 to 47 years (M = 30.83, SD = 5.93). Their handedness was assessed with an Edinburgh Handedness Inventory (DRAGOVIC, 2004) and only one subject was shown to be left-handed. Five subjects had long hair, six had short hair and one was bald. We found no effect of age, gender, handedness, or hair density on their performance during the tasks. In a preliminary questionnaire, three subjects reported having some problem on the skin: a scar on the left side, a scar on the right side, and a scar on the front of the head, respectively. In all cases, the placement of the headband did not cover the mentioned regions.

4.1.1.2 Apparatus

A vibrotactile headband was constructed with *eleven* electromechanical tactors controlled with an Arduino Mega ADK board. Each vibration motors - 10*mm* shaftless, 3.4*mm* button type (310-101 Precision Microdrives) - was positioned vertically in a cell made of a soft elastic material to attenuate the reverberation through the headband. Then, the cells were attached to a piece of Velcro to be easily worn around the head (see Figure 4.2 (left)). The vertical orientation allowed the eccentric rotating mass motors to produce a punctual stimulation on the desired points. Such configuration also allowed a finer measurement as the distance between each cell was of 5*mm*. The vibrotactile array had a total length of 10.5*cm*.

Figure 4.2 - Vibrotactile headband (left) and assessed regions (right). On the Frontal, Temporal, and Occipital regions, three points were used as reference: the central point and two on the extremities of the array. On Frontotemporal region only the central point was used as reference



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4.1.1.3 Body Sites

The vibrotactile array was moved between sessions to assess four regions around the head. It was placed on the *Frontal* region about $1cm$ above the eyebrows with its central tactor touching the midline on the forehead. On the *Temporal* region, the central tactor was positioned about $1cm$ above the right ear. On the *Occipital* region (back of the head), the central tactor was also placed on the midline. Finally, an intermediary point was assessed between the Frontal and Temporal regions (*Frontotemporal*). The central tactor of the array was placed half way between the forehead midline and the right ear line (see Figure 4.2 (right)).

4.1.1.4 Task and Stimuli

The stimuli consisted of the sequential activation of two tactors. The task of the observer was to indicate whether the second tactor was to the left or the right of the first (2AFC). Each pair of stimuli could have an inter-stimulus interval of $700ms$, $1000ms$, or $1300ms$. Each tactor was activated for $500ms$ at $150Hz$ ($1.25g$), and the inter-stimulus interval was selected randomly across trials. The physical distance between the pairs also varied from $5mm$ to $25mm$, keeping one fixed position (standard) and activating the second one on a given distance to the left or to the right (comparison).

Three tactors were designated as standard location for Frontal, Temporal and Occipital regions: the middle tactor, the tactor on the left extremity of the array, and the one at the right extremity. For the Frontotemporal, only the middle tactor was used as the standard. The central standards were paired to six comparisons, with inter-stimuli separation of $5mm$ to $25mm$ to the left and to the right of each standard. For the standards on the extremities of the array only three comparisons were used (see Figure 4.2 (right)). Each standard-comparison pair was presented ten times, resulting in a set of 420 stimuli per subject and 5040 trials overall. The order of presentation of each comparison was random, as well as the order of appearance of the standard (e.g. standard-comparison or comparison-standard).

4.1.1.5 Experimental Protocol

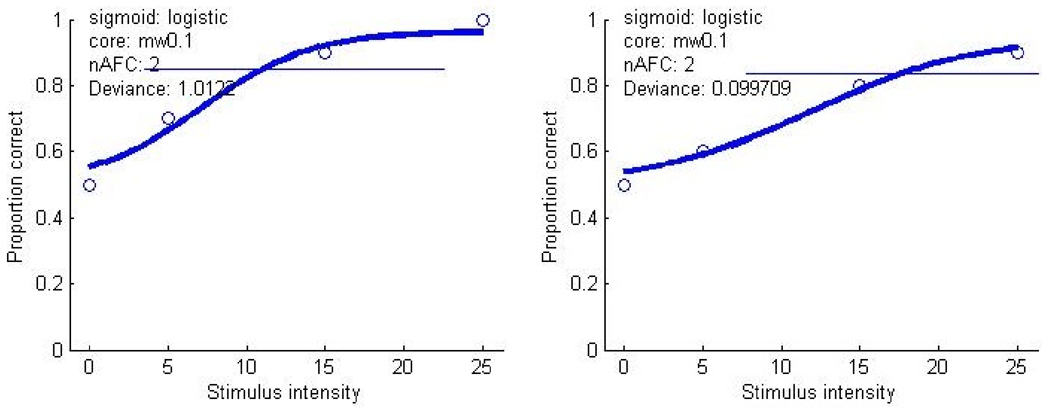
For each trial, the subject was advised to perceive the dyadic stimuli and answer whether the second stimulus was to the left or the right of the first, as soon as they felt the second vibration. Except for the Occipital region, "to the right" concerned to the clockwise direction. Then, the answer should be made by pressing the left or right button on a small keyboard that was built ad hoc and connected to the Arduino board. Thus, each reaction time comprehends the time between the second vibration and the answer. After each response, the next trial started automatically after a random time that varied from 0*ms* to 1500*ms*. Across the trials, subjects wore earphones to reduce the humming sound of the tactors and kept their eyes closed for better concentration.

After a set of 60 trials, we offered to the subjects a resting break. They were also allowed to ask for a break at any time. The experiment was executed in four sessions, according to the tested locations, counterbalanced with a 4x4 Latin square. Between each session, the subject had to rank its experience on two 7-point scales for pleasantness (KLÖCKER et al., 2013) and easiness (Single Easy Question - SEQ) (SAURO; DUMAS, 2009). Then, the subjects filled out a NASA Task Load Index (NASA-TLX) questionnaire (HART, 2006) to self-judge their task load. The whole experiment took on average 1 hour.

4.1.1.6 Statistical Analyses

We analyzed data with MATLAB (GUIDE, 1998) and BioEstat (AYRES JUNIOR; AYRES; SANTOS, 2007) software. We evaluated psychometric functions with the *psignifit* package (KUSS; JÄKEL; WICHMANN, 2005; WICHMANN; HILL, 2001). The acuity was calculated as the JND (Just Noticeable Difference), accounting for the 75% of correct responses estimated on the fitted function (see Figure 4.3). Threshold values above three times the standard deviation were excluded as outliers. Body location, inter-tactor distance, and kind of skin (hairy or glabrous) were taken as independent variables, while precision, reaction time, workload and pleasantness were the dependent variables. The effect of the independent variables on the dependent ones was evaluated by One-Way ANOVA and post-hoc Tukey analyses. When distributions were not Gaussian (according to Shapiro-Wilks test), non-parametric Kruskal-Wallis (with post-hoc Dunn analyses) and Friedman (with post-hoc Wilcoxon analyses) tests were respectively used for analyses of variance according to the number of samples.

Figure 4.3 - Example of psychometric functions for each standard tactor



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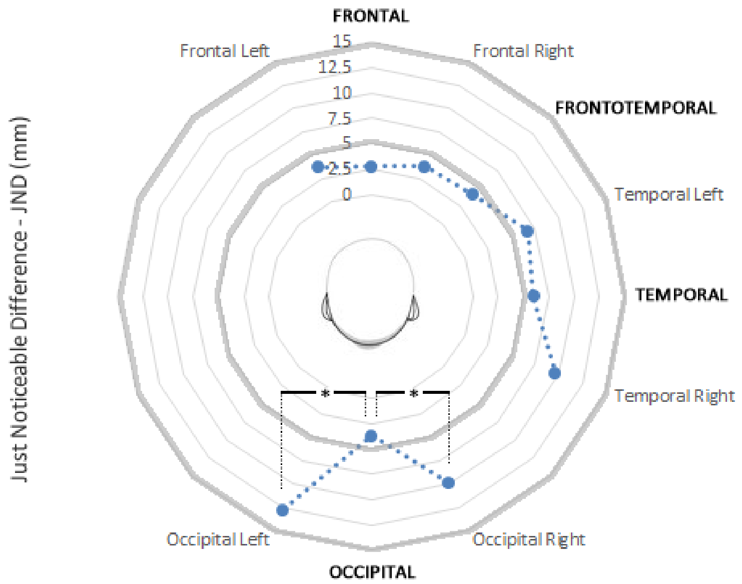
4.1.2 Results

4.1.2.1 Spatial Acuity

Figure 4.4 presents mean thresholds for each standard point.

Figure 4.4 - Mean threshold values across four regions around the head



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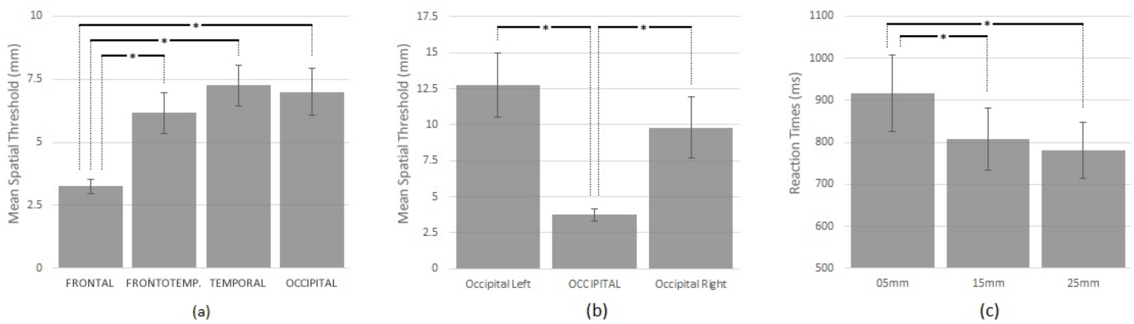
There was a statistically significant difference between the thresholds across the four assessed regions (H(3) = 21.0456, p = 0.0001). A post-hoc Dunn test revealed that the thresholds in the Frontal region differed significantly from all the other areas ($p < 0.05$). With threshold values under 5*mm*, the Frontal region is the most accurate, outrunning the Temporal, the Occipital, and even the Frontotemporal location (see Figure 4.5(a)).

Figure 4.5 - (a) Precision on the Frontal region (M=3.25, SD=1.79) was significantly higher then on the Frontotemporal (F/T) (M=6.15, SD=4.92), Temporal (M=7.26, SD=4.71), and Occipital (M=6.99, SD=5.67) regions. (b) On the Occipital region, the acuity on the central reference (M=3.72, SD=1.99) was higher than the left (M=12.75, SD=5.85) and right (M=9.80, SD=6.42) neighbors. (c) Reaction times were higher for stimuli with 5*mm* (M=916, SD=317) of separation than for 15*mm* (M=808, SD=258) and 25*mm* (M=781, SD=229)



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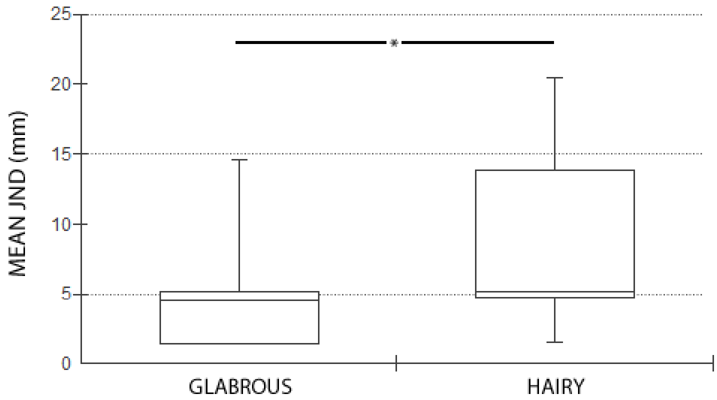
Threshold values were also analyzed for the different skin types around the head (see Figure 4.6). Points of the Frontal, Frontotemporal and Temporal glabrous sites were compared to Temporal and Occipital hairy ones. Hairy skin showed a significant effect on spatial acuity (H(1) = 13.2554, p = 0.0003). The mean threshold on hairy skin was equal to 7.5*mm* (SD = 5.61) while, for smooth sites, the mean threshold was 3.9*mm* (SD = 3.02).

Figure 4.6 - Mean threshold on glabrous skin (M=3.9, SD=3.02) was significantly lower then hairy skin (M=7.5, SD=5.61)



Source: the author.

Not all assessed points on hairy skin presented equally low acuity for vibration. There was a statistically significant difference between the threshold values on the Occipital region (H(2) = 12.7607, p = 0.0017). The tactor positioned over the midline presented higher acuity than its neighbors (p <0.05), and was shown to be as accurate as some points of the forehead (see Figure 4.5(b)).

A multiple linear regression was calculated to predict spatial acuity based on distance from the head midline and skin type (hairy or glabrous skin). A significant regression equation was found (F(2,130) = 12.6216, p <0.0001), with a R_2 of 0.1626. Subjects' spatial acuity was predicted as

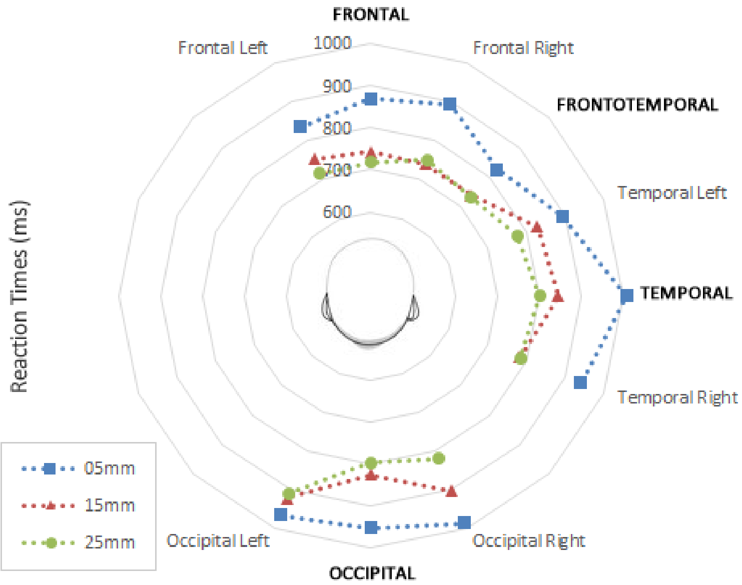
$$JND = 3.1672 + 0.0285 \times dist + 2.9336 \times skin \quad (4.1)$$

where *JND* is coded in millimeters, *dist* is coded as integer numbers (0 to 90) for the tactors positioned from the midline (0°) to the ear line (90°), and *skin* is coded as 0 = Glabrous and 1 = Hairy. Spatial acuity decreased 0.03*mm* for each degree, from the midline to the ear position, and acuity on hairy skin was 2.93*mm* lower than glabrous skin. Both distance from head midline (p = 0.0193) and skin type (p = 0.0001) were significant predictors of spatial acuity. This phenomenon can be graphically seen in Figure 4.4. The figure shows a general increasing trend of thresholds (or decreasing spatial acuity) from the central midline to the ears.

4.1.2.2 Reaction Times

There was a significant effect of the inter-tactor distance on reaction times [F(2,357) = 8.4834, p = 0.0005]. Post-hoc comparisons using the Tukey test indicated that the mean reaction time for stimuli with 5*mm* separation (M = 916, SD = 317) was significantly higher than either condition for stimuli with a 15*mm* separation (M = 808, SD = 258, p <0.01) and with a 25*mm* separation (M = 781, SD = 229, p <0.01). However, the reaction times between 15*mm* and 25*mm* did not significantly differ (see Figure 4.5(c)). Those values are consistent across all assessed locations on the head (see Figure 4.7).

Figure 4.7 - Mean reaction times for three inter stimuli values of 5*mm*, 15*mm*, and 25*mm* across the head



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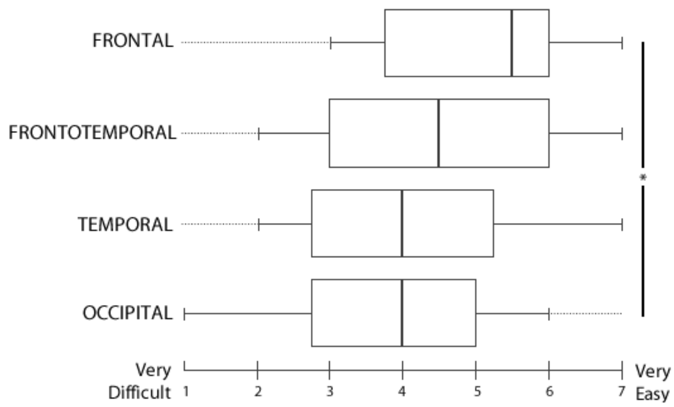
4.1.2.3 *Subjective Evaluation*

The scores of NASA-TLX (non-weighted) did not show correlation with assessed conditions. However, the scale for easiness presented a high significance for stimulation on the Frontal region (Fr(3) = 11.62, p = 0.0088). A Wilcoxon Signed-ranks test indicated that performing the psychophysical experiment with tactors placed on the Frontal region was easier then on the Occipital region (Z = 2.80, p = 0.0051), as shown in Figure 4.8.

Figure 4.8 - Easiness across regions. The task was felt to be easier when vibrations were delivered to Frontal region and more difficult on the Occipital



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The pleasantness for Frontal (M = 5.6, SD = 1.2), Frontotemporal (M = 5.7, SD = 0.9), Temporal (M = 5.6, SD = 1.1), and Occipital (M = 5.7, SD = 1.3) regions did not present significant differences. Pleasantness scored positively (above neutral) for all positions.

4.1.3 Discussion

4.1.3.1 Midline Effect

Our results present an evidence of the influence of the midline on spatial discrimination on the head. With less influence than the skin type (hairy or glabrous), the precision for spatial discrimination on the head decreases as the stimulated zone gets farther from the head midline and closer to the ear line. That effect seems to not have been reported for head stimulation before. However, other authors indirectly identified the midline effect on trunk stimulation (VAN ERP, 2005). They reported a dramatically lower two-point threshold when points straddled the torso midline compared to the situation in which the two points were beside the midline.

One of the reasons could be the improvement of performance near anatomical reference points (CHOLEWIAK, 1999; GALLACE; TAN; SPENCE, 2007). The body midline can act as an anchor point and can aid the user in absolute localization. However, it does not seem to be the case as the present experiment measured relative location of two stimuli and not absolute location. Moreover, in our experiments the tactor positioned on the midline of the Occipital region showed much lower thresholds than its neighbors. That region is quite homogeneous. So our result does not seem to be caused by the underlying bone structure too. Finally, the midline effect may be caused by the way the central nervous system processes stimuli, as concluded by Van Erp (VAN ERP, 2005).

The finding of this effect for the head reinforces results obtained for other body sites. It can also support the construction of models for the perception of vibration across the human body.

4.1.3.2 Quantitative and Qualitative Measures

Although the Frontal and the Frontotemporal regions presented thresholds under $5mm$, reaction times for all areas around the head were much higher for such small inter-stimuli distance. Based on our results, the distance between tactors should be kept above $15mm$ if the response time of the application is crucial, as for emergency signals and alert, for instance. However, if response time is not critical, the glabrous region of the forehead should be the best choice to deliver vibrotactile cues. Such region should also be studied for multiple simultaneous stimulations and temporal factors.

Although the skin around the human head is shown to be sensitive to much lower frequencies (BIKAH; HALLBECK; FLOWERS, 2008), in our study we delivered stimuli at $150Hz$. Frequencies above $150Hz$ become uncomfortable and may cause headaches. As we mentioned in our results, pleasantness scored high values for all assessed regions. Such result indicates that the frequency we used was adequate. To guarantee good performance and comfortability, designers of tactile head-mounted displays should keep the frequency of the stimulus under such value.

Furthermore, we show that discrimination at the forehead was not only more precise but also easier to perform. Stimulation on the forehead may therefore be reputed as more suitable for vibrotactile head mounted displays. The result also suggests that other subjective factors beyond performance have to be considered when designing vibrotactile devices.

4.1.3.3 Limitations and Recommendations

Myles and Kalb (MYLES; KALB, 2010) showed that the head is less sensitive to vibrating stimuli as it goes up towards the parietal and central regions. We did not involve parietal regions in this study also for practical reasons: our goal was not to study the whole scalp, but to mirror the azimuth plane surrounding a human being on the transverse plane of the head. Therefore, the whole set of positions of the tactors had to form a coplanar setup. As well ipsilateral and controlateral thresholds were assumed as similar, therefore the temporal zones of the left hemisphere were not analyzed.

In our study, we positioned the motors vertically. That allowed us to assess much closer pairs of vibratory stimuli, but it is not a common approach in other studies. However, Sofia and Jones (SOFIA; JONES, 2013) mention that the size of the contact area may influence the ability to localize vibrotactile stimuli, although there do not appear to be any study in which this has been systematically investigated. Above 50 Hz, vibrotactile thresholds decrease as contact area increases, presumably due to the spatial summation of afferent signals from Pacinian corpuscles (SOFIA; JONES, 2013). Thus, if the motors are placed horizontally in contact with the skin of the head and the stimulation is perpendicularly to the skin, we should expect better results, at least for localization of the vibrating stimuli.

4.1.4 Conclusion

Our results showed that the glabrous skin of the Frontal region of the head is the most accurate for spatial discrimination of vibrotactile stimuli. Therefore, it should be the most suitable head region to perceive tactile cues delivered by head-mounted displays, such as glasses, hats, helmets and headbands. Our results also show that the center of the Occipital region has high precision, which makes it also suitable to process tactile cues, such as warning signals. Moreover, we found an influence of both distance from the head midline and skin type on the precision of a discrimination task. Our results were reported at (JESUS OLIVEIRA et al., 2016a).

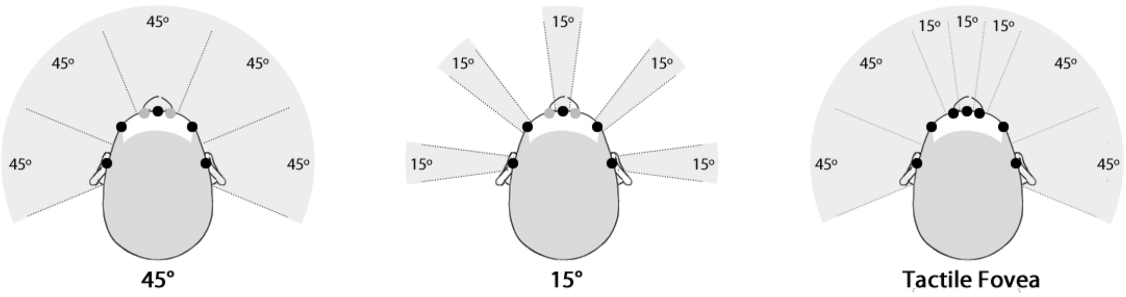
Although high precision for head stimulation and high pleasantness were found in this work, the amount and kind of information to be displayed on the head is still to be investigated. How many tactors can be simultaneously perceived to construct tactile patterns that are meaningful and ease to discriminate? Is there a suitable tactile vocabulary for head-mounted displays? How such vocabulary should be shaped to convey expressive content and avoid ambiguity with predefined patterns? We started such investigation assessing different configurations for the tactile display based on our results concerning the acuity for tactile stimuli around the head.

4.2 Localized Magnification in Vibrotactile HMDs (Tactile Fovea)

When it comes to designing vibrotactile displays, actuator density is an important parameter (VAN ERP, 2002). And when a high density is needed, only certain body parts have a sufficiently high spatial resolution (CHOLEWIAK; BRILL; SCHWAB, 2004). The skin on the head is far from being homogeneous. The glabrous skin of the forehead, for instance, offers much more acuity than the hairy occipital and temporal regions (JESUS OLIVEIRA et al., 2016a). Therefore, studies exploring vibrotactile localization around the head recommend the use of lower density arrays, composed by four or five tactors (DOBRZYNSKI et al., 2012). Unfortunately, lower density tactile arrays are usually less informative. There might be cases in which more motors could provide better performance and usability (HAWES et al., 2005; TSUKADA; YASUMURA, 2004). Thus, the trade-off between actuator density and performance still demands optimal solutions for head stimulation.

One way to support more precise selection with a lower density tactile array would involve modulation of vibration parameters, such as frequency and rhythm (PIELOT et al., 2008; VAN ERP, 2005). However, most commonly used actuators do not provide satisfactory control over hardware parameters (JONES; SARTER, 2008). In those cases, it is hard to have proper control over the output stimuli and, consequently, over perceptual responses. In this work, we explore alternatives to provide more precision for target detection, keeping the frequency and magnitude of stimulation fixed. We compare a conventional design made with tactors placed on the user's head on cardinal and collateral points, each one covering an angle of 45° around the user, with two different alternatives for higher precision. In one alternative, we reduce the angle covered by each tactor to 15°, keeping the array density homogeneous but leaving zones without vibration between them. In the second alternative, we increased the array density only on the forehead, where each tactor covers a range of 15°, while the remaining tactors still cover 45° each. The latter condition provides a localized magnification that we call "Tactile Fovea"[1] (see Figure 4.9).

Figure 4.9 - The three modalities of directional cueing. The 45° modality is the baseline condition; Commonly, the density of the array is increased to reduce the angle covered by each tactor in this modality. The 15° is a proposed condition to increase precision without manipulation of vibration parameter and array density. The Tactile Fovea condition is a second proposal to achieve higher precision by locally increasing the array density



Source: the author.

We hypothesize that the lower range in the 15° condition would slow down the detection of the target, but make it more precise than the 45° baseline. However, the effect of the spaces between the tactors on user experience is unpredictable. It could either provide a better user experience since the vibrations would not be continuously activated, or increase workload since the spaces between the tactors are not informative. In this context, the Tactile Fovea could be a good alternative to the 15° condition. We then hypothesize that the Tactile Fovea would be less restrictive as it provides a wider "field of touch"[2] than the 15° for each tactor. Therefore, the Tactile Fovea would allow faster detection and less workload than the 15° condition.

To assess those haptic modalities, we performed a within-subject experiment aimed at pointing directions by head motion. After presenting the design of our experimental setup

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[1]Such metaphor is also used to explain the behavioral focus of the star-nosed mole's snout. The snout of the star-nosed mole (*Condylura cristata*) has a "fovea" at the center, used for detailed explorations of objects of interest (CATANIA, 1999).

[2]Therm used by Jan van Erp to contrast the range covered by a tactile array and the human field of view. (ERP, 2001)

and results, we discuss the characteristics of each tactile modality and their application to head stimulation.

4.2.1 Materials and Methods

We wanted to understand the link between an active pointing task, where the head must be aligned to specific spatial directions, and the optimal amount of tactile information to achieve it. Therefore, we performed a within-subject assessment with the three tactile modalities (45°, 15°, and Tactile Fovea) and the five frontal positions (W, NW, N, NE, and E) as independent variables. Each subject, using a head-mounted vibrotactile display, had to find a set of virtual targets following the directional cues provided by each modality. Then, we assessed accuracy, reaction times, precision and workload as dependent variables.

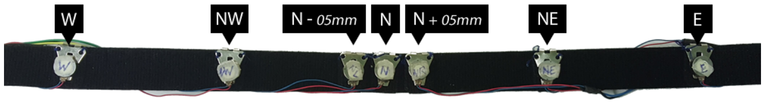
4.2.1.1 Subjects

Twelve subjects participated voluntarily in the study (seven males and five females). Their ages ranged from 27 to 37 years (M = 31, SD = 4.1). Their handedness was assessed with an Edinburgh Handedness Inventory (DRAGOVIC, 2004) and two subjects were shown to be left-handed. Five subjects had long hair; Five had short hair, and two were bald. Two subjects reported having a scar on the back of the head. The placement of the headband did not cover the mentioned scars. One subject reported having a light exfoliation issue. No subject reported having hearing loss. The demographic information was taken into consideration in the assessment of the dependent variables.

4.2.1.2 Apparatus

We built a vibrotactile headband with seven electromechanical tactors controlled with an Arduino Mega ADK board and seven Adafruit DRV2605L haptic controllers (see Figure 4.10). Each tactor - 10*mm* Linear Resonant Actuator, 4*mm* type (C10-100 Precision Microdrives) - was attached to a piece of Velcro to be easily worn around the head. Five tactors were placed at equal distance from the center of the forehead over the Cardinal (West, North, and East) and Collateral points (NW and NE). The remaining two tactors were placed on the forehead to be used during the Tactile Fovea condition. They were set 5*mm* apart from the central tactor to convey more precise information about the target in the North position.

Figure 4.10 - Vibrotactile headband. The tactor "N" was centered on the subject's forehead while the tactors "W", "NW", "NE" and "E" were equally spaced from midline to ear line. Two other tactors were added to compose the Tactile Fovea on forehead



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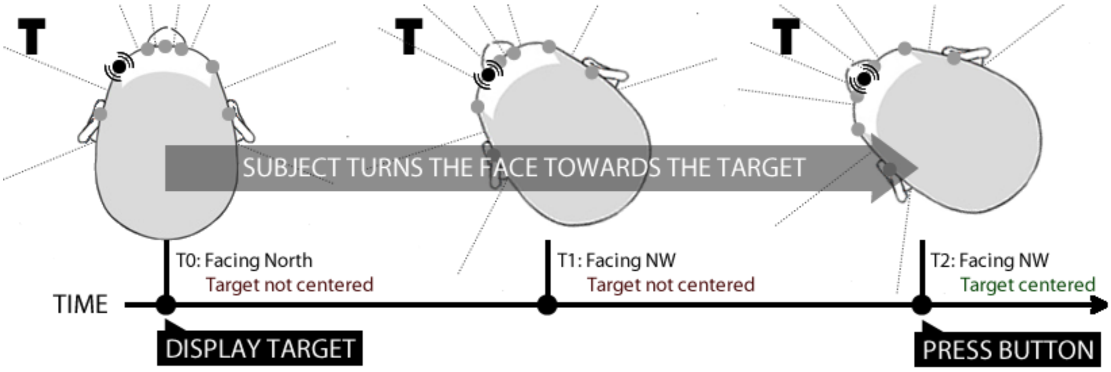
4.2.1.3 Task and Stimuli

Each subject filled out a demographic questionnaire before starting the experiment. After wearing the headband, each subject had to perform a naive search task looking for virtual targets on the azimuthal plane. Each target was virtually placed in a fixed direction related to the subject. In the beginning of each trial, marked by a beep, the tactor facing the target position started vibrating indicating its position. Subjects were asked to turn their faces towards the virtual target until they could feel that the vibration moved to the center of their forehead. They were requested to be fast and precise. Once they reached the correct position, with the central tactor vibrating, they should press a button to register their answer (see Figure 4.11).

Figure 4.11 - Each trial started with a beep (3000Hz, 500ms). Then, subjects had to turn their heads to face the virtual target (T). When they could feel that the vibration moved to the center of their forehead, they should register their answer by pressing a button



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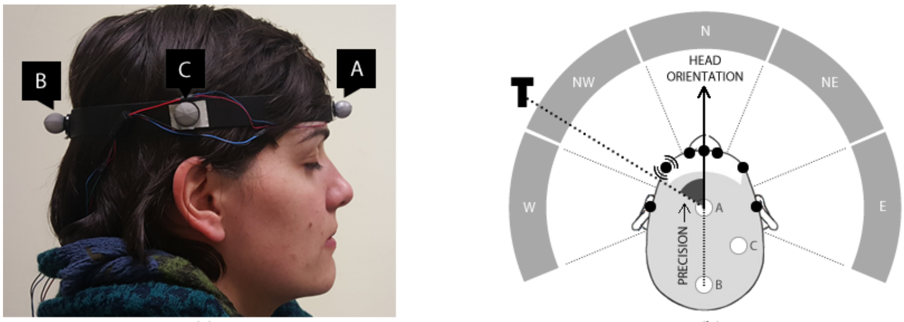
As shown in Figure 4.11, the location of the vibrating stimuli was dynamically updated in function of head motion. For example, a target at -45° would initially activate the tactor facing NW. Then, as the subject moves the head towards the target direction, the other tactors are activated until it gets to the central tactor. Subjects performed the task seated on a not swivel chair, so they had to turn their heads to face the target instead of turning their whole bodies. Subjects kept their eyes closed for better concentration. They also wore earphones to hear the beep that marked the start of each trial, and a pink noise to attenuate the humming noise of the tactors. They were allowed to ask for a break at any time. Accuracy was calculated based on the detection of the correct position of each virtual target, when subject was facing the target. Reaction times were calculated from beep onset at the moment the answer button was pressed.

Each vibration was delivered at $175Hz$. For each direction (W, NW, N, NE, and E), there were ten repetitions. Therefore, 150 trials overall. The position of each virtual target within the set of possible directions was displayed randomly across each session. Each session concerned to one modality of directional cueing. The sessions were counterbalanced with a 3x3 Latin Square. Between sessions, the subject also had to fill out a NASA-TLX questionnaire (HART, 2006) to self-judge their task load. The NASA TLX is a two-part evaluation procedure. First the subject has to evaluate the contribution of each of six factors to the workload of the task, then rate the magnitude of the load on each factor. The process was repeated for each modality of directional cueing. The whole experiment took on average 30 minutes.

4.2.1.4 Data Acquisition

Continuous acquisition of head orientation was made using a Vicon MX motion capture system. Three reflective spherical VICON markers (*A*, *B*, and *C*) of $12.5mm$ each were attached to the vibrotactile array (see Figure 4.12). The markers were automatically labeled in real-time by VICON Nexus (version 1.8.5). Marker *A* was always centered on the forehead while Marker *B* was centered on the back of the head for each subject. The orientation of the vector from *B* to *A* represented the orientation of the head.

Figure 4.12 - Three reflective markers were attached to the vibrotactile array (a). Marker *C* was added to compose the tracked model, while *A* and *B* were used to get the orientation of the head (b). The angle between the head orientation and the target direction corresponded to the precision of the selection



(a) (b)

Source: the author.

Precision values corresponded to the angle between the head orientation and the target direction vectors. The positions of the VICON markers were acquired in real-time via the VICON DataStream SDK (version 1.5) by the laptop that controlled the vibrotactile array. The commands sent to the array to support the target detection were calculated according to the positions of the markers on the head of the subject.

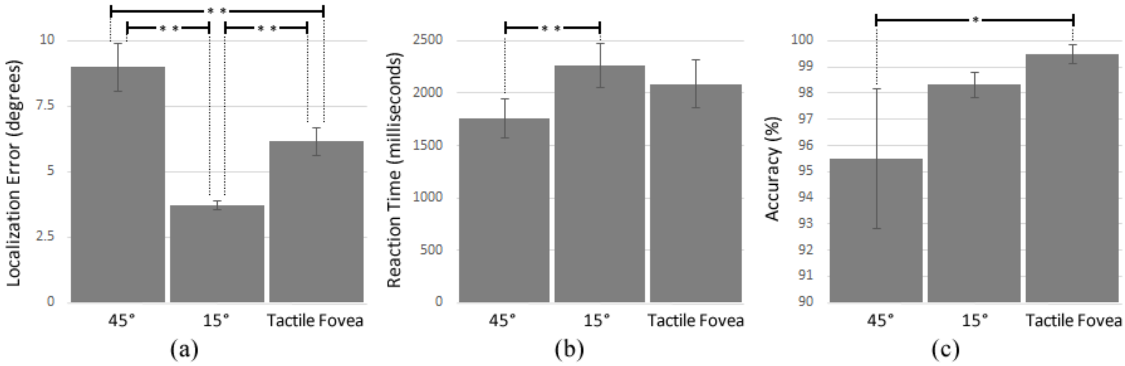
4.2.2 Results

We tested the three modalities of directional cueing (independent variable) on accuracy, reaction time, and precision (dependent variables) in the pointing task. We also tested each specific pointed spatial direction on the dependent variables. The effect of the independent variables on the dependent ones was evaluated by One-Way ANOVA and posthoc Tukey analysis. We found no effect of age, gender, handedness, or hair density on subject's performance.

As we hypothesized, One-way ANOVA test revealed a significant effect of tactile modality on precision scores ($F(2, 177) = 42.3060$, $p < 0.0001$). Precision for the Tactile Fovea condition was significantly higher than that for 45° ($p < 0.01$). In addition, precision for the 15° condition was significantly higher than both 45° ($p < 0.01$) and Tactile Fovea ($p < 0.01$). 45° was the less precise condition. In addition, when it comes to accuracy ($F(2, 177) = 3.2556$, $p = 0.0396$), 45° condition was significantly lower than the Tactile Fovea ($p < 0.05$), as shown in Figure 4.13.

However, the wider angle of the 45° condition not only provides less precision. It also allows subjects to be faster in this condition. Reaction times had a significant effect ($F(2, 177) = 5.0995$, $p = 0.0072$), with the 45° being significantly faster than the 15° ($p < 0.01$), with the latter being the slowest. As we hypothesized, the lower range in the 15° condition slows down the detection of the target but also makes it more precise than the 45° baseline.

Figure 4.13 - In (a) 15° was the more precise (M = 3.7, SE = 0.1), followed by TF (M = 6.1, SE = 0.5), and 45° (M = 8.9, SE = 0.9). In (b) Tactile Fovea did not present difference in RT (M = 2078.1, SE = 226.2), but the 45° (M = 1650.9, SE = 173.6) was faster than the 15° (M = 2218.1, SE = 212.4). (c) 15° did not significantly differ from the others in accuracy (M = 98.3, SE = 0.5), but accuracy for 45° (M = 95.5, SE = 2.7) were much lower then for Tactile Fovea (M = 99.5, SE = 0.3)



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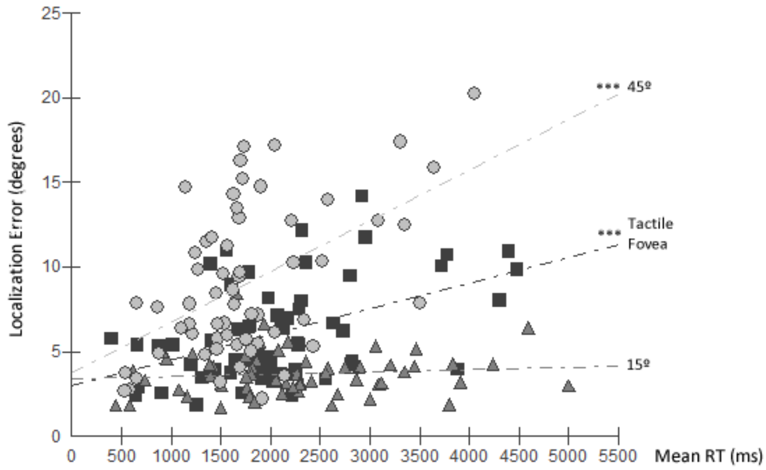
4.2.2.1 Precision vs Reaction Times

Precision in detection of target positions significantly predicted reaction times in 45° (b = 86.2190, t(58) = 4.5041, p <0.0001) and Tactile Fovea (b = 143.3859, t(58) = 3.9906, p <0.0001). Precision also explained a significant proportion of variance in reaction times for 45° (R2 = 0.2464, F(1, 58) = 20.2872, p = 0.0001), and for Tactile Fovea (R2 = 0.2019, F(1, 58) = 15.9249, p = 0.0004). Figure 4.14 shows Tactile Fovea between the 45° and 15° conditions. Since Tactile Fovea is more informative than 15°, it allowed users to select directions with both high and low precision. The 15° condition is restrictive and, therefore, more precise.

Figure 4.14 - There was a significant difference in correlation coefficients between 45° and Tactile Fovea (p <0.05), and between Tactile Fovea and 15° (p <0.001). The later took much more time to achieve the reported precision



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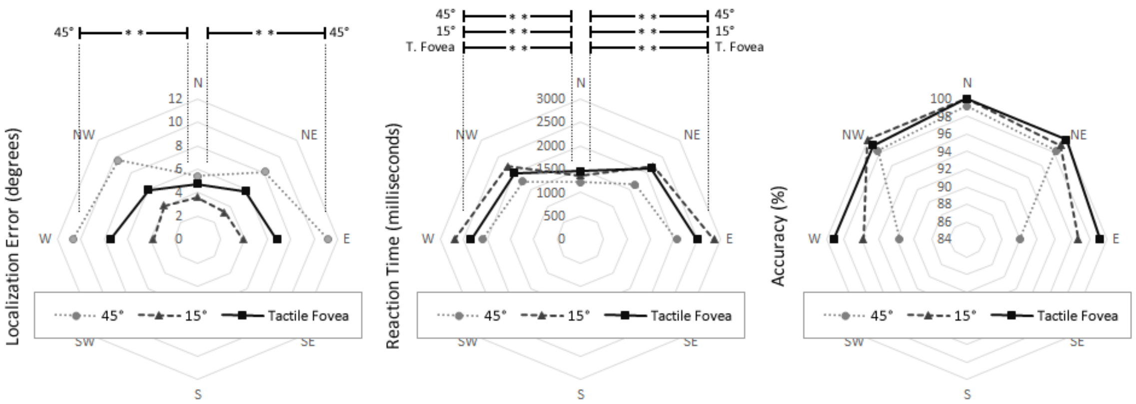
4.2.2.2 Target Position

For all conditions, the position of the targets around the subject and reaction times were strongly correlated ($r(180) = 0.4342$, $p < 0.0001$). It took more time to select targets far from the central position. The selection of peripheral targets was also performed with less precision. We tested the five sets of direction (W, NW, N, NE, and E) looking for differences in accuracy, reaction times, and precision. According to Shapiro-Wilks test, distributions were not Gaussian. Therefore, based on the number of samples, Friedman test was used with posthoc Wilcoxon analyzes.

There was a significant effect of target position on precision scores for the 45° condition ($Fr(4) = 20.4667$, $p = 0.0004$) (see Figure 4.15). Precision in pointing to targets on the North was significantly higher than pointing to targets placed at West ($Z = 3.0594$, $p = 0.0022$) and East ($Z = 2.8241$, $p = 0.0047$). The higher errors and lower accuracy for selecting targets on West and East positions are intrinsic to the nature of the stimuli. Subjects can only perceive the virtual object as being in front of them when the frontal tactor is triggered. Such vibration could start even before the complete movement of the head, at maximum 22.5° for the 45° condition, which gets more evident for West and East positions. Such results highlight the problems in using tactors to cover wide angles in low resolution tactile arrays.

A significant effect of target position was also found on reaction times for the 45° condition ($Fr(4) = 34.0667$, $p < 0.0001$), for the 15° condition ($Fr(4) = 27.5333$, $p < 0.0001$), and for the Tactile Fovea condition ($Fr(4) = 27.5333$, $p < 0.0001$). Reaction times for detection of targets on the North were significantly lower than West and East across conditions (see Figure 4.15). Since the subjects performed the detection task seated on a chair, they frequently faced North. Thus, it is expected that subjects would take more time to move their heads to select targets far from North. Such result concerns only movements in the horizontal plane as the subjects did not moved their heads significantly out of the azimuthal plane into the elevation plane.

Figure 4.15 - Target position had a significant effect on precision for 45° (a), and on reaction times for all conditions (b). However, it did not show effect on accuracy (c)



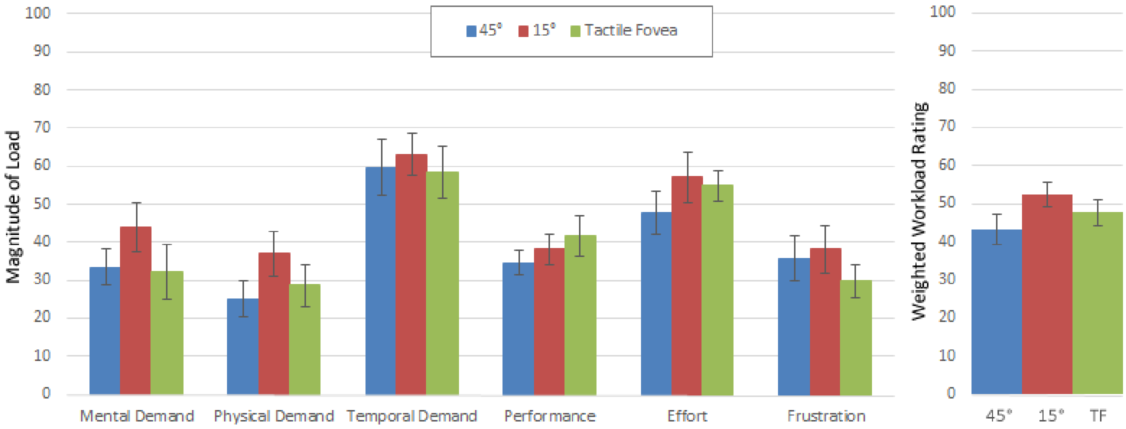
(a) (b) (c)

Source: the author.

4.2.2.3 Workload

Figure 4.16 shows the result of the NASA TLX for each tested condition. We hypothesized that the 15° condition could increase workload since the spaces between the tactors are not informative. In fact, by using the 15° condition, subjects had to be more active in the search for the virtual target. At the beginning of the trial, if the subject's head were not aligned with the initial position of the virtual target, the subject would not know the direction unless he/her search for it. Moreover, the subject had to move the head more, until the virtual object was found inside the short angle of 15°. Therefore, 15° yielded higher means for different factors and for the general workload. However, the differences between conditions were not significant. Moreover, subjects did not report any frustration or unpleasantness due to the intensity or sound of the tactors.

Figure 4.16 - NASA TLX scores for each factor and for workload in 45° (M = 43.3, SE = 3.9), 15° (M = 52.2, SE = 3.1), and Tactile Fovea (M = 47.6, SE = 3.2)



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4.2.3 Discussion and Conclusion

In the literature about tactile guidance, it is not uncommon to find the assessment of vibrotactile arrays with different densities. Tactile devices made of 4, 6, 8, 12, even 16 tactors are made to cover a wide region around the user with more detail (CHOLEWIAK; BRILL; SCHWAB, 2004; TSETSERUKOU; SUGIYAMA; MIURA, 2011). However, although some authors agree that the system should use very high spatial resolutions to increase haptic device ease of use (CARTER; FOURNEY, 2005; TSUKADA; YASUMURA, 2004), it is not just about number of tactors (DOBRZYNSKI et al., 2012; JONES; SARTER, 2008; ERP, 2001). In this study, we propose alternatives for increasing resolution with little or no change in array density. Our contribution is to validate approaches for directional cueing that can be applied to simple arrays that need to keep a lower density, or that have limitations in controlling vibration parameters.

In this study, we showed that a regular tactor coverage of 45° allows the user to be fast but not accurate, nor precise. By simply reducing the spatial angle in which vibration is delivered to 15°, linked to head motion, it is possible to increase precision. Moreover, by adding just two more motors on the forehead instead of duplicating the number of actuators on the whole array, it is also possible to increase precision and accuracy in an active detection task.

When it comes to 15°, its spacing may cause more effort in practical applications where target would be unluckily aligned with the dead spatial zones; The correspondent visual metaphor would be to fail in watching an object through a keyhole when the object is not aligned with the observer. This should imply a much higher search time. The localized magnification provided by the Tactile Fovea allows a better coverage of the azimuthal plane, with no blind spots like those in the 15° configuration.

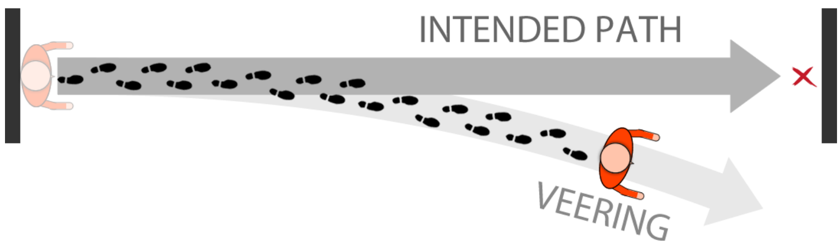
Another contribution of this work is the assessment of both user performance and vibrotactile perception during an active pointing task. Studies show that a reduction in tactile perception systematically occurs during movement (VITELLO; ERNST; FRITSCHI, 2006; ZIAT et al., 2010; VOUDOURIS; FIEHLER, 2017). Thus, even though our device was designed according to the spatial acuity around the head, such tactile suppression could impair user performance during an active task. Results show that user could localize targets with 99.5% of accuracy using the Tactile Fovea in an active task.

Our results concerning the Tactile Fovea (JESUS OLIVEIRA et al., 2016b) were mentioned or applied in several other studies that implemented our technique using different actuators or even to support directional cueing of gaze (CHEN; PEIRIS; MINAMIZAWA, 2017a,b; KANGAS; RANTALA; RAISAMO, 2017; LANGE et al., 2017; PEIRIS et al., 2017; RANTALA; KANGAS; RAISAMO, 2017). To demonstrate that such a technique can be applied to different tasks and contexts, we implement the Tactile Fovea technique for an unobtrusive guidance and to support a straight walking task. Such anti-Veering device was then assessed for assistance of blind pedestrians.

4.3 Anti-Veering Vibrotactile Head-Mounted Display for Assistance of Blind Pedestrians

Humans tend to veer when trying to perform a straight walk through environments that lack reliable orienting cues (MILLAR, 1999) (see Figure 4.17). For impaired pedestrians, it represents a critical problem in everyday life (SHANGGUAN et al., 2014). When crossing the street, for instance, blind pedestrians may veer from the ideal path and end up in the middle of a busy street. To minimize the risk, audible pedestrian signals are commonly used to assist visually impaired individuals when crossing the street (WALL et al., 2004). However, such cues are not always available or can be confusing in a noisy setting such as busy intersections in a city (UEMATSU et al., 2011). Without the assistance of pedestrian signals, blind people often rely on sighted people to help them navigate unknown spaces (FIANNACA; APOSTOLOPOULOUS; FOLMER, 2014). This dependency on others reduces their autonomy and so their mobility (KEMPEN et al., 2012). To avoid this, visually impaired pedestrians can recur to both orientation and mobility (O&M) training and to assistive devices.

Figure 4.17 - Veering is the tendency to depart from linearity in locomotion



Source: the author.

When blind, walking requires extensive training lasting several years. Nonetheless, studies show that training can, in fact, reduce blind pedestrians' veering (GUTH, 2008). Almost no technological aid is available at the training stage and the ones available are limited to turn-by-turn, audio-based cues that rely on GPS and odometric data. Thus, blind pedestrians have to work closely with O&M instructors to improve their performance when trying to walk a straight line without assistance. Most navigation and anti-veering systems are designed to assist visually impaired pedestrians during the walk and not for training. However, autonomy is essential for blind pedestrians. Thus, a navigational and anti-veering device could be used for training the straight walking task at home or in familiar open spaces (e.g. gyms, courtyards) to optimize the time that the blind individuals spend at their O&M sessions. In addition, it could provide assistance during the walking task, minimizing the risks of veering anytime pedestrians feel necessary even after being trained (GUTH, 2008).

Navigational aids are commonly made to convey information through the auditory or tactile sense (DAKOPOULOS; BOURBAKIS, 2010; LOOMIS et al., 2007). In this context, the tactile feedback has the main advantage of not blocking the auditory sense, which is the most important perceptual input source for a visually impaired user in large spaces (CARDIN; THALMANN; VEXO, 2006). In addition, vibrotactile devices are wearable which also allows a free-hands interaction. However, even though the existing literature on head stimulation motivates the design of tactile devices that can be worn around the head to aid locomotion, orientation, obstacle detection and attentional redirection (KAUL; ROHS, 2016; KERDEGARI; PRESCOTT; KIM, 2016), it is still unknown whether it can be used as an anti-veering device.

In this study, we propose the implementation of our vibrotactile HMD as an anti-veering device for the assistance of blind pedestrians. Deviation errors are assessed while the subjects perform a straight walking task in a series of assisted and non-assisted sessions. For the assisted conditions, the vibrotactile HMD is also compared to a conventional O&M session using ambient audible walking signals. Both blind and blindfolded sighted subjects participated in the experiments. Learning effects, trajectories, anxiety levels, workload, and easiness are assessed as a function of the stimulus modality and group profile. Our main contribution is on the assessment and adjustment of a haptic guidance technique based on head stimulation to support the straight walking assistance.

4.3.1 Materials and Methods

We designed and assessed a vibrotactile HMD to provide anti-veering assistance. Deviation errors were assessed across five sessions of assisted and non-assisted walk (three non-assisted sessions, one audio-assisted, and one vibration-assisted). Blind and blindfolded subjects participated in this evaluation. We also assessed the subject anxiety, the task workload, and easiness as dependent variables.

We hypothesize that the vibrotactile HMD might aid subjects to deviate less from their intended path than their baseline veering; We also hypothesize that a short training session should be enough to show some learning effect after using audio and/or vibration (NAGY; WERSÉNYI, 2016).

4.3.1.1 Subjects

Fourteen subjects (9 female, 5 male) participated in the experiment with ages varying from 11 to 38 years old (M = 22, SD = 9.62). Seven were blind and seven were sighted. From the blind group, three were severely blind (from childhood) and four were moderately blind (seeing some shadows and light).

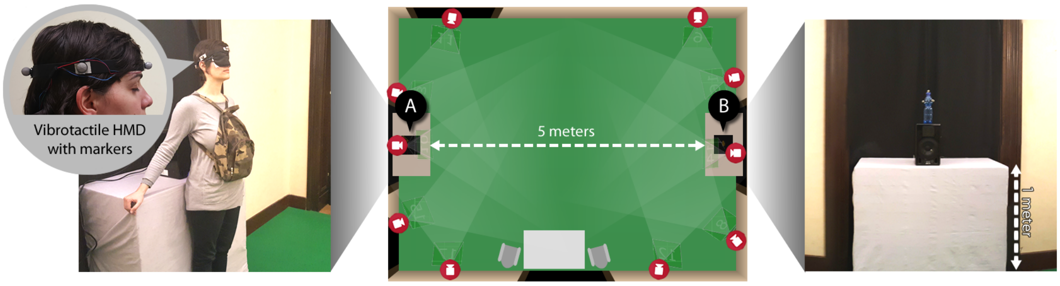
The sample was selected by the Rehabilitation Institute for Blind People *Istituto David Chiossone onlus* in Genoa, Italy, which also hosted the experiments. The recruitment was accomplished according to the local Ethical Committee. Six blind subjects reported having constant O&M instruction in the Institute about how to get aligned (head, shoulders, and feet) and perform a straight walk across the room. The other subjects reported never having done the mentioned training before. We applied an Edinburgh Handedness Inventory (DRAGOVIC, 2004) and two subjects were shown to be left-handed.

4.3.1.2 Experimental Setup

4.3.1.2.1 Venue

The walking task concerned the subject walking across the room from point A to point B, then from point B to point A. Figure 4.18 shows a top-view of the room and the setup.

Figure 4.18 - The walking straight task was performed in a room with 10 cameras of a motion capture system. (left) Subjects wore the vibrotactile display with three reflective markers and a bag with a small computer in the front. (right) Loudspeakers were placed on both sides of the room for the audio-assisted session



Source: the author.

Continuous acquisition of subject position and orientation was made using a Vicon MX motion capture system with 10 cameras. Three reflective spherical VICON markers of 12.5*mm* each were attached to the subject's head to compose a trackable *head template* (see Figure 4.18(left)). The head template was automatically labeled in real-time by VICON Nexus (version 1.8.5). Its position was acquired in real-time via the VICON DataStream SDK (version 1.5) by a laptop placed inside a frontal bag. The bag was placed in the front of the subjects so they could align their back with the starting points (a very common practice in O&M training) and to not induce a veering to the right or to the left (MILLAR, 1999).

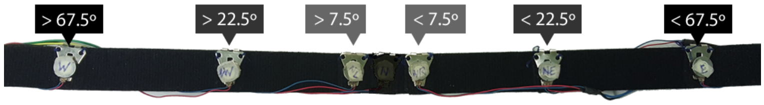
Instead of observing when subjects cross checkpoints on the floor, we use a motion capture system for more precision. Due to the volume that could be sensed by the motion capture system, the distance between points A and B was 5 meters. A 5-m long path might be enough to detect subjects with severe veering (GUTH, 2008) as some crossings measure about the same length.

4.3.1.2.2 Vibrotactile Feedback

We assembled a vibrotactile headband according to the literature on head stimulation (JESUS OLIVEIRA et al., 2016b,a) (see Figure 4.19). Accordingly, seven electromechanical tactors - 10*mm* Linear Resonant Actuator, 4*mm* type (C10-100 Precision

Microdrives) - were attached to a piece of Velcro to be worn around the head. The tactors were controlled with an Arduino Mega ADK board and Adafruit DRV2605L haptic controllers, vibrating at 175Hz.

Figure 4.19 - Vibrotactile headband based on a Tactile Fovea technique (showed at Chapter 4.2). For this setup, the activation of the central motor was adapted



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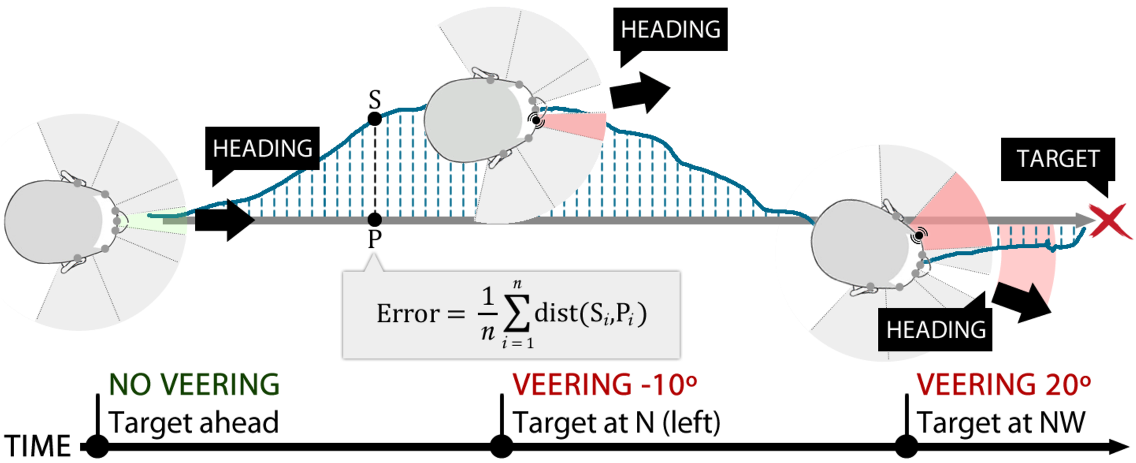
The deviation error was measured as the distance between the center of the head template and the intended path (MARSTON et al., 2007), while the vibrotactile warning was triggered according to the rotation from the target direction (GUTH, 2008; NAGY; WERSÉNYI, 2016) (see Figure 4.20). Then, the location of the vibrating stimuli was dynamically updated in function of head motion and used by the subjects to align their whole body accordingly (head, then shoulders and feet). As subjects walked a straight line, the central motor would indicate that the target was still in front of them, at the end of the intended path. If the subject veered, the actuator corresponding to the direction of the target would vibrate until the subject returns to the intended path.

Figure 4.20 - Vibrotactile cues were provided only when the veering was detected. So, if the pedestrian turns -10°, the right motor on the forehead vibrates. If the pedestrian turns 20° instead, the motor facing NW would vibrate, and so on. The distance from the subject (S) to the planned straight path (P) was aquired every 3cm to calculate the mean deviation



Source: the author.

Studies show that the absence of feedback when walking straight is considered more natural and preferred by blind participants (PANËELS et al., 2013). Thus, no stimulus was delivered if the subject kept heading the target. However, when the subject was off-target by the threshold of 7.5 degrees (NAGY; WERSÉNYI, 2016; ROSS; BLASCH, 2000), then the corresponding tactor would vibrate indicating that there was a veering. Finally, as vibrations are only triggered when the subject goes out of the intended path, vibrations should be less felt as subjects improve in the task (for the sake of learning).

4.3.1.2.3 Auditory Feedback

Auditory stimuli were sent through two ADAM5 speakers placed on each side of the room exactly on the target position (see Figure 4.18). Only one speaker, at the opposite side of the room, would be activated during the assisted walk. The speakers were placed at 1 meter from the ground to account for the different heights of the underage participants.

The audible signals were produced with 880Hz, following the American Manual on Uniform Traffic Control Devices (MUTCD, Section 4E.11, P7 & P8 (FEDERAL HIGHWAY ADMINISTRATION, 2017)). In a conventional O&M session, auditory feedback is systematically reduced during the assisted walk. Therefore, different walk signals were composed by beeps of 200ms with a variable inter-stimulus duration, from 500ms up to 1700ms. These walking signals varied across trials. The room was also covered with a carpet to limit acoustic feedback and the sound of the subject steps.

4.3.1.3 Protocol

Each subject performed *five blocks* of assisted (by audio or vibration) and non-assisted sessions (see Figure 4.21).

Figure 4.21 - Experimental protocol

Source: the author.

Each subject answered a demographic questionnaire before starting the experiment. While wearing the prototype device (headband and bag with the computer) and a blindfold, each subject was guided to walk across the room and feel the start and end points with their hands. Even the blind subjects were blindfolded to avoid receiving cues from any light or shadows. Sighted subjects were blindfolded before entering the room.

Then, each subject performed a non-assisted walking across the room. They were asked to walk as straight as possible. The first session was taken as the baseline as it registered their normal veering pattern. Then, subjects performed *two blocks* of an assisted session (audio or vibration) and *two blocks* of non-assisted sessions, counterbalanced across subjects. Each session has six trials. All sessions were performed on the same day. Subjects could ask for a break at any moment. The whole participation took on average 1 hour for each subject.

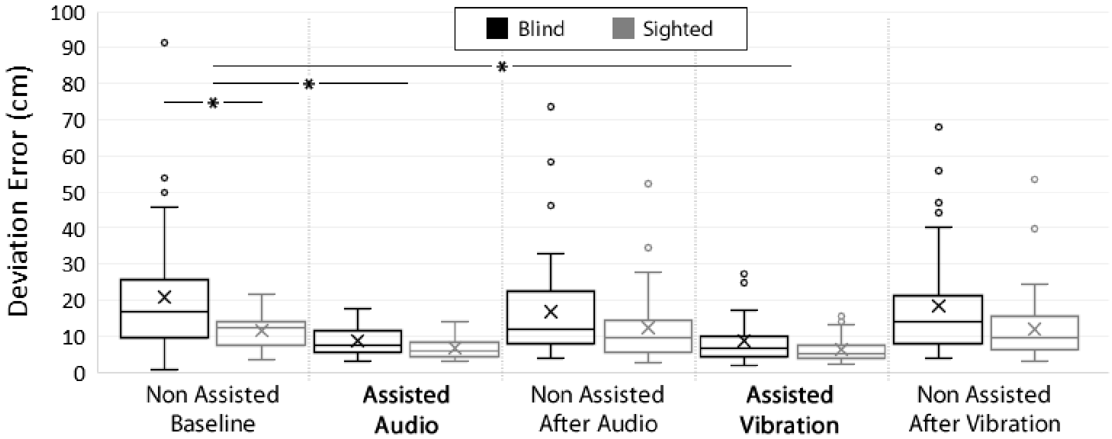
After each session, subjects answered to a six-item short-form of the State-Trait Anxiety Inventory (STAI-6) (MARTEAU; BEKKER, 1992), a 20-point SEQ (SAURO; DUMAS, 2009), and a non-weighted NASA-TLX questionnaire (HART, 2006) with two tangible scales carved in hard foam.

4.3.2 Results

4.3.2.1 Performance

Figure 4.22 shows the results of blind and blindfolded subjects for each session.

Figure 4.22 - Mean deviation errors for the five sessions: First Non assisted for Blind (M = 21cm, SD = 17.5) and Sighted (M = 11cm, SD = 4.7), Audio-Assisted for Blind (M = 9cm, SD = 3.9) and Sighted (M = 7cm, SD = 2.6), Non assisted after Audio for Blind (M = 17cm, SD = 14.6) and Sighted (M = 12cm, SD = 10.0), Vibration-Assisted for Blind (M = 9cm, SD = 6.7) and Sighted (M = 6cm, SD = 3.4), Non assisted after Vibration for Blind (M = 18cm, SD = 14.6) and Sighted (M = 12cm, SD = 9.5). The baseline veering error for blind subjects was higher than for sighted subjects. Assisted conditions reduced the veering error for both blind and sighted (blindfolded) subjects



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A Two-way analysis of variance was conducted on the influence of condition and sight on the deviation errors. Condition included the five sessions and sight consisted of two levels (blind and sighted). All effects were statistically significant at the .05 significance level.

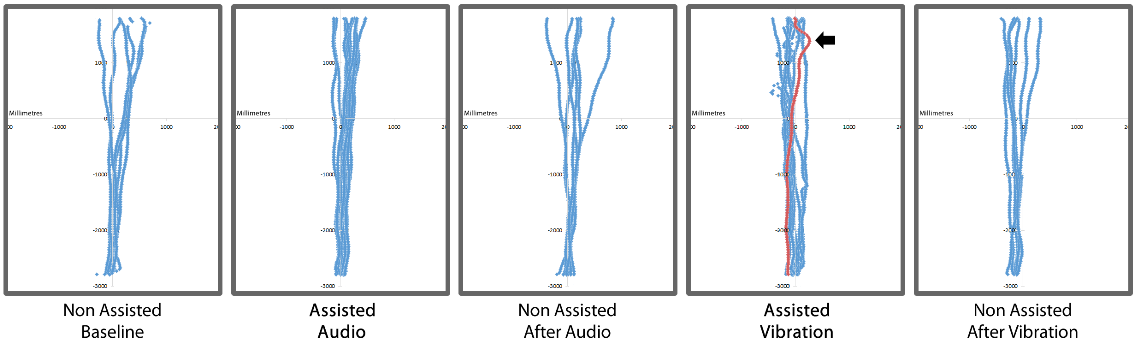
There was a significant difference between the mean deviation (error) for the conditions ($F(4,410) = 15.011$, $p < .001$). There was also an effect of sight on mean deviation ($F(1,410) = 24.727$, $p < .001$). The interaction effect was not significant though ($p = .134$).

Post hoc tests using the Bonferroni correction revealed that both the audio-assisted and the vibration-assisted conditions yielded fewer errors than the non-assisted baseline condition for both blind ($p < .001$) and sighted subjects ($p < .01$). Overall, blind subjects deviated more from the intended path than sighted subjects. The baseline veer of blind subjects was already higher than the baseline veer of sighted subjects ($p < .01$). However, there was no difference between sighted and blind subjects when assisted by audio or vibration ($p = .99$).

The non-assisted sessions after audio and after vibration were also compared to the non-assisted baseline to observe whether there was a learning effect coming from the previous assisted sessions. There was no significant difference between the conditions concerning the mean deviation from the planned path.

Figure 4.23 shows the trajectories of a blind subject across the five experimental conditions. The veering tendency registered in the non-assisted baseline is clearly reduced on the audio and vibration assistance. In addition, it is possible to see the course changes caused by the directional cues received during the session assisted by vibration. These trajectories are representative of both groups of blind and sighted subjects.

Figure 4.23 - Trajectories of a blind subject across the five experimental conditions. The arrow points to a course change induced by the vibrotactile cue



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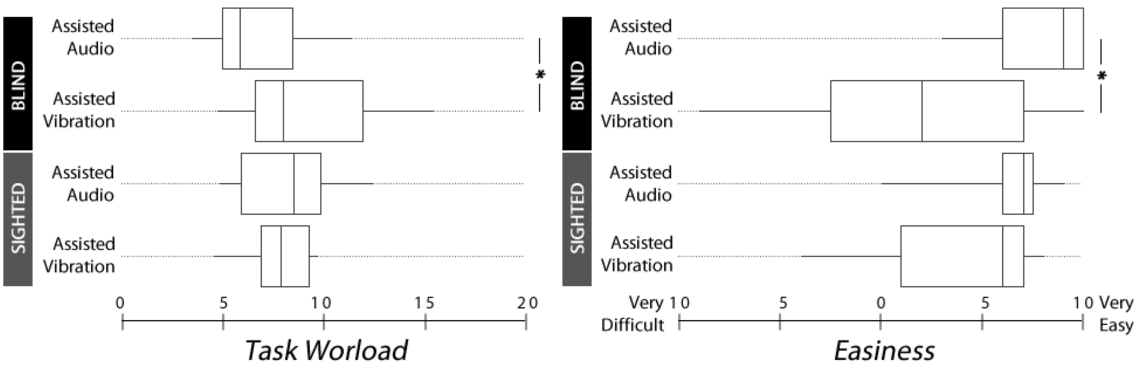
4.3.2.2 Subjective Measures

A Wilcoxon Signed-Ranks Test indicated that the workload for the audio-assisted condition (Mdn = 5.8) was statistically significantly higher than the vibration-assisted (Mdn = 8.0) for blind subjects (Z = 2.3664, p <.009). Audio-assisted (Mdn = 8.5) and vibration-assisted (Mdn = 7.8) did not vary significantly for the sighted subjects though (see Figure 4.24(left)).

In addition, the audio-assisted condition (Mdn = 19) was shown to be easier to perform compared to the vibration-assisted (Mdn = 12) for blind subjects (Z = 1.5724, p = .05). Again, audio-assisted (Mdn = 17) and vibration-assisted (Mdn = 16) did not vary significantly for the sighted subjects (see Figure 4.24(right)).

Figure 4.24 - (left) Scores of NASA-TLX (20-point scale, non-weighted). (right) Easiness across modalities (SEQ with a 20-point scale)



Source: the author.

The anxiety levels did not increase according to the specific use of tactile or audio assistance though. Overall, subjects yielded low scores for the STAI questionnaire. Thus, subjects presented low levels of anxiety during the experiment. Levels of anxiety dropped after the first assisted session, which was lower than the levels reported in the beginning of the experiment (Z = 2.00, p <0.05). The scores kept low throughout the subsequent sessions.

4.3.3 Discussion and Conclusion

We designed and assessed a vibrotactile HMD to be used as an anti-veering device. Subjects performed a straight walking task on a series of non-assisted and assisted sessions. For the assisted sessions, audible walking signals conventionally used in O&M sessions were compared to vibrotactile cues rendered by our device on the subject's head. As hypothesized, results show that the deviation errors were reduced in average 11% from the baseline veering when using the vibrotactile HMD. When it comes to the baseline deviation, subjects could arrive even at 1m far from the target. However, the veering tendency was significantly reduced with vibration for both blind and blindfolded subjects. With the vibration assistance, the deviation was of only 11cm on average.

To attenuate the effect of some basic sources of veering, such as initial orientation and biases in step direction (KALLIE; SCHRATER; LEGGE, 2007), O&M instructors guide blind pedestrians to keep their head, shoulders and feet always aligned during the initial positioning and while walking. A change in the head direction might affect the pedestrians moving direction (GUTH, 2008). Thus, the vibrotactile HMD notifies the pedestrian about changes in the head positioning and how far it deviated from the intended path. Trajectories of the subjects using the vibrotactile HMD show the points in which subjects deviate beyond the threshold (see Figure 4.23). At these points, the vibrotactile feedback is perceived and, then, the subjects can change their routes to recover from veering. Thus, the vibrotactile HMD works by restricting the pedestrian to a virtual corridor. Such corridor might be translated later to a crosswalk, a sidewalk or a platform, for instance.

The main advantage of the vibrotactile device is to be worn and carried around. The vibrotactile actuators might be attached to hats, helmets, or even a headband. Thus, pedestrians may use our device for assistance anytime they need to. Unless the pedestrian is making a turn or engaged in communication with another pedestrian, the stimuli can be activated to support anti-veering support. Since vibration is not attached to a traffic light, as it is with audible walking signals, our stimulation mode can be used in different venues with arbitrary landmarks, possibly chosen by rehabilitation practitioners or by the blind person. Then, for larger distances, landmarks can be fixed to predefined GPS locations and rendered on the user's head, so that a blind person can be trained or even self-train with autonomy.

In addition, by using different environmental sensors (such as GPS, sonars, and cameras), the vibrotactile HMD can also point the position of other pedestrians, vehicles, and different obstacles in the street and sidewalks. Results also show that the vibrotactile feedback can be useful for sighted subjects as well. Sighted subjects can use the vibrotactile guidance in different contexts, such as for display-free navigation, navigating unknown spaces, guidance in dark environments or in the fog, for instance.

We also have hypothesized that a short training session could lead to a better performance in a subsequent session without assistance as reported in the literature (NAGY; WERSÉNYI, 2016). However, such effect was not shown for the non-assisted sessions after audio nor after vibration. The deviation errors did not vary significantly between the non-assisted sessions and the baseline. As pointed by Maclean (MACLEAN; HAYWARD, 2008), subjects have been using audition for the kinds of tasks we test since early childhood, and they've been using the tactile version for a short training period. Thus, as the vibrotactile feedback is an unconventional modality, blind subjects had to be more attentive during the walk which might have increased task workload. Future studies should also consider the use of the vibrotactile HMD across time, which is likely to more firmly set the advantages of vibrational cues. Moreover, since rehabilitation sessions may last years, future studies should also verify how vibrational cues correct veering tendency (with no assistance) after several sessions. Finally, the vibrotactile HMD should also be assessed for guidance in more complex trajectories, including piecewise straight lines (typical in O&M scenarios) or even curved paths.

4.4 Summary

Our approach to develop this Thesis starts with the study and design of an effective and versatile vibrotactile display. To do so, perceptual experiments, as well as performance experiments, were made to support the assessment of different applications and user profiles. The contributions of the studies presented in this chapter include:

- The prospecting of different body sites for tactile communication;
- The assessment of the acuity of the head for vibrotactile stimulation;
- The assessment of different configurations for tactile cueing around the head;
- The design of a vibrotactile headband using the Tactile Fovea technique;
- The demonstration of the practical use of our vibrotactile display in a classical O&M task.

Differently from the vibrotactile belt designed in our previous studies, the vibrotactile headband is designed to support not only navigation, but spatial awareness and attention redirection in both virtual and real spaces. However, the tactile interaction paradigm with this device is still the same of our previous studies, having the tactile signals rendered by the computer and providing only an one-way communication with the user. Therefore, we give continuity to our study assessing a different paradigm for communication, allowing users to intercommunicate using expressive vibrotactile cues.

5 PROACTIVE HAPTICS FOR INTERCOMMUNICATION

With touch, we can communicate different emotions, and enhance the meaning of other forms of verbal and non-verbal communication. However, although interpersonal touch is so present and important in our social interactions, surprisingly little scientific research has been conducted on that topic (GALLACE; SPENCE, 2010). In addition, when it comes to informative tactile interaction, tactile cues are usually rendered reactively by the system as response to the user's passive or active exploration (ZIAT et al., 2012). However, an important part of social interaction is to perceive the others' needs and intentions and *proactively* act on these perceptions. Thus, in virtual environments as in real life, touch should be rendered proactively by the user as well.

Some tactile devices are designed to allow users to express emotions and also to trigger tactile cues for interpersonal communication (SMITH; MACLEAN, 2007; HUISMAN et al., 2016; CHAN; MACLEAN; MCGRENERE, 2008; ISRAR; ZHAO; SCHNEIDER, 2015). However, the interface constraints, when triggering tactile cues or for personalizing tactile signals, may hinder the user's autonomy and control. In a two-way interaction, interlocutors should be able to express their intentions through tactile cues whenever they need or want to.

Therefore, as our utterances are related to our control over our vocal apparatus, we propose that *haptic articulation* be related to our control over haptic parameters. Moreover, the possibility to access different sets of haptic parameters gives the user the ability to articulate the tactons proactively in any manner they want to. In such a way, the tactile intercommunication should be not only proactive but expressive, dynamic and straightforward such as speech articulation. We applied such approach in the design of a vibrotactile display to support intercommunication in a collaborative virtual environment (see Figure 5.1). We hypothesize that the ability to freely render the stimuli will allow users to create their own variations of the vibrotactile language spontaneously, producing a vibrotactile dialect. Such tactile articulation may be the key to construct better vocabularies for tactile intercommunication as it allows the tactile language to be dynamically adapted to different tasks and contexts according to the user's preferences and needs.

The introduction of proactive haptic articulation as an approach to construct dynamic and adaptive vocabularies is the most significant contribution of this study.

5.1 Proactive Haptic Articulation

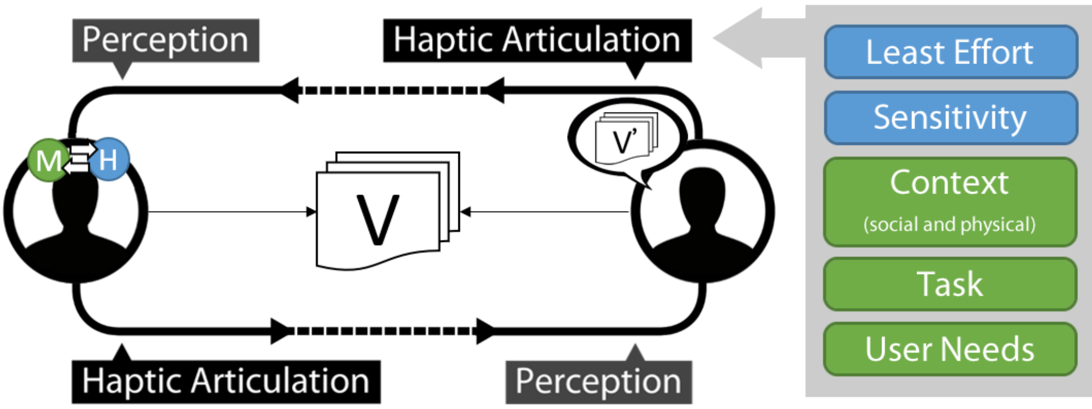
Figure 5.2 shows a schematic model of tactile intercommunication in which a sender acts to produce the stimulus perceived by the receiver. We propose that the smaller the gulf between the nature of the action needed to trigger the tactile signal and the tactile stimuli that encode the message is, the more dynamic and adaptable the tactile vocabulary will be.

Figure 5.1 - The proactive articulation of tactile cues supports intercommunication between teammates. It was meant to increase user's autonomy and provides flexibility to the tactile language

Source: the author.

Thus, as our utterances are related to our control over our vocal apparatus (SAUSSURE, 2006), the haptic articulation must be related to the control the user has over the resources of the haptic device. Such control gives users the power to decide how they render a tactile signal.

Figure 5.2 - The haptic articulation is equivalent to the action that leads to a tactile stimulation. Even though both interlocutors share a given vocabulary (*V*), changes related to haptization and meanings might affect the way the vocabulary is reproduced (*V'*)

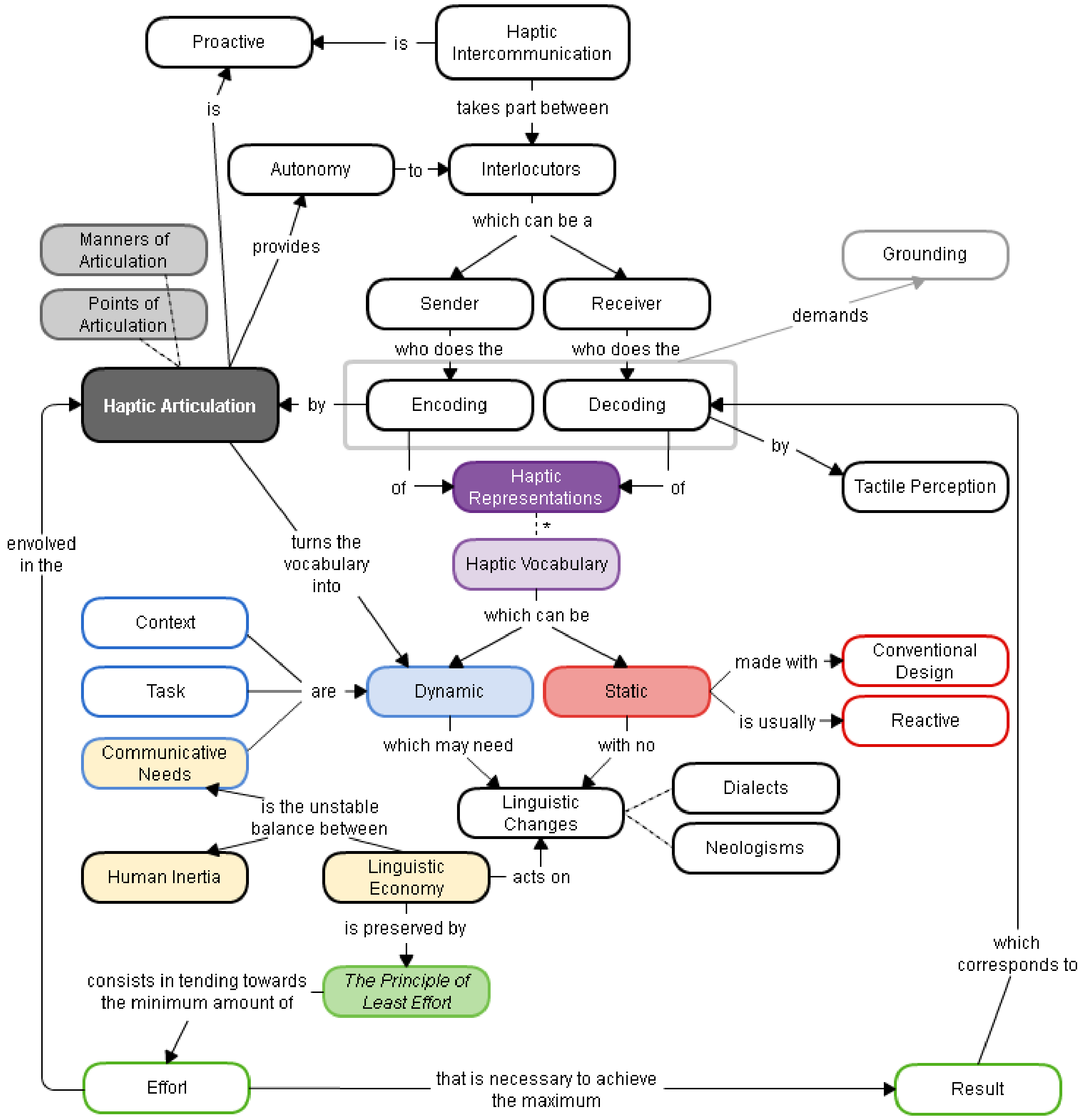


Source: Adapted from Saussure (2006).

Our vocal apparatus limits the number of sounds or phonemes we can articulate. Nonetheless, we can compose infinite utterances. It should be the same for haptic articulation. The capability of the hardware can limit the number of parameters we can use to render the stimuli, but, even so, we could compose unlimited variations of haptic signals. Nonetheless, the utilization of a predefined set of tactile patterns is still necessary. Designers still need to follow methods for syntax construction of tactile vocabularies (SWINDELLS; SMITH; MACLEAN, 2005; RIDDLE; CHAPMAN, 2012; CHAN; MACLEAN; MCGRENERE, 2005). However, with the articulation capability, the standard tactile vocabulary becomes a dynamic tactile vocabulary.

The capability of producing the stimulus in the way you wish, instead of only triggering predefined signs, is the core of the haptic articulation. Users may reproduce those patterns differently by mistake or by will, but that is what turns the vocabulary *dynamic*. Such dynamic vocabulary fits better for intercommunication because human language is naturally dynamic. As pointed out by Vicentini (2003), in such dynamic process as linguistic change, words are constantly being shortened, permuted, eliminated, borrowed and altered in meaning. However, such dynamicity is not out of control; it is constrained by principles of the economy including *need* and *least effort*. A more detailed schematic model for tactile intercommunication underlying its interaction with the principles of the linguistic economy can be seen in Figure 5.3.

Figure 5.3 - Mental map on the haptic intercommunication process showing the role of the haptic articulation and how the "Principle of Least Effort" affects it



Source: the author.

Martinet (1969) says that "the evolution of a language depends on changes in the needs of communication of the group that *uses* it". He also says that "the need to designate new objects or experiences will bring about not only an enlargement of the vocabulary but essentially an increase in the complexity of utterance" (PERKINS, 1992). With the use of the language comes the need for new expressions and the change in pronunciation. With the capability of haptic articulation, new haptic signs can be created according to the needs of the users. If the construction of the sign turns to be too complex for the interlocutors, the sign can be shortened or eliminated maintaining the language understandable.

The linguistic economy can be seen as the unstable balance between the needs of communication and natural human inertia. The freedom to compose different tactile patterns is limited by the possibility of combining the right articulatory movements. Thus, the maintenance of the vocabulary – which is always changing with the user needs – should happen according to the principle of the least effort. Any non-economical change in the language, which would bring about an excessive cost in terms of effort and constitute an obstacle to comprehension, will be automatically removed or avoided (VICENTINI, 2003). Thus, this mechanism should maintain the balance between the complexity of tactile patterns and the way to reproduce them, supporting an ergonomic design.

The haptic intercommunication should also depend on the situation (context). Therefore, the dynamic vocabulary may be adapted according to the task that is being supported by the tactile aid and also by the culture and background knowledge shared by the interlocutors. Moreover, the articulation of haptic signals, such as for speech articulation (LINELL, 2004), should be continuously accompanied and supplemented by other communication means. Whereas the communication happens face-to-face or remotely, users may use gestures, facial expressions, or speech as they use haptics. It should support grounding (CLARK; BRENNAN, 1991) and leads to a mutual agreement on the adoption of new signs.

In the next section, we present a case study with the design of a vibrotactile language and display made for proactive haptic articulation. Such design took into consideration the elements of the haptic articulation mentioned above. The versatility of the vibrotactile vocabulary is demonstrated by its adaptation during a collaborative assembly task.

5.2 Case Study

5.2.1 Materials and Methods

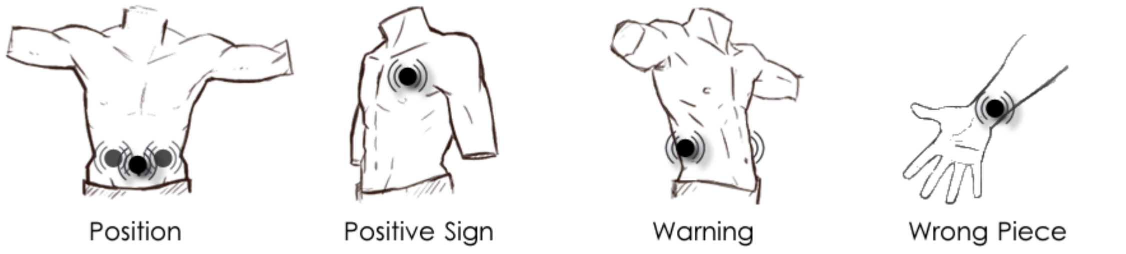
We defined a collaborative task that includes three important characteristics of a collaborative work: equal participation, individual responsibility, and positive interdependence. Users were grouped in pairs and were invited to assemble a puzzle together. Each user should assemble his/her own puzzle on a table placed in front of him/her, using the pieces placed on the table of the other user. Thus, users need to exchange pieces for completing the task, and they do this by asking for the pieces, one by one. The pieces have arbitrary shapes that cannot be identified by a simple name (e.g. triangle, cube, circle). Additionally, there are extra pieces on the table that do not match the template to increase the cognitive load of the task.

Based on this task, we designed an immersive setup, as well as a vibrotactile language and display to support intercommunication between peers during the task execution.

5.2.1.1 Vibrotactile Language

A pilot experiment with real pieces helped us to identify terms that were most adopted by the users during the task. We refined them until we obtained a small vocabulary sufficient for this task (see Figure 5.4). The designed vibrotactile vocabulary conveys four kinds of messages: Position, Warning, Wrong Selection and a Positive Sign. The tactile patterns were designed to be expressive enough to support the given collaborative task, and to be minimally obstructive in the immersive virtual environment. Thus, *simple signs* (single vibrational stimuli at different body sites) were chosen instead of more complex tactons. The body sites were selected based on perception, performance, and metaphors related to each kind of message (SMITH; MACLEAN, 2007).

Figure 5.4 - Vibrotactile vocabulary. The spheres indicate the positions of the motors. The user must touch the motor position on their own body to send the tactile sign to the partner in the same position



Source: the author.

The *Position* of the pieces is given from an egocentric perspective. Thus, three actuators placed on the waist inform that the desired piece is located in front, to the left or to the right side of the user. Then, the information can be rapidly processed as the stimulus is delivered to the body position that faces the informed object. If the subjects make a wrong selection, a vibration delivered directly on their hands can inform that it is the *Wrong Piece*. A vibration on the hand quickly informs that something is wrong with the manipulated object or action, as it adds an iconic factor on the tactile language since the sensation directly evokes the behavior.

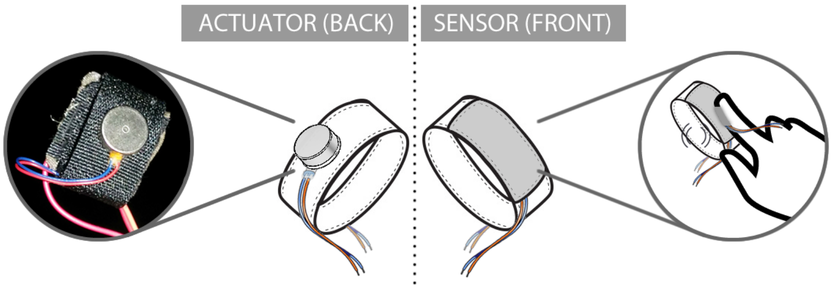
The two remaining signs used to support the task are more arbitrary than the others. The *Positive Sign* is used to deliver an "okay" sign. With it, one can inform that they are ready to interact or that their job is done. A *Warning Sign* gives an alert. It is used to inform things as diverse as that something is wrong or to hurry up. These signs bring expressiveness to the language since a single significant can express different things. Such *polysemy* was intentionally added to the tactile vocabulary because this is a fundamental feature of the human speech, which gives us freedom of thought and expression. In that manner, the tactile vocabulary could be more dynamic and adaptable to the user's needs.

5.2.1.2 Vibrotactile Display

A vibrotactile vest was constructed with *eight* electromechanical tactors. Each vibration motors – 10*mm* shaftless, 3.4*mm* button type (310-101 Precision Microdrives) – was attached to pieces of Velcro to be easily positioned at different body sites (see Figure 5.5).

To activate the actuators, users proactively trigger the tactile patterns. To do so, they must touch on the area of their bodies corresponding to that on their partners where they want to stimulate. We propose that such approach provide an intuitive way to express vibrotactile cues, keeping it simple and straightforward. We then attached pieces of conductive cloth to the back of each motor and at the fingertips of the data gloves. The contact of the conductive fabric works as a button, activating the vibration when the user touches the corresponding position with the index finger (see Figure 5.5). An Arduino Mega board was used to control the actuators and sensors.

Figure 5.5 - Each vibrating motor is attached to a sensor. The user can activate each motor by pressing it with the index fingers



Source: the author.

5.2.1.3 *Haptic Articulation*

If a person *A* wants a piece of the puzzle that is on the left side of his/her partner *B*, *A* can touch on the left side of his/her own waist. That way, *B* receives the tactile signal at the indicated position and looks for the piece on the left side of the table. Then, *B* moves his/her right hand to grab the piece placed on the left. If *A* realizes that *B* is about to do a wrong selection, *A* can send a message to *B* by touching his/her own right hand. *B* understands the signal and selects the correct piece. *A* can send a positive sign to *B* by touching the motor on the chest and proceed with the task.

All vibrotactile signals are rendered with the same amplitude and frequency. However, since the signals are proactively produced, their occurrence and time of activation depend on the user. That gives more autonomy to the users to produce different tactile patterns. Another advantage of using their bodies as the interface to trigger the vibrational signals is that users have a proprioceptive feedback when they touch themselves. Moreover, to make sure users are aware of the stimuli they produce on their team partners, they also receive a vibrating feedback. Thus, every time a person *A* touches one of those predefined positions, the same site is stimulated in both *A* and *B*. Therefore, the vibrotactile communication channel implements a binary semaphore for concurrency control.

5.2.1.4 *Collaborative Virtual Environment*

To provide visibility and copresence, users are positioned in front of a Kinect camera, wearing a Sensics zSight HMD and a pair of 5DT Data Gloves. Thus, they should be able to use natural movements of arms and head to grasp and handle the virtual pieces, as well as to look around and interact with their partners. Users could see each other's avatars in the virtual environment and also hear each other's voices through a microphone/headphone set, for audibility (see Figure 5.6).

Although the defined task could be performed in a real environment, the virtual environment allows us to implement an interaction protocol that can be extended to different scenarios and contexts. For instance, since the users have fixed positions and do not touch each other, partners could be farther apart exchanging pieces through a conveyor belt or rope, or even remotely exchanging digital information.

5.2.1.5 *Experimental Protocol*

After an interactive tutorial, each subject was exposed to a **familiarization phase**. Such phase also provided an assessment of the vocabulary effectiveness. Users started

Figure 5.6 - (right) Users wearing the tactile display, data gloves, and the HMD to perform the puzzle assembly. (left) Shared virtual environment

Source: the author.

by performing a task that assesses their *perception* of the vibrating stimuli. In that task, a set of 16 tactile patterns was rendered randomly for each subject. The subject should reach the position of the motor while it was activated and touch it with the finger as fast as they could. Then, they performed another task to both assess and practice their *interpretation* of the predefined vibrotactile vocabulary. For each activated motor, the user should mark its meaning on an interactive GUI. Users also trained how to *express* sentences by activating the motors on their own. They had to translate a set of written phrases to tactile expressions. Thus, every user trained the roles of speaker and listener of the proposed vocabulary.

Then, the users were invited to perform the **assembly task**. Before the task starts, each user is positioned in front of a Kinect, had their data gloves and HMD calibrated, for counterbalancing the pairs. By increasing or decreasing noise during the task, we alternated between discouraging and encouraging the use of verbal communication. Moreover, the 6-piece puzzle templates were varied throughout the levels. Although the pieces were the same, templates with different compositions were displayed randomly for different teams. At the end of the experiment, each user filled a form to provide their subjective opinions on the collaborative task. The whole procedure took from 40 to 60 minutes.

A population of 30 individuals has volunteered to participate in the tests (15 pairs); twenty-six are male and four females. The participants are computer science students, covering an age range of 19 - 39 years. Testing was done in a dedicated room where remained only the volunteers and two evaluators to avoid distractions.

5.2.2 Results

5.2.2.1 Vocabulary Assessment

In the **perception trial** a set of 16 tactile patterns was rendered randomly for each subject. The subjects should reach the position of the motor while it was activated and touch it with the finger as fast as they could. Only four trials were mismarked, which means 0.83% of 480 trials. A one-way ANOVA test shows that there is a significant effect of motor position on response time ($F(7,269) = 3.93$, $p < 0.01$). It takes longer to touch the motors on the ribs, with mean time of 4s ($\sigma = 1$s), while it is 3s for the other body locations ($\sigma \leq 1$s). In the **interpretation trial**, for each activated motor, the user should mark its meaning on an interactive GUI. The confusion matrix (see Table 5.1) shows the results of this task. Even with an avatar on the GUI to provide a reference and guide the comprehension of left and right sides, there were confusions related to the position of the vibrating signal. The same confusion did not appear in the CVE since the side-by-side positioning benefited the collaborative task.

Table 5.1 Confusion matrix for the signs interpretation.

	Response (%)								
Info	"PR"	"PF"	"PL"	"BR"	"BL"	"PS"	"WR"	"DK"	NA
Piece (right)	**75.00**	0.00	2.78	5.56	0.00	0.00	5.56	0.00	11.11
Piece (front)	0.00	**88.89**	0.00	0.00	0.00	0.00	2.78	0.00	8.33
Piece (left)	0.00	0.00	**88.89**	0.00	5.56	0.00	5.56	0.00	0.00
Bad selection (right)	4.17	0.00	0.00	**87.50**	5.56	0.00	1.39	0.00	1.39
Bad selection (left)	0.00	0.00	5.56	5.56	**72.22**	0.00	11.11	0.00	5.56
Positive	0.00	0.00	0.00	0.00	0.00	**81.94**	6.94	1.39	9.72
Warning	4.17	0.00	6.94	5.56	1.39	0.00	**72.22**	8.33	1.39

* PR: Piece on the right; PF: Piece on the front; PL: Piece on the left;
BR: Bad selection on right; BL: Bad selection on left; PS: Positive signal;
WR: Warning signal; DK: Don't Know; NA: No Answer.

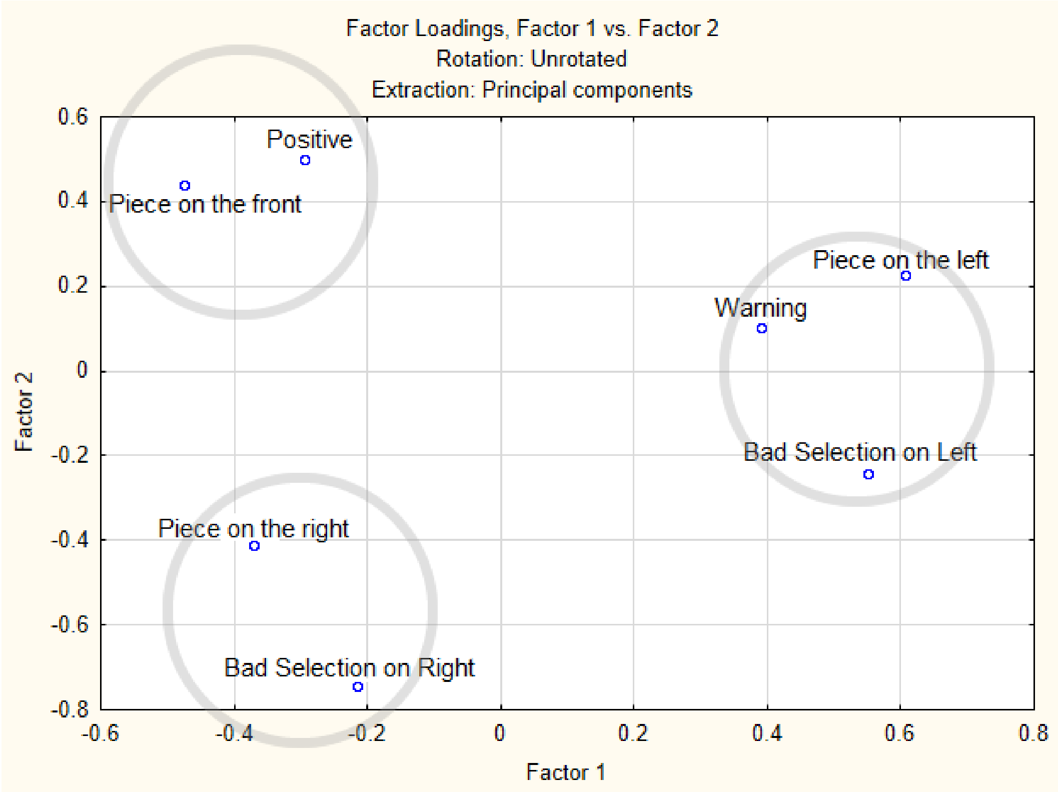
The same happened to the interpretation of the *Warning* signal. *Warning* could be activated by touching on the ribs on any side (on the left or on the right side). Thus, it presented some confusion during the training. A factor analysis, using the results of the interpretation task as input, clustered the patterns according to the position of the motors. Notice that *Warning* is close to the *Piece on the Left* (see Figure 5.7). That happened because in several occurrences of *Warning* on the left side it was marked as *Piece on the Left*. The term "Warning" also had some ambiguity with "Wrong selection". Although all those confusions with the term "Warning" in the training phase, the same confusion did not appear during the remaining phases of the study.

To complete the familiarization phase, the participants performed an **expression trial**. In each trial, we presented a sentence which they should express through vibration. Some of the sentences directly evoke the sign as it was learned with the interactive tutorial. For instance, *The piece is on your left side* which is expressed by pressing the left motor on the navel. However, there were also a few sentences that were more arbitrary, such as *Hurry! Hurry!* which we expected to be expressed with the Warning. So, in that trial, the users became familiarized with the polysemic nature of those signals. The users took a mean of 3s (σ = 1s) in the translation of each sentence, which is close to the answer time on the perception task. There, it took a mean of 3s (σ <1s) from the moment a motor was activated to reach the position and touch it. So, the translation took almost the same time of reaching a given position, which evidences the easiness to express the vocabulary with the proposed design.

5.2.2.2 Assembly Task

There were no instructions about the tactile intercommunication being mandatory during the task. When the first level of the assembly task started, pairs came up with their own strategies and some of them even chose to drop the use of the tactile display. We then classified the users into two groups according to an exploratory cluster analysis on their use of the tactile feedback during the task: 18 subjects who preferred to talk to each other mostly rather than using the tactile cues (Group A); and 12 others who mostly used the tactile vocabulary to conclude the task (Group B). Taking the mean of tactile cues triggered by each pair, Group A emitted around 13 tactile signals (σ = 3.41) during the whole

Figure 5.7 - Factor analysis of the results of the tactile vocabulary interpretation. The term descriptions (piece position and hand of manipulation) are far away showing a great conceptual distinction. The signs ended by being grouped according the side (front, left and right), revealing some instability of the “Warning” term



Source: the author.

task while teams of Group B emitted a mean of 284 signals (σ = 82.30). That means a tactile signal every 37s (σ = 11.79s) for group A and a tactile signal every 4s (σ = 1.28s) for group B. One-way ANOVA showed no significant effect of audio conditions on the use of the tactile display during the task. The groups did not have significant differences concerning the number of errors during the assembly nor the time to accomplish the task. Group B, the one that privileged tactile communication, spent a mean of 683s to perform the task; 14s less than Group A.

The breakthrough occurred when some pairs *adapted* the predefined tactile vocabulary to attend their needs. Four different teams mentioned, after the task, that they used patterns different from those learned in the tutorial. One of them used predefined signs to convey different meanings. They dropped the use of the warning sign and used the motors on the ribs to convey *far-left* and *far-right* signs. Another pair even defined compositions of signs to mean new things, e.g. touching the *piece on the left* sensor twice to mean *far-left*. Such adaptation was made only by pairs that exclusively used vibration for communication. Therefore, it is not related to a lower performance in expressing the tactile patterns, but to the design of the vocabulary and display. The way the sign can be triggered on the tactile interface gives autonomy to the user. Such design can be scaled to different applications, and the way that tactile vocabularies can be produced and expanded proactively should be a major step for tactile intercommunication systems.

5.2.3 Discussion and Conclusion

Although the use of vibrational cues is unusual in intercommunication, results showed that the performance of subjects that used it predominantly was not significantly affected. Also, a case study has shown that some of them indeed adapted the proposed vocabulary by doing syntactic and semantic neologisms. Even if we consider the possibility that some subjects might have used the tactile communication only because it was trained for the task, the verified adaptation of the vibrotactile vocabulary ratifies our assumptions and opens new possibilities for experimentation.

Our contribution does not concern novel technology for actuation or a new method for construction of tactile patterns for communication, but a novel approach to designing adaptive tactile intercommunication based on the concept of articulation. Thus, dynamic adaptation of the tactile vocabulary became possible due the ability to pronounce tactile signs proactively. We expect that our design approach improves media richness as it permits the tactile language to be adapted to different tasks and contexts because it changes as it is used.

We proceeded with a series of new user studies in virtual environments to validate the factors we judge to be related to the dynamicity of the tactile articulation. Our aim in this study was at investigating if the changes in performance would become significantly higher for other tasks in collaborative virtual environments and scenarios. Our first step was to design a vibrotactile HMD for interaction with virtual environments, applying the knowledge from the first phase (Chapter 4). Then, implementing and assessing articulatory interfaces and methods in this new vibrotactile HMD.

6 TACTILE INTERACTION IN IMMERSIVE VR

In this final phase of our Thesis development, we applied the results presented at Chapter 4 and Chapter 5 to the design and assessment of a vibrotactile HMD for interaction with virtual environments.

In the remainder of this chapter, in Section 6.1 we present the design and assessment of a vibrotactile HMD made to render the position of objects in a 3D space (i.e. encoding both azimuth and elevation). In Section 6.2, we present the design and assessment of a articulatory interface embedded to the vibrotactile HMD to support tactile intercommunication in immersive virtual environments. Finally, in Section 6.3, we assessed different approaches for tactile articulation to understand the trade-off between freedom of articulation and mutual understanding.

6.1 Vibrotactile HMD for Spatial Awareness in 3D Spaces

Visual cues can be embedded in VR headsets to reorient the user to events and objects in the surrounding virtual world. Commonly, centrally positioned arrow cues, and peripheral onset cues (such as an object appearing in the user's peripheral vision or an existing object changing its color on the display) are used for reorientation. However, as it is pointed by Ward et al. (WARD et al., 2016), peripheral onset cues are unusable in some cases. For instance, when targets are positioned outside the person's peripheral vision. Moreover, even if the use of arrow cues are the second best visual cueing option for reorientation (WARD et al., 2016), it implies to have a visual clutter constantly on. In a quest for an alternative for reorientation, vibrotactile displays outperform the auditory cueing (KAUL; ROHS, 2016).

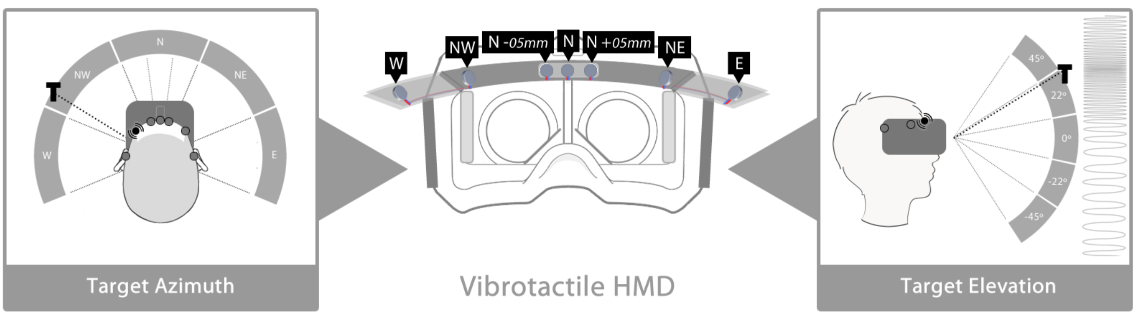
A vibrotactile display can be made with tactors pointing to different places around a person. It allows the vibrotactile display to provide a wide field of touch, compensating the lack of a wide visual field (ERP, 2001). Then, vibrotactile cues can be used to reorient a person's attention. Visual and auditory stimuli have to be presented in close spatial proximity to produce performance benefits (GRAY; TAN; YOUNG, 2002; SMITH et al., 2001), but proximal haptic signals can effectively reorient attention to areas in distal space (JONES; SARTER, 2008; GRAY; TAN; YOUNG, 2002). Moreover, the use of tactile cues helps to reduce the visual clutter that can be a hindrance to performance in many human-machine interfaces (GRAY; TAN; YOUNG, 2002).

Different designs for vibrotactile displays mounted on the head are becoming more and more common (BERNING et al., 2015; DOBRZYNSKI et al., 2012; KERDEGARI; KIM; PRESCOTT, 2015; NUKARINEN et al., 2015). However, vibrotactile HMDs are still not a fundamental part of virtual and augmented reality headsets. Yet, a vibrotactile HMD made as a VR/AR headset would have the potential to provide multisensory interaction with virtual 3D spaces with the benefit of being a single wearable item. The design of such non-conventional system, however, is not trivial. It must take into account factors related to its usability, and most importantly, to perception and processing of vibrotactile cues around the head.

Previous studies have shown that, opposite to the scalp, the forehead, the occipital, and the temple regions of the head are the most sensitive to vibration (MYLES; KALB, 2010). Therefore, studies exploring vibrotactile localization around the head recommend the use of tactile displays with low actuator density, composed by four or five tactors (DOBRZYNSKI et al., 2012). In our previous study, we showed that even with a low actuator density, it is possible to precisely indicate the position of objects around a person in the azimuthal plane (JESUS OLIVEIRA et al., 2016b). However, *elevation* is also an elementary dimension in 3D spaces. Even though elevation can be encoded by adding more tactors to the displays (for instance, in tactile belts), the same should not be done for the head. Indeed, while the height of a vibrotactile belt on the abdomen has no significant effect on the perception of vibrations (CHOLEWIAK; BRILL; SCHWAB, 2004), the skin on the head is less sensitive to vibrations as it goes up to frontal and central regions of the scalp (MYLES; KALB, 2010).

Our idea in this work is to keep the density of the tactile array low and to encode the information about the elevation of the target with variable frequency (see Figure 6.1). Thus, the elevation cue is given on the azimuthal plane, but the low/high frequencies are associated to the low/high elevations. A previous work has shown that frequency can be manipulated to encode additional information on vibrotactile cues (BREWSTER; BROWN, 2004). However, the responses of the mechanoreceptors in the skin to the vibrotactile stimulus depend on how it is implemented (JONES; SARTER, 2008). A perceptual assessment is a fundamental part in the design of a stimulus set and it must be accounted for in such interface (CHAN; MACLEAN; MCGRENERE, 2008).

Figure 6.1 - Vibrotactile HMD. The position of the target in the azimuthal plane is informed by the tactor position in the vibrotactile HMD, while the target elevation is informed by frequency modulation



Source: the author.

In this study, we present a perceptual assessment of different frequency modulation functions to define a growth function that can be used to indicate target elevation. Then, a tactile guidance technique is assessed for spatial awareness in 3D spaces, being the main contribution of this study. Accuracy, precision, reaction times and the system usability were assessed while the subjects performed an active head pointing task on three different scenarios. Moreover, in terms of design, we also contribute to the adaptation of a conventional vibrotactile display by applying variable frequency in such way that a person can simultaneously receive information about the position of an object in the azimuthal plane, and its elevation.

6.1.1 Experiment I: Perceptual Assessment

We modulated the stimulus frequency to convey information about target elevation. Thus, the frequency of the vibrating motor is modulated according to the head pitch orientation in an active pointing task. The maximum frequency indicates the current elevation of the target. As the subject pitches his head far up or far down from the target, the frequency is reduced allowing the subject to perform relative comparisons (as in a "warm-cold" metaphor).

We assessed three different growth functions to choose the one that provides the best target detection. Accuracy, precision, reaction times during an active pointing task were assessed as a function of the three modulating modalities. Targets were placed systematically in five different elevation angles (45°, 22.5°, 0°, -22.5°, -45°), following a similar approach to that for testing targets in the azimuthal plane (JESUS OLIVEIRA et al., 2016b). We also assessed subjective measures, such as the task workload and easiness as dependent variables.

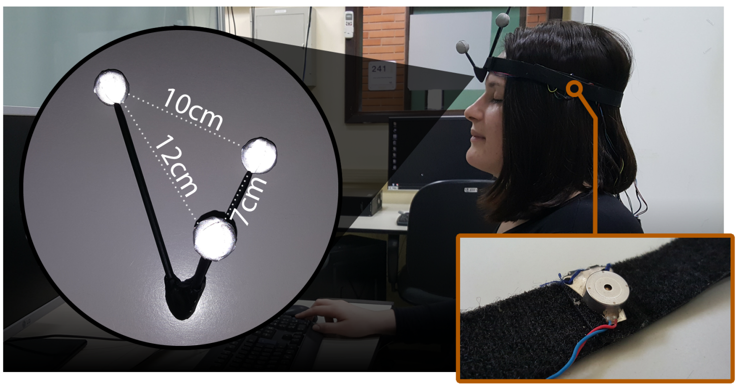
Hereinafter, we describe the setup design, results and a discussion about this first perceptual experiment.

6.1.1.1 Materials and Methods

6.1.1.1.1 Apparatus

We built a vibrotactile headband with electromechanical tactors (10*mm* Linear Resonant Actuator, 4*mm* type - C10-100 Precision Microdrives). The tactors were controlled with an Arduino Mega ADK board and Adafruit DRV2605L haptic controllers. The headband was built with Velcro to be easily worn around the head (see Figure 6.2). Only a central tactor (to be positioned on the forehead) was used for the pointing task. Variable frequency was reproduced by PWM modulation.

Figure 6.2 - User with the vibrotactile headband. The head pitch movement was acquired using an optical tracking system



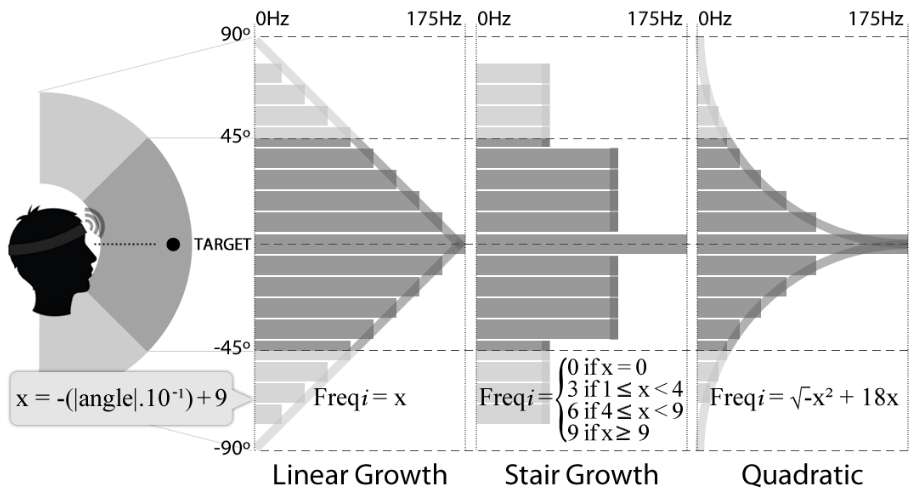
Source: the author.

Besides the headband, the head pitch movement was continuously acquired using an Optical Stereo Tracking System (BraTrack) (PINTO et al., 2008). Thus, three reflective spherical markers of 12.5*mm* each composed an artifact, weighing 25*g*, that was attached to the vibrotactile array (see Figure 6.2). The position of the artifact was acquired in real-time and its orientation represented the orientation of the head. As the typical rise time for the actuator is of $63ms$, the overall latency accounting the optical tracking system can get around $80ms$.

6.1.1.1.2 Stimuli

We varied between frequency levels up to $175Hz$. The maximum frequency indicates that the subject is facing the target in its actual elevation. As the subject pitches his head far from the target, the frequency is reduced following a given modulating function. The modulating functions were selected going from a more continuous variation (Linear Growth), passing by a more discrete one (Stair Growth), until a steep frequency variation (Quadratic Growth), as shown in Figre 6.3. In the three assessed modalities, the subject could still obtain information at the lower levels of frequency, indicating that the head is not aligned with the target. Thus, higher degree functions, such as an exponential growth, were not included as they would behave more like an on-off modality. The shape of the modulating functions is always the same no matter the target elevation.

Figure 6.3 - Frequencies varied stairwise between nine frequency levels, going from $0Hz$ up to $175Hz$. The frequency levels were modulated according to three modulating functions



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Due to the human perception to frequency variations, we hypothesized that the Linear Growth would yield the worst performance scores. Moreover, we hypothesized that the Quadratic Growth ease the detection of the target elevation, but that it may be less informative than the Stair Growth since the first presents an abrupt variation.

6.1.1.1.3 Experimental Protocol

Each subject filled out a demographic questionnaire before starting the experiment. While wearing the headband, each subject had to perform a naïve and blind search task looking for virtual targets on the elevation plane. Each target was virtually placed at a fixed elevation angle related to the subject. At the beginning of each trial, marked by a beep, the central tactor (centered on the forehead) started vibrating in a certain frequency according to the target position. The frequency of the vibrating signal was dynamically updated in function of head motion. Subjects were asked to turn their faces towards the virtual target in a pitch movement until they could feel that the vibration reached its highest frequency. They were requested to be precise. When they were confident enough to be pointing to the correct direction, they had to press a button to register their answer.

Subjects performed the task seated on a non-swivel chair. No visual information of any kind was provided. They kept their eyes closed for better concentration. They also wore earphones to hear the beep that marked the start of each trial, and a pink noise to attenuate the humming noise of the tactors. They were allowed to ask for a break at any time. Accuracy was calculated based on the detection of the correct position of each virtual target. Reaction times were calculated from the beep onset to the moment the answer button was pressed. Precision values corresponded to the angle between the head orientation and the target direction vectors.

The target position was repeated ten times for each angle (45°, 22.5°, 0°, -22.5°, and -45°) and each subject performed three sessions, 150 trials overall. The position of each virtual target within the set of possible angles was displayed randomly across each session. Each session concerned to one modality of frequency modulation. The sessions were counterbalanced with a 3x3 Latin Square. Between sessions, the subject also had to fill out a SEQ (SAURO; DUMAS, 2009) and a NASA-TLX questionnaire (HART, 2006) to self-judge their task load. The NASA TLX is a two-part evaluation procedure. First, the subject has to evaluate the contribution of each of six factors to the workload of the task, then rate the magnitude of the load on each factor. The process was repeated for each modality of frequency modulation. The whole experiment took on average 50 minutes.

6.1.1.1.4 Subjects

Fifteen naïve subjects participated voluntarily in the study (13 males and 2 females). All subjects read and agreed with an Informed Consent Form before the experiment. Their ages ranged from 24 to 33 years (M = 26, SD = 2.6). Two subjects reported having a slight degree of hearing loss. One subject also reported having occasional Labyrinthitis crises. In all these cases, these individual differences did not affect their performance during the experiment.

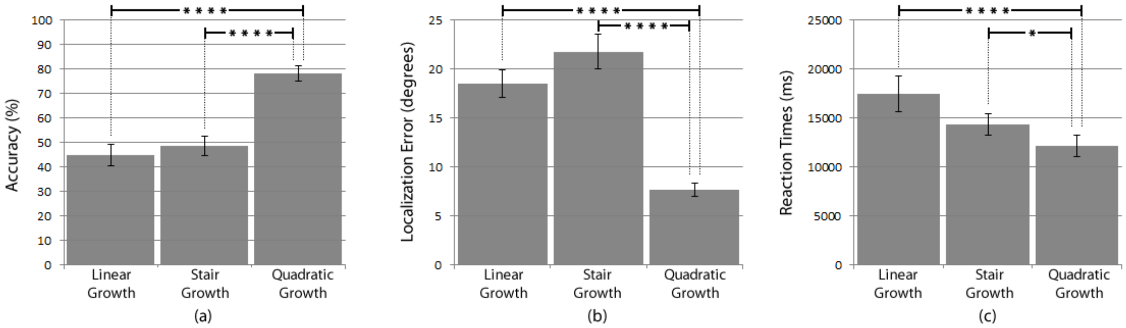
6.1.1.2 Results

6.1.1.2.1 Modalities of Frequency Modulation

Figure 6.4 shows a summary of the results across modalities. The effect of the three assessed modalities on scores, precision and reaction times was evaluated by non-parametric Friedman analyses when distributions were not Gaussian (according to Shapiro-Wilks test). There was a statistically significant difference between the accuracy in target detection across the three assessed modalities (Fr(2) = 57.17, p <0.0001). A post-hoc Wilcoxon analysis shows that the accuracy on detecting target elevation with the Quadratic Growth function was significantly higher than both Linear (Z = 6.60, p <0.0001) and Stair (Z = 58.30, p <0.0001) growth functions (see Figure 6.4(a)).

The modalities for frequency modulation also present a significant effect on precision (Fr(2) = 74.43, p <0.0001). The Quadratic Growth function yields a higher precision (less degrees in detection error) compared to both Linear (Z = 72.13, p <0.0001) and Stair (Z = 66.43, p <0.0001) functions (see Figure 6.4(b)). Figure 6.4(c) shows that the same happens to reaction times which differed significantly across modalities (Fr(2) = 15.39, p = 0.0005). The Quadratic Growth demanded much less time for target selection compared to the Linear (Z = 39.66, p <0.0001) and the Stair (Z = 22.13, p = 0.0269) conditions.

Figure 6.4 - (a) Accuracy for the Quadratic function (M = 78.1, SD = 27.2) was significantly higher than for the Linear (M = 45.1, SD = 38.0) and Stair (M = 48.7, SD = 33.3) functions. (b) Error on localization were significantly lower for the Quadratic function (M = 7.7°, SD = 5.6) compared to the Linear (M = 18.5°, SD = 12.5) and Stair (M = 21.8°, SD = 15.5) cases. Finally, (c) Reaction Times for the Quadratic function (M = 12186ms, SD = 9375) was also lower than for the Linear (M = 17460ms, SD = 15885) and Stair (M = 14337ms, SD = 9521) conditions



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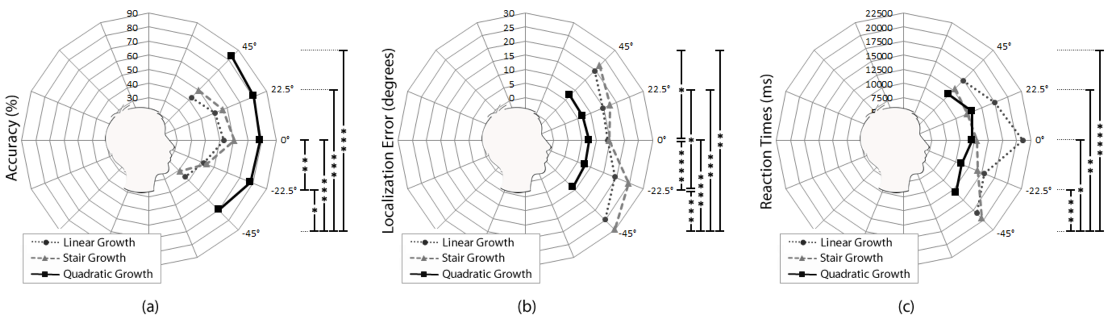
6.1.1.2.2 Target Positions

There was a significant effect of target position on the selection accuracy (Fr(4) = 15.59, p = 0.0036). Overall, targets placed down to -45° yielded lower scores than the higher angles, namely 45° (Z = 34.87, p = 0.0005), 22.5° (Z = 34.57, p = 0.0005), 0° (Z = 34.69, p = 0.0005), and -22.5° (Z = 20.28, p = 0.0425). Targets placed at 0°, in front of the user, yielded more accurate results not only compared to the -45°, but also compared to the -22.5° (Z = 30.39, p = 0.0024) (see Figure 6.5(a)).

Figure 6.5 - (a) Targets placed bellow 0° were selected with less accuracy than the upper positions. (b) Targets placed bellow 0° were also selected with more error than the upper positions while targets on 0° yielded much less precision error. (c) Targets placed down to -45° needed much more time for selection compared to upper positions



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As shown in Figure 6.5(b), target position has a even higher effect on precision (Fr(4) = 25.72, p <0.0001). Targets placed down to -45° yielded more errors than 45° (Z = 30.87, p = 0.0020), 22.5° (Z = 33.24, p = 0.0009), 0° (Z = 39.79, p <0.0001), and -22.5° (Z = 25.45, p = 0.0109). The same happened for targets placed at -22.5° which yielded more errors than 22.5° (Z = 24.66, p = 0.0137) and 0° (Z = 39.90, p <0.0001). Targets placed at

0° still obtained the best results for precision, with much less errors than other positions, such as, for example, the 45° (Z = 21.84, p = 0.0290).

Finally, target position also presented an effect on reaction times (Fr(4) = 24.76, p <0.0001) (see Figure 6.5(c)). Again, targets placed down to -45° needed much more time to be selected compared to 45° (Z = 42.05, p <0.0001), 22.5° (Z = 31.44, p = 0.0017), 0° (Z = 2.14, p = 0.0324), and -22.5° (Z = 37.64, p = 0.0002).

6.1.1.2.3 Workload and Easiness

Figure 6.6 - (left) Weighted NASA TLX scores for each factor and workload for Linear (M = 61.37, SD = 16.2), Stair (M = 62.35, SD = 14.3), and Quadratic (M = 55.55, SD = 16.7) functions. (right) SEQ scores for Linear (M = 3.66, SD = 1.5), Stair (M = 3.33, SD = 1.4) and Quadratic (M = 4.2, SD = 1.4) conditions

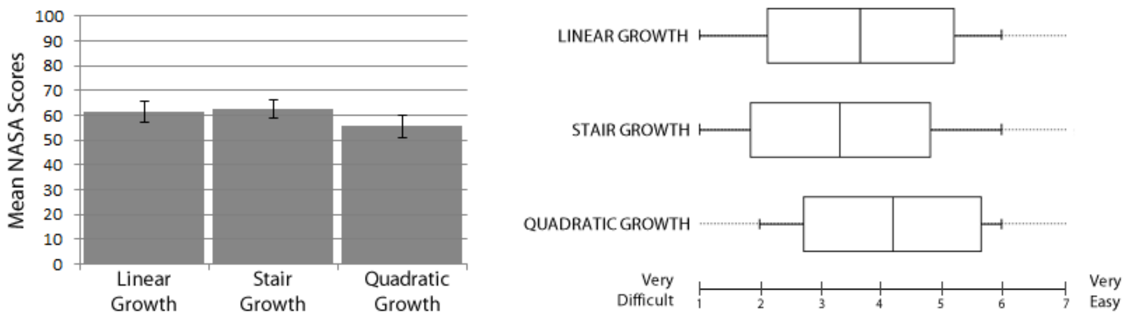

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Figure 6.6 (left) shows the result of the NASA TLX for each tested condition. The Quadratic Growth modality yielded lower means for different factors and for the general workload. However, the differences between conditions were not significant. A significant effect of modality was found on *mental demand* though (Fr(2) = 103, p = 0.0058). Again, the Quadratic Growth function supported the selection of targets with much less mental demand than both Linear (Z = 24.17, p = 0.0157) and Stair (Z = 24.32, p = 0.0150) modalities. The same tendency can be seen in the SEQ scores which show that the Quadratic function supports the target selection with more easiness than the remaining conditions (see Figure 6.6 (right)).

6.1.1.3 Discussion

6.1.1.3.1 Frequency Modulation

After testing three different functions for frequency modulation, a Quadratic function was shown to support a more accurate, precise and fast selection of targets. The more steep variation of the growth function of that modality allowed the subjects to better detect the position of the virtual objects. The Quadratic function also presented less mental demand than both Linear and Stair conditions, which tended to reduce the mean workload of the task.

It was expected for the Linear condition to present less perceptually distinct levels, but also the Stair condition presented some difficulty to be performed. As the Stair condition had less variable levels, the frequency dwells more on each level while the subject moves the head. That slow variation affected the subject's performance and experience.

6.1.1.3.2 Target Position

Overall, targets placed on -45° were selected with less accuracy and precision. In addition, it took much more time to select targets on that same position. In fact, to move the head down this far for some subjects was physically demanding. Moreover, some subjects did seem to focus more on the upper region before even trying to look down for the targets. While it is possible to display information about the elevation of the targets all around the user, due to the physical limitation, we can focus on the upper region. Thus, we can convey the information about the position of higher targets with more precision and accuracy, but lower targets should be placed as far as -22.5°.

The shape of the modulating functions does not change regardless of the target positions. Thus, a less discrete distribution of targets in the tested configuration is not expected to produce different results. However, having a less discrete distribution of the targets could affect the results when the set of frequency levels is also less discrete. In that case, an assessment of the Just-noticeable Difference (JND) would be necessary to understand what should be the minimum distance between the targets. An assessment of the JND could also provide more information about the maximum range that can be covered in front of the subject.

6.1.1.3.3 Task Workload

The general workload did not present significant difference between conditions besides the mental demand factor. Overall, the task consisted mostly of relative comparisons between different frequency levels. Therefore, the experiment took twice the time of a head pointing task using only the body loci as parameter (JESUS OLIVEIRA et al., 2016b). Moreover, to perform the task by following the variable stimulus of one single tactor also made it more difficult due to the rapid adaptation of the skin to vibration. By applying the modulating frequency on a vibrotactile HMD with more tactors, it is expected for the task to become easier to perform. When other tactors are activated, the stimuli are not concentrated on the forehead, reducing the effect of adaptation.

In the next section, we present the design of a vibrotactile VR headset that uses both tactor position and frequency modulation to convey the position of objects in a 3D space. After presenting its design and assessment, we present and discuss the results and its applications.

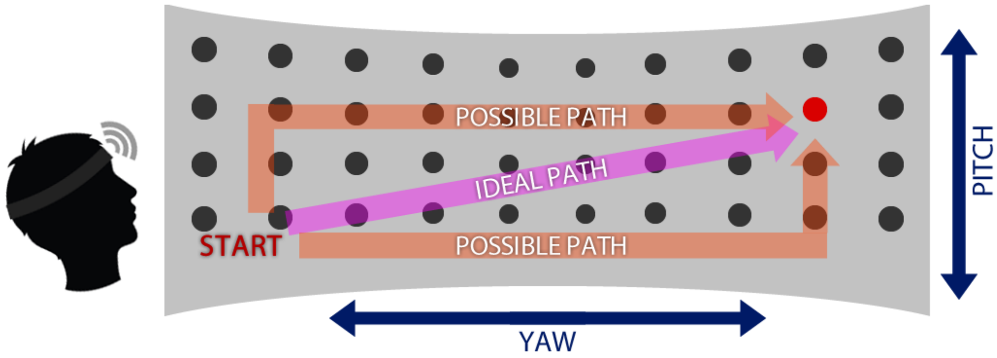
6.1.2 Experiment II: Vibrotactile HMD

Two vibration parameters were used to convey information about the position of a target in a 3D virtual space. The position of the target in the azimuthal plane was informed by the tactor position in the vibrotactile HMD, while the target elevation was given by frequency modulation. Based on the previous experiment, the frequency modulation followed the quadratic growth function.

To understand whether and how a subject will be able to combine the two parameters to estimate the actual position of the target, we performed a second active search task (see Figure 6.7). This time, the possible targets were displayed in a grid in front and around the subject, but the position of the target was conveyed only by vibrotactile cues.

Accuracy, precision, and reactions times were assessed across sessions. Each session corresponded to a scenario and possible application for the tactile HMD. Three scenarios were used to assess possible learning effects. In each scenario, 40 points were distributed in four elevation angles (45°, 22.5°, 0°, and -22.5°) and ten columns along 202.5° in front of the subject. In each one of them, the distance between the selectable objects, their colliders, and the interaction mechanisms were the same. However, the visual part of each scene was changed to assess the effect of conflicting visual cues on tactile perception. Finally, we also assessed the easiness of task and the usability of the system as dependent variables.

Figure 6.7 - The possible targets were displayed in a grid in front and around the subject to understand whereas a subject would be able to combine the two parameters to get the actual position of the target



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6.1.2.1 Materials and Methods

6.1.2.1.1 Apparatus

We built a vibrotactile headband with seven electromechanical tactors. The tactors are controlled with an Arduino Mega ADK board and seven Adafruit DRV2605L haptic controllers (see Figure 6.8). Each tactor - 10*mm* Linear Resonant Actuator, 4*mm* type (C10-100 Precision Microdrives) - was attached to a piece of Velcro to be easily worn around the head. Five tactors were placed at equal distance from the center of the forehead over the Cardinal (West, North, and East) and Collateral points (NW and NE). The remaining two tactors were set 5*mm* apart from the central tactor to provide additional resolution around the sagittal plane. That configuration has been tested in a previous experiment.

This time, the headband was combined with an Oculus Rift Development Kit 2 (DK2) (see Figure 6.8). Both, pitch and yaw movements of the head were then acquired by the Oculus Rift and used for updating the vibration parameters in the headband.

6.1.2.1.2 Experimental Protocol

Each subject filled out a demographic questionnaire before starting the experiment. While wearing the vibrotactile headband and the Oculus Rift, each subject had to perform a naïve search task identifying 15 virtual targets, which means 45 for the three sessions (see Figure 6.9). The position of each virtual target within the set of possible angles was displayed randomly across each session. The subjects could start the session when they felt comfortable to do so. They were also allowed to ask for a break at any time.

In the beginning of each trial, the tactor facing the target position started vibrating indicating its position. The activated tactor vibrates in a frequency respective to the target elevation. Subjects were asked to turn their faces towards the virtual target until they

Figure 6.8 - VR vibrotactile HMD. Both tactor position and frequency modulation were used to convey information about the position of the target in a 3D virtual environment

Source: the author.

Figure 6.9 - Virtual scenes for tactile search. The distribution of the selectable points was the same across scenes. The first scene was abstract, with the targets represented by spheres. The second and third scenes were more application-related: a selection of products in a market and a selection of pieces in a structure to be fixed. The second and third scenes were counterbalanced across subjects

Source: the author.

could feel that the vibration moved to the center of their forehead in its highest frequency. They were requested to be precise.

A small reticle was added in the center of the field of view to provide a reference. When they believed that they reached the correct target, with the central tactor vibrating at its highest frequency, they had to press a button to register their answer. Then, the target was colored according to the answer, whether it was right (green) or wrong (red). Accuracy was calculated based on the selection of the correct target. Reaction times were calculated from the beep onset to the moment the answer button was pressed.

The same constraints applied during the perceptual assessment were now removed. This time, subjects performed the task seated on a swivel chair for a more comfortable interaction and did not use headphones. Thus, only the experience with the vibrotactile display affects the usability assessment. At the end of the three sessions, the subjects filled out a SEQ (SAURO; DUMAS, 2009) and a System Usability Scale (SUS) questionnaire (BROOKE, 2013).

The whole experiment took on average 20 minutes.

6.1.2.1.3 Subjects

Thirty subjects took part voluntarily in the study (24 males and 6 females). Their ages ranged from 19 to 60 years (M = 27, SD = 8.1). All subjects read and agreed with an Informed Consent Form before the experiment.

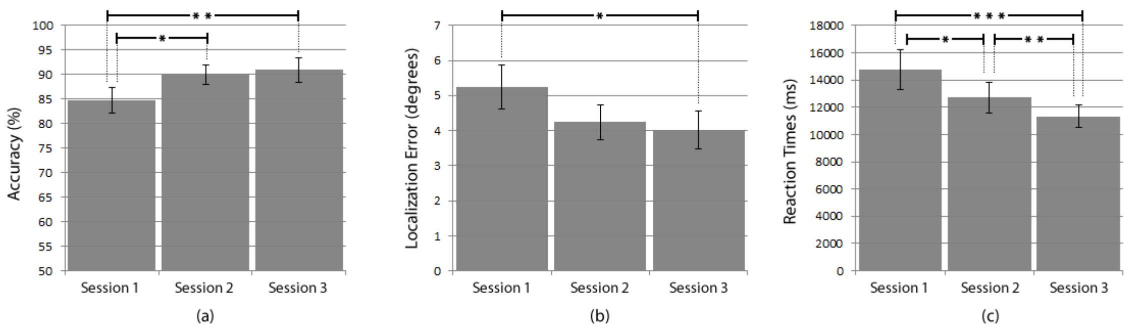
Nine subjects have previously participated in Experiment I, and the remaining subjects were fresh. All of them were naïve to the second experiment and protocol. We found no effect of the previous experience on the results of Experiment II. Seventeen subjects reported having some visual problem, namely 11 cases of Myopia, 8 cases of Astigmatism, 1 case of Keratoconus, 1 case of Colour Blindness and 2 cases of Presbyopia. In all these cases, we found no correlation between these individual differences and their performance during the experiment.

6.1.2.2 Results

6.1.2.2.1 Learning Effect

We assessed scores, precision, and reaction times as a function of the order in which the sessions were performed. There was a significant effect of task repetition on accuracy (Fr(2) = 76.17, p = 0.0222). In the first session, subjects were much less accurate than both the second (Z = 20.99, p = 0.0358) and third (Z = 29.72, p = 0.0030) sessions (see Figure 6.10(a)). There was also a significant effect of task repetition on precision (Fr(2) = 60.67, p = 0.0482), with the third task yielding much less errors of localization compared to the first session (Z = 23.96, p = 0.0166) (see Figure 6.10(b)). Finally, reaction times present significant difference between all the sessions (Fr(2) = 112.67, p = 0.0036). Target detection was performed in the second session much faster than the first (Z = 23.55, p = 0.0185). Moreover, in the third session subjects could select targets faster than both first (Z = 3.55, p = 0.0004) and second (Z = 27.05, p = 0.0068) sessions (see Figure 6.10(c)). We did not find any effect of the different scenarios on the performance of the subjects.

Figure 6.10 - (a) In the first session (M = 84.7, SD = 14.2), subjects were much less accurate than both the second (M = 90, SD = 11.0) and third (M = 90.9, SD = 13.3) sessions. (b) The third session (M = 4.1°, SD = 2.9) yielded much less localization errors compared to the first one (M = 5.2°, SD = 3.4). Localization errors in the second session (M = 4.2°, SD = 2.7) were smaller just on average. (c) Reaction times were smaller for the third session (M = 11329ms, SD = 4499) which was much faster than both the first (M = 14786ms, SD = 8014) and second sessions (M = 12710ms, SD = 6098). The second session was also much faster than the first one



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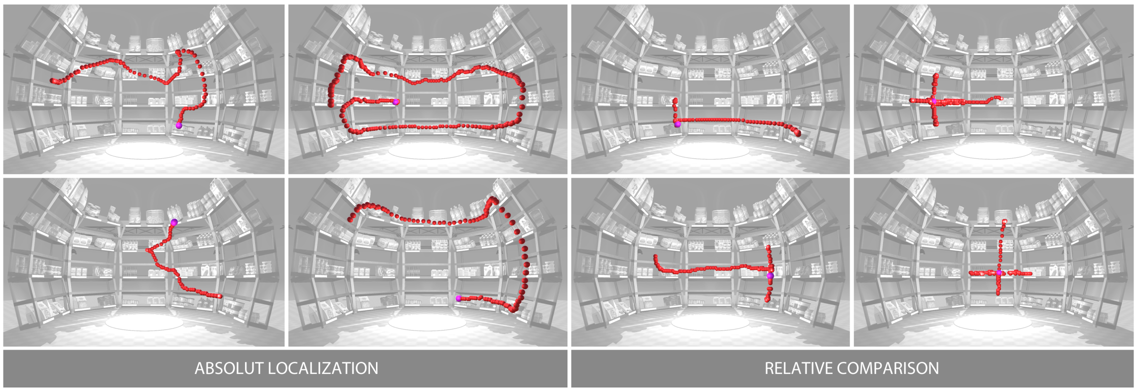
6.1.2.2.2 Target Positions

Figure 6.11 - Examples of trajectories (red path) of the subjects' head movement during exploration. By the trajectories it is possible to note the subjects that selected targets by absolute localization (without rescanning) and those who relied more on the relative comparison by going back and forth on each plane before finally selecting the target



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Even though the horizontal selection of targets did not present differences in performance, the elevation angles of the targets did it. There was a significant effect of target elevation on accuracy (Fr(3) = 81.9, p = 0.0422). Targets placed at 0°, in front of the user, yielded higher scores compared to the 45° (Z = 2.8, p = 0.0051). There was also a significant effect of target elevation on reaction times (Fr(3) = 139.6, p = 0.0030). The selection of targets placed on 0° was performed faster than for targets placed on the extremities, namely on 45° (Z = 28.28, p = 0.0047) and -22.5° (Z = 36.71, p = 0.0002). In addition, the selection of targets placed on 22.5° was also performed faster than for targets on the 45° (Z = 2.03, p = 0.0428) and -22.5° (Z = 2.79, p = 0.0053).

Overall, the mislocalization of targets' elevation corresponded to 4.5% of all the trials. The mislocalization of the target's horizontal position corresponded to 7% of the trials.

6.1.2.2.3 Exploration Behavior

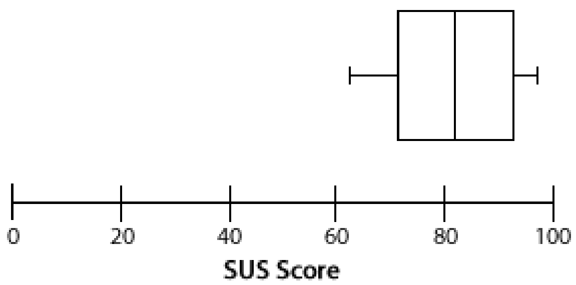
Figure 6.11 shows examples of trajectories of the subjects' head during the trials. Distinct patterns in the trajectories show that some subjects could process the tactile information to find the target and give a straight answer while other subjects had to rescan the column and/or line before selecting the target. The trajectories were then encoded from 0 to 2 according to such behavior. If the subject selected a target by absolute detection (without rescanning) the trajectory was labeled as 0. If the subject scanned only one plane after have found the target in order to confirm its position, the trajectory was labeled as 1. Finally, if the subject went back and forth on each plane before finally selecting the target, it was labeled 2.

The trajectories of 1350 trials were analyzed. From those, 29.6% were labeled as 0, 44.4% of the trajectories were labeled as 1, and the remaining 26% were labeled as 2. Subjects were systematic in their behavior across all sessions. Such behavior and the reaction times across the three sessions were strongly correlated (r(88) = 0.69, p <0.0001). In addition, the behavior and the precision were also correlated (r(88) = 0.27, p = 0.0085). Subjects that selected targets without rescanning column and/or line were faster and more precise than the remaining subjects. Accordingly, the behavior and the scores were also correlated (r(88) = -0.31, p = 0.0027), with subjects that performed more comparisons before the selection yielding lower scores.

6.1.2.2.4 Usability

As shown in Figure 6.12, mean SUS scores ranged from 62.5 to 97.5 (M = 82.25, SD = 10.5). According to surveys that compare SUS scores for different systems, an average score of 82.25 receives a grade "A" and is considered an "Excellent" system (BROOKE, 2013; BANGOR; KORTUM; MILLER, 2009).

Figure 6.12 - Mean SUS score for all subjects (M = 82.25, SD = 10.5)



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6.1.2.3 Discussion

6.1.2.3.1 The Learning Effect

Nine out of thirty subjects have participated in the perceptual experiment weeks before the experiment with the virtual setup. However, we found no effect of their previous experience on their performance in the second experiment. It is most probably due to the differences between the two setups. While the subjects had to perform a blind search in the perceptual setup, the virtual setup was more interactive and the subjects could relate the objects that they saw around them with the tactile feedback. Moreover, the stimuli on the perceptual experiment were delivered only in one position, while that for the virtual setup was delivered around the head in different positions.

As the subjects were not asked to perform the task rapidly but rather precisely, it could take a while before selecting the right target. However, subjects could perform the task with more accuracy, precision, and in much less time, systematically, as they passed by each session. It is possible to perceive that subjects can learn fast how to use the haptic interface and how their performance increases with practice.

6.1.2.3.2 The Exploratory Behavior

Observing the trajectories of the subjects' heads, there were subjects that looked straight to the target and press the answer button without demonstrating any uncertainty. Moreover, there are trajectories that describe small movements of the subject's head, made to confirm the target's position once it was found. Finally, there are trajectories that show a repetitive head movement, scanning right and left, up and down, to confirm column and line before selecting the target. It was found no correlation between these exploration patterns and the order in which the task was performed. However, subjects were systematic in their strategies across all sessions and their exploration behaviors were strongly correlated to their performance.

It was expected for those that attentively moved their heads before registering their answers to be thorough and possibly more successful in their search. However, such exploration behavior was found to be more related to a lower accuracy and higher response times. It is possible that the subjects who presented such behavior had more difficulty with the presented stimulus. Such problem could be related to the frequency discrimination as the changing rate of perceived frequency varies considerably across people (JONES; SARTER, 2008). However, when applied to the haptic headset, the elevation of only 4.5% of the trials was mistaken. In addition, the quadratic frequency modulation yielded high accuracy and low reaction times during the perceptual assessment using the same frequency range.

Such behavior could then be related to the proposed tactile interface as it involves a non-conventional modality for pointing in a 3D environment. As stated by MacLean and Hayward (MACLEAN; HAYWARD, 2008), in the assessment of tactile interfaces, "our subjects have been using vision for the kinds of tasks we test since early childhood, and they have been using the tactile version for perhaps a 3-30 min training period". Thus, the result could be affected by the non-familiarity with the tested modality and new interface. However, subjects consistently improved during the sessions and the usability of the system was rated with high scores. Finally, the uncertainty perceived in some of the trials can be caused by the setup in which the VR headset was worn over the tactors. Such configuration may ease or partially impair the perception of the vibrotactile cues according to the way in which the headset presses the tactors against the subject's head. Although the VR setup was shown to be efficient and usable, a final setup should have the tactors uniformly embedded into the VR headset as a single wearable item.

6.1.2.3.3 Application Scenarios

When using head-mounted displays, head motion can be used for selecting items of a list or even for pointing out a place where to navigate in the environment. A vibrotactile HMD then can provide guidance for interaction and navigation without displaying any extra graphical information that may be distracting or occlusive in virtual scenes. The vibrotactile component can also extend the capabilities of the conventional headset by delivering information about elements out of the field-of-view, thus enhancing spatial awareness in the virtual environment. It can also convey information about avatars or peers in a collaborative environment to provide a sense of co-presence.

Right after filling out the usability questionnaire, the subjects had to answer to the question "For which other scenarios this technique could be useful?". Thirty per cent of the users suggested applications for guidance and orientation of visually impaired persons. Vibrotactile interfaces for assistive purposes are the main concern of some studies (CARDIN; THALMANN; VEXO, 2006). Since sighted and blind individuals discriminate frequency in the same optimal way (ALARY et al., 2009), blind subjects are expected to have similar performance to the perception of the stimuli provided by the proposed vibrotactile HMD. This similarity was also found when comparing exploratory strategies in search tasks involving tactile feedback (BRAYDA et al., 2011). Subjects also suggested applications for guidance in environments with low visibility, such as dark or smoke environments (e.g. guidance for firemen and mine workers). Applications for guidance in libraries, museums, and shops were also suggested, showing that our technique could be applied to work environments and on a daily basis. In such scenarios, the haptic component can also complement Augmented and Mixed Reality applications.

Twenty-three per cent of the subjects suggested that the vibrotactile cues could also be applied to entertainment and gaming. The vibrotactile HMD could provide guidance on first-person shooter games, puzzle games, or even for navigation in a role-playing game. The technique could also be applied to serious games and virtual training scenarios. The remaining subjects had different propositions concerning interpersonal communication and support to drivers. Another mentioned application was the visualization of complex data. In such scenario, the vibrotactile HMD could provide an extra channel to represent or to find data. It could also be used as a haptic pop-up to highlight data, signalizing events, or for attentional reorientation.

6.1.3 Conclusion

We have designed a vibrotactile HMD for spatial awareness in virtual and real environments. In order to convey the position of 3D objects around a person, the vibrotactile HMD points towards the direction of the object in the azimuthal plane using only seven tactors placed around the user's head. The object elevation, in turn, is indicated by varying the vibration frequency, which peaks at the correct elevation angle. We thoroughly assessed the device and technique in a target localization task, going from a perceptual assessment to an interactive haptic search in a virtual setup.

Three different functions for frequency modulation were assessed to select the proper stimuli set. By comparing a Linear (continuous growth), a Stair (discrete growth), and a Quadratic (speeding growth) growth functions, it was demonstrated that the Quadratic condition allowed a more accurate, precise, and faster target localization in an active head pointing task. It was also shown that the performance in localizing targets placed in upper positions, namely -22.5° to 45° in front of the observer, was higher compared to -45°. As the pitch movement of the head is limited by the neck when the observer looks to more distal regions, the positions covered by the tactile cues correspond to the exact positions the observer could look for objects of interest.

When integrating both vibration parameters for cueing, subjects could find targets in different positions with higher accuracy, precision and lower reaction times as they repeated the task across different virtual scenarios according to a strong learning effect. In the active pointing task with several possible targets placed around the subject, the variable frequency was shown to be even easier to process as the elevation of only 4.5% of trials were mistaken. The interface was also rated with high usability scores.

A final version of the vibrotactile headset would present embedded actuators to make it even easier to wear. Thus, the VR headset could be a complete item for multisensory interaction, with graphics, audio feedback (present in most commercial versions), and haptics. A piece like a vibrotactile headset can be used not only in virtual environments but also in different contexts and applications in real scenarios and on a daily basis. As shown by the scenarios tested in the VR setup, virtual reality headsets could support remote collaboration, guidance in dark environments, support in activities such as shopping or interactive tours, and so on. It could also make the use of haptics in VR applications, gaming, and scientific studies much more popular.

The vibrotactile HMD should be further assessed for interpersonal communication in collaborative virtual environments. Thus, peers could share the same virtual workspace and exchange tactile signals to supplement their means of communication. In the next section, we present the design and assessment of an interface to support the application of our vibrotactile HMD for intercommunication between peers in an immersive setup.

6.2 Articulatory Interface for Intercommunication in Immersive VE

The literature on tactile communication supports the clear understanding of how people perceive and process vibrotactile signals (BREWSTER; BROWN, 2004; TERNES; MACLEAN, 2008) and how to construct and validate vibrotactile vocabularies and devices to support different tasks (JESUS OLIVEIRA; NEDEL; MACIEL, 2016; KERDEGARI; PRESCOTT; KIM, 2016; CHAN; MACLEAN; MCGRENERE, 2008). However, there is still a lot to understand about computer-mediated interpersonal touch (FIELD, 2001; GALLACE; SPENCE, 2010; SMITH; MACLEAN, 2007). In addition, it is important to understand not only how people perceive tactile cues but also how people articulate signals in order to communicate with others. For instance, how can the user of a tactile HMD not only be guided by the system but also guide a peer in a collaborative setup? How is this computer-mediated tactile intercommunication performed?

To answer these questions, we propose a device that is built on the back of a vibrotactile HMD to capture touch gestures and translate them into tactile feedback (see Figure 6.13). Having the articulatory device integrated with the tactile display, the user would be interacting with the environment and other users by touching on the same body area where the tactile feedback is delivered in a direct and intuitive way (JESUS OLIVEIRA; NEDEL; MACIEL, 2016). Such on-body interaction offers the advantage of leveraging human proprioception as an extra feedback mechanism (SERRANO; ENS; IRANI, 2014; WALK; PICK, 2013). Some interfaces exist, in the literature, that explore the HMD for input interactions with VR content (GUGENHEIMER et al., 2016, 2017). However, it is still unknown how an HMD-based input interface would perform for reproducing tactile signals and for tactile intercommunication between peers.

Figure 6.13 - Gestures are captured by the touch surface while the resulting tactile feedback is felt into the HMD through vibrotactile actuators

Source: the author.

In this study, we present the design and assessment of an interface centered on a tactile HMD for reproducing vibrotactile cues in a collaborative setup. First, we try out different touch gestures to define which gestures can be used to trigger tactile cues. Then, we assess whether and how subjects are able to apply such interface for intercommunication in a collaborative VR setup. Accuracy and precision of gesture reproduction, the comprehension and articulation of tactile signals, and the system usability were assessed as dependent variables. One practical result of this research is the accomplishment of a VR setup in which individuals are able to effectively use tactile feedback as the only means for intercommunication.

6.2.1 Experiment I: Back-of-HMD Interface

We have assessed a back-of-HMD interface made for reproduction of simple 1D gestures in immersive scenarios. Three different gestures were selected. Accuracy and precision of gesture reproduction were assessed as a function of different conditions for each of the three gesture modalities. We also assessed subjective measures, such as the task workload and easiness as dependent variables.

Hereinafter, we describe the setup design, results and a discussion about this first experiment.

6.2.1.1 Materials and Methods

6.2.1.1.1 Apparatus

We have attached a smartphone Samsung Galaxy S6 SM-G920F (143.4 x 70.5 x 6.8mm) to the back of an Oculus Rift DK2 to serve as input device. A compatible ZEISS VR ONE tray was used to keep the smartphone fixed on the VR headset. The screen setup weighted 138g. The multitouch screen has 5.1 inches, with resolution of 1440 x 2560 pixels. The smartphone runs the version 7.0 of Android OS.

An application was developed to capture touch gestures on the smartphone and it was connected to the server through TCP (Transmission Control Protocol) channel to avoid packet loss. Each packet carried touch coordinates, touch duration, and the offset from the previous touch. As the smartphone has a Super AMOLED capacitive touchscreen, a black screen allowed long hours of use without recharging the phone. The overall latency of the wireless network was about 97*ms* (SD = 137.8).

In this first experiment, only gesture interaction was assessed. Thus, no tactile apparatus was used.

6.2.1.1.2 Experimental Conditions

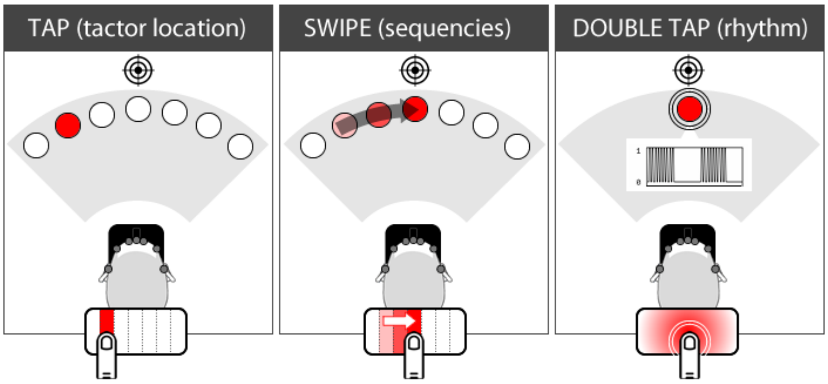
Nielsen et al. (2003) describe static and dynamic gestures. Static gestures are postures, i.e. relative hand- and finger positions, not taking the movements into account. Dynamic gestures are movements, i.e. the hand trajectory and/or posture switching over time. In order to work with simple 1D gestures, the assessed modalities were shaped by fixing one posture (index finger) and varying dynamics according to basic gestures (for instance, taps, swipes, and waves (SAFFER, 2008)). Three gesture modalities were then assessed: Tap, Swipe, and Double Tap (accounting for tap and between taps duration). As shown in Figure 6.14, the gestures also represent spatial features in a 3D environment.

In the assessment of the *Tap* modality, we wanted to discover to which extent subjects would be able to point at targets by tapping the touch surface. We hypothesized that the number of targets would affect the localization during the tapping task. Therefore, five densities were tested for this modality, varying the number of targets (05, 10, 15, 20, and 25 targets) inside an angle of 90° in front of the subject.

In the assessment of the *Swipe* modality, we wanted to find to which extent subjects would be able to track sequences of targets placed at different angles in front of the subject. Thus, sequences varied across six angles (15°, 30°, 45°, 60°, 75°, and 90°), where sequences moving toward the left and the right sides were counterbalanced.

Finally, in the assessment of the *Double Tap* modality, we wanted to find to which extent subjects would be able to reproduce tap and between tap duration of two cues

Figure 6.14 - Gesture modalities were selected to match basic hardware parameters and to represent spatial features



Source: the author.

delivered at the same pace (rhythm). Five stimuli/between stimuli durations were used [1] (200ms, 400ms, 600ms, 800ms, and 1000ms), with both cues and the interval between the cues following the same duration per trial.

For each condition of each gesture modality, 12 trials were performed resulting in 192 trials overall. Accuracy in gesture reproduction was calculated as true or false according to the proximity, in position or in time, of the expected gesture. Precision was assessed from the absolute position (in pixels) or time (in ms) of the reproduced gesture.

6.2.1.1.3 Experimental Protocol

Each subject filled out a demographic questionnaire before starting the experiment. While wearing the virtual reality headset/articulatory screen, each subject had to reproduce a given gesture as precise as possible.

For the *Tap* modality, the subject would see a number of targets (05, 10, 15, 20, or 25 targets) in front of him and one of them would turn red. Facing the center of the set of targets, the subject had to touch the articulatory screen in the position that would better correspond to the direction of the red target (see Figure 6.14 (left)). Regardless of the density, targets had the same size. Targets were placed equidistant in front of the subject in an angle of 90°.

For the *Swipe* modality, the subject would see only seven targets and a subset of them would turn red in sequence (moving to the left or to the right in front of the user). Facing the center of the set of targets, the subject had to swipe across the articulatory screen to reproduce the angle formed by the sequence path (see Figure 6.14 (middle)). The distance between the start and end points were taken as answer for this gesture.

Finally, for the *Double Tap* modality, the subject would see just one target that would turn red twice at a given pace. This time, the subject could touch anywhere on the screen, to reproduce the stimulus duration (blink duration and the interval between two blinks) as accurately as possible (see Figure 6.14 (right)).

Each subject performed three sessions. Each session tested one gesture modality. The sessions were counterbalanced with a 3x3 Latin Square. They were allowed to ask for a break at any time. Between sessions, the subject also had to fill out a SEQ (SAURO; DUMAS, 2009) and a NASA-TLX questionnaire (HART, 2006) to self-judge their task

[1] A threshold has to be set (e.g. 200 ms) during which two touch events in the same location are counted as a double click (SAFFER, 2008).

load. The process was repeated for each gesture modality. The whole experiment took on average 25 minutes.

6.2.1.1.4 Subjects

Sixteen naive subjects participated voluntarily in the study (13 males and 3 females). Their ages ranged from 19 to 34 years (M = 25, SD = 3.9). All subjects read and agreed with an Informed Consent Form before the experiment as required by the Helsinki declaration.

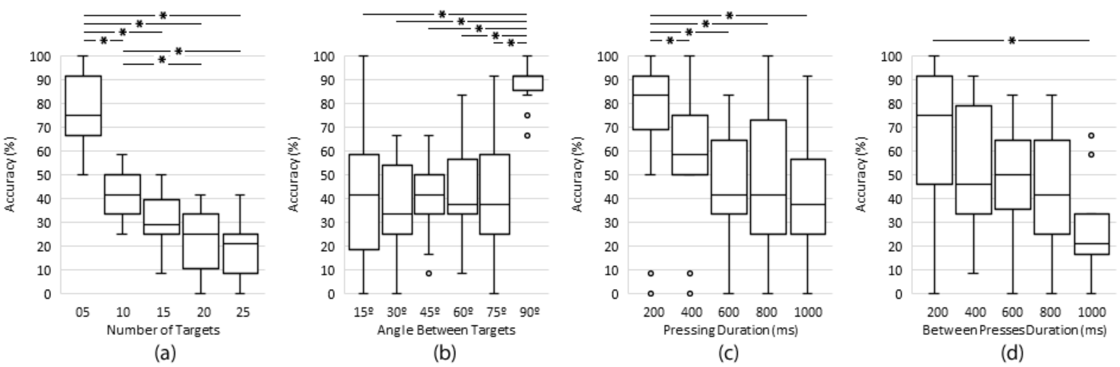
Handedness was assessed with an Edinburgh Handedness Inventory (DRAGOVIC, 2004) and one subject was shown to be left-handed, while nine subjects were shown to be right-handed (the remaining were marked as mixed-handed). Seven subjects reported having some visual problem, namely five cases of Myopia and two cases of Astigmatism. Four subjects reported that they never had used a virtual reality headset before. No correlation was found between these individual differences and their performance during the experiment.

6.2.1.2 Results

6.2.1.2.1 Accuracy

Figure 6.15 shows the accuracy for each condition assessed for tap, swipe, and double tap gestures. Means and standard errors are shown in Table 6.1.

Figure 6.15 - (a) Mean accuracy for sets of 05 targets was higher than for sets of 10, 15, 20, and 25 targets. Sets of 10 also yielded higher accuracy than sets of 20 and 25. (b) Accuracy in angle reproduction was higher for 90° compared to the remaining. (c) Tapping duration was more accurate for 200ms compared to the remaining. Finally, (d) interval reproduction for 200ms was higher than 1000ms, but not for 400ms, 600ms, and 800ms



Source: the author.

A One-Way ANOVA test shows that there is an effect of the number of targets [F(4,75) = 55.2735, p <0.0001] on localization accuracy during tapping (see Figure 6.15 (a)). Post-hoc comparisons with Tukey analyses indicated that the mean accuracy for tapping targets in a set of 05 targets was higher than for sets of 10, 15, 20, and 25 targets (p <0.01). Tapping targets in a set of 10 also yielded higher accuracy than sets of 20 and 25 targets (p <0.01).

When swiping across targets placed in different angles, there was an effect of the angle [F(5,90) = 15.8671, p <0.0001] on accuracy as well (see Figure 6.15 (b)). Mean accuracy

Table 6.1 Mean accuracy for each condition of each gesture modality

Number of Targets			Angle Between Targets			Pressing Duration			Between Presses Duration		
CND	M	SE	**CND**	M	SE	**CND**	M	SE	**CND**	M	SE
05	75.5	14.0	**15°**	43.2	28.5	**200ms**	78.6	23.6	**200ms**	66.6	30.8
10	41.1	9.3	**30°**	34.3	18.2	**400ms**	55.4	27.4	**400ms**	51.5	26.5
15	29.6	10.9	**45°**	41.6	15.8	**600ms**	45.0	23.7	**600ms**	49.4	20.5
20	23.9	13.2	**60°**	42.1	19.1	**800ms**	44.7	2.0	**800ms**	44.7	24.8
25	18.7	12.7	**75°**	43.2	23.8	**1000ms**	39.3	23.4	**1000ms**	28.6	19.4
			90°	89.0	8.4						

* CND: Condition

in angle reproduction was higher for 90° in comparison to 15°, 30°, 45°, 60°, and 75° ($p < 0.01$).

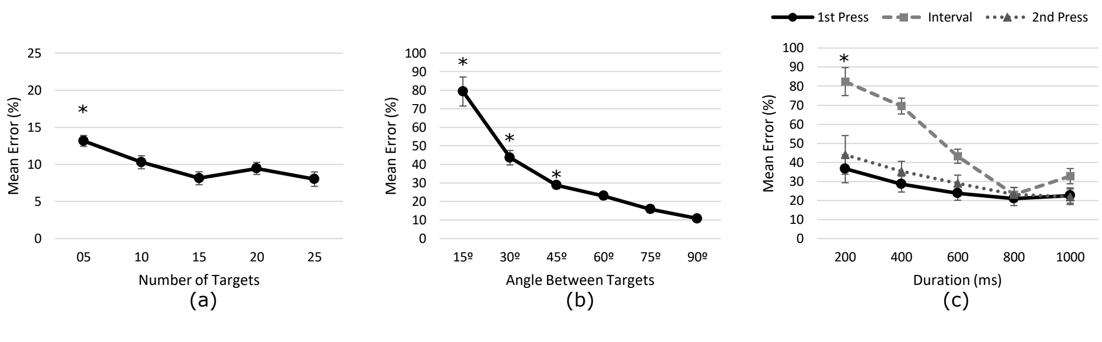
Concerning rhythm reproduction, we assessed both the accuracy for pressing duration and for the interval between two taps. Figure 6.15 (c) shows that there was a significant effect of stimulus duration [$F(4,155) = 12.4317$, $p < 0.0001$] on accuracy for tapping duration. Subjects were more accurate in reproducing the tapping duration of stimuli delivered at 200ms compared to 400ms, 600ms, 800ms, and 1000ms ($p < 0.01$), with accuracy decreasing progressively with the stimulus pace.

There was also an effect of stimulus duration [$F(4,75) = 4.8583$, $p = 0.0019$] on accuracy for reproducing the interval between two taps (see Figure 6.15 (d)). The mean accuracy for interval reproduction of stimuli delivered at 200ms was significantly higher than for stimuli at 1000ms ($p < 0.01$). No significance was found for accuracy between the conditions 400ms, 600ms, and 800ms though.

6.2.1.2.2 Precision

Figure 6.16 shows the error during tapping, swiping, and double tapping across conditions. Means and standard errors are shown in Table 6.2.

Figure 6.16 - Errors are normalized according to the magnitude of each condition. (a) Errors for 05 targets were higher than 15, 20, and 25, but not than 10. (b) Errors for 15° were lower than 30°, 45°, 60°, 75°, and 90°. Finally, (c) Tapping duration in 200ms yielded more errors than 800ms, and 1000ms, but not than 400ms and 600ms. While interval duration for 200ms yielded more errors than 800ms and not than 400ms, 600ms, and 1000ms



Source: the author.

Table 6.2 Percentage of errors in precision for each condition of each gesture modality

Number of Targets			Angle Between Targets			Pressing Duration			Between Presses Duration		
CND	M	SE	**CND**	M	SE	**CND**	M	SE	**CND**	M	SE
05	13.1	0.7	**15°**	79.3	7.8	**200ms**	40.2	35.0	**200ms**	82.3	22.2
10	10.2	0.8	**30°**	43.6	3.9	**400ms**	31.9	18.9	**400ms**	69.5	18.7
15	8.1	0.8	**45°**	28.7	1.8	**600ms**	26.4	16.0	**600ms**	43.2	11.8
20	9.4	0.8	**60°**	23.0	1.8	**800ms**	22.0	14.4	**800ms**	23.0	4.21
25	8.0	0.9	**75°**	15.8	1.8	**1000ms**	22.2	15.9	**1000ms**	32.7	5.47
			90°	10.8	1.0						

* CND: Condition

Results showed an effect of the number of targets [F(4,75) = 5.9971, p = 0.0005] on precision (see Figure 6.16 (a)). Post-hoc comparisons indicated that the mean error for tapping targets in a set of 05 targets was higher than for sets of 15 (p <0.01), 20 (p <0.05), and 25 targets (p <0.01). Tapping targets in sets of 10 and 15 also yielded less error than sets of 20 and 25 targets (p <0.01).

There was also an effect of the angle [F(5,90) = 42.922, p <0.0001] on precision of swipe (see Figure 6.16 (b)). Mean error for sequences of targets in 15° and 30° was higher than for all the remaining angles (p <0.01). In addition, error for sequences of targets in 45° was higher than 90° (p <0.05).

For double tap, there was an effect of stimulus duration [F(4,75) = 3.019, p = 0.0227] on precision of tapping duration. Tapping in 200ms condition yielded more errors than 800ms (p <0.05). There was also an effect of stimulus duration for interval duration [F(4,155) = 4.0878, p = 0.0039]. Intervals with 200ms yielded more errors than 800ms and 1000ms (p <0.01) (see Figure 6.16 (c)). In general, the reproduction of intervals yielded more errors than both the reproduction of duration of both first and second taps (p <0.01).

6.2.1.2.3 Workload and Easiness

Concerning mean NASA TLX scores, the *Double Tap* (M = 56.14, SD = 10.37) modality yielded higher means for different factors and for the general workload related to Tap (M = 51.77, SD = 12.07), and Swipe (M = 54.58, SD = 11.37). In fact, three subjects reported that task as more tiring for their eyes, as they have to focus only on one target in the scene. However, the differences between the three conditions were not significant.

In addition, SEQ scores show that the *Swipe* (M = 3.75, SD = 1.39) modality yielded slight lower scores than Tap (M = 4.06, SD = 1.56), and Double Tap (M = 4.06, SD = 1.52) modalities. Yet, the differences between conditions were not significant.

6.2.1.3 Discussion

After testing different conditions for each gesture modality we found that, for the *Tap* modality, the localization of the proper position in the back-of-HMD screen is better articulated with lower density. Fairly, with only five possible positions on the screen, subjects were more accurate than for the remaining modalities. On the other hand, the *Swipe* accuracy did not increase according to the reproduced angle. In fact, the only condition that presented a good performance was the condition in which subjects had to reproduce sequences crossing 90°, which concerned swiping from edge to edge in the screen. Thus, subjects had feedback from the screen limits. Finally, for the *Double Tap* modality, accuracy, and precision increased with stimulus pace, i.e., faster sequences were reproduced with more accuracy than slower sequences. In addition, subjects were better in reproducing the pressing duration then reproducing the interval between two taps.

Gesture modalities with higher accuracy did not present fewer errors in general, as expected. Higher densities during *Tap* yielded less error than the 05 targets condition. During *Swipe*, 15° and 30° presented much lower error than the remaining conditions. Finally, slower pace stimuli in *Double Tap* presented more errors than the remaining conditions. These results are expected for gestures such as swipe, with errors reducing as subjects perform gestures that cross wider regions of the screen. In this case, the edges of the screen are used as a reference while the center of the screen is flat with no point of reference. However, the results for precision are surprising for the *Tap* modality. In this modality, it was expected for subjects to struggle more to discriminate large sets of targets. The reduction of the errors across modalities is probably due to a motor adjustment when subjects have to choose targets between large sets. For instance, subjects can be less careful selecting targets in a 05 targets condition and achieve a good accuracy in general. However, being less careful during the selection also yields more errors.

In the next section, we present the design of a vibrotactile HMD that uses the back-of-HMD interface for articulating vibrotactile cues. After presenting the design and assessment of the interface, we present and discuss the results and potential applications.

6.2.2 Experiment II: Tactile Articulation

In a quest for understanding how subjects express themselves through vibrotactile symbols using only the tactile channel, we built a vibrotactile HMD with vibration motors attached to a VR headset. Then, we added our touch interface to the back of the vibrotactile HMD for the articulation of tactile cues. Thus, different vibrotactile signals can be triggered by performing different gestures on the surface of the HMD. A set of vibrotactile signals was developed as a vocabulary that subjects could use in a collaborative task.

Hereinafter, we describe the design of the vibrotactile apparatus, the collaborative task, the vibrotactile vocabulary, and the protocol to assess the usage of our articulatory interface.

6.2.2.1 Materials and Methods

6.2.2.1.1 Apparatus

This time, two vibrotactile headbands were built according the Tactile Fovea approach. Each headband had seven electromechanical tactors. The tactors are controlled with an Arduino Mega ADK board and Adafruit DRV2605L haptic controllers (see Figure 6.17 (left)). Each tactor - 10*mm* Linear Resonant Actuator, 4*mm* type (C10-100 Precision Microdrives) - was attached to a piece of Velcro to be easily worn around the head.

For each headband, five tactors were placed at an equal distance from the center of the forehead over the Cardinal and Collateral points (with no tactor in the back of the head). Two extra tactors were set 5*mm* apart from the central tactor to provide additional resolution around the sagittal plane. Each headband was combined with an Oculus Rift Consumer Version 1 (CV1). Movements of the head were used for updating the vibration parameters in the headband. Stimuli were delivered at 175Hz.

In addition to the screen tested in the first experiment (Figure 6.2.1), a Leap Motion

Figure 6.17 - Final experimental setup. (left) Vibrotactile headband and articulatory screen added to the VR headset. (right) Subjects could use their hand to manipulate objects and send vibrotactile cues with gestures in the articulatory screen

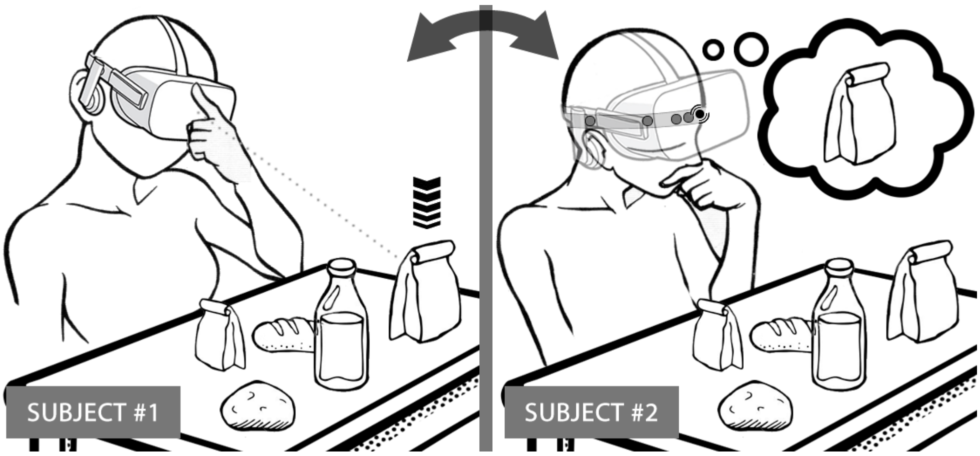
Source: the author.

device was also attached to the Oculus for gestural interaction with the virtual environment. The client-server setup was built with Unity3D in a local network. Taking into account the network latency of 97*ms* and the tactile apparatus, with the typical rise time for the actuator of 35*ms* and a typical lag time of 12*ms*, the overall latency was about 144*ms*. For the Leap Motion, render time was of 16*ms*.

6.2.2.1.2 Collaborative Task

To understand how subjects will be able to express themselves through vibrotactile symbols, we designed a collaborative tactile guidance task (see Figure 6.18). Every two subjects had to work together in a collaborative recipe by taking ingredients in a given order. Either partner knows which ingredient the other has to take in a given moment, but the only way to communicate such information is by activating vibrotactile cues on the other user.

Figure 6.18 - Task *schema*. Subjects had to communicate only with vibrotactile cues to guide each other during the collaborative task



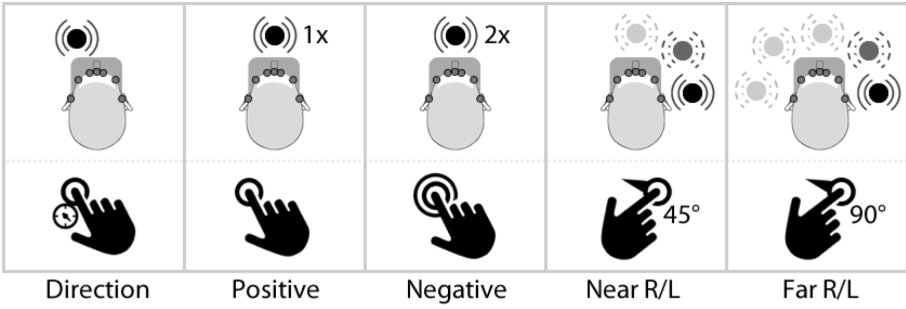
Source: the author.

During the collaborative task, subjects could use their hands to manipulate the ingredients placed on their own table. They also could see which ingredient was grabbed by the other, but they could not talk with the other so we could see how they would interact using only the tactile channel.

6.2.2.1.3 Vibrotactile and Gestural Vocabulary

Conventionally, a set of tactile signals is prototyped according to the messages that are needed to support a given task and the available hardware parameters. The messages we wanted to convey with vibration were chosen after observing how people would perform the collaborative task orally during a pre-test. Then, based on the most used instructions, our vibrotactile vocabulary was composed of five kinds of signals: Direction, Positive signal, Negative signal, and Right/Left signals (see Figure 6.19).

Figure 6.19 - Gestures and resulting vibrotactile feedback. The burst duration for all signals had 200*ms*. The interval between two bursts on the Negative signal also had 200*ms*. Near and Far R/L were activated in sequence without interval between bursts



Source: the author.

In our setup, we have to consider the articulation of the signals. Thus, when it comes to the hardware parameters chosen to encode the message set, they were selected to be perceptually distinguishable and to match basic gestures according to our first experiment (Sec. 6.2.1).

The *Direction* of an ingredient was given from an egocentric perspective. When triggered, the tactor facing the ingredient starts to vibrate indicating its direction. The other subject feels a vibration and turns the face towards the felt target until the vibration is perceived on the center of the forehead, indicating that the subject is now facing the proper ingredient. Such stimulus is conventionally used for guidance as well (JESUS OLIVEIRA et al., 2016b). Since subjects are able to reproduce long taps with accuracy, the Direction signal is triggered when the subject performs a long tap anywhere on the screen while facing an ingredient.

When a subject grabs an ingredient, the partner can confirm the selection with a *Positive* signal with a simple tap or a *Negative* signal with a double tap. To minimize density, tap and double tap can be performed anywhere on the screen. The subject can also say that an ingredient is more on the left or more on the right of the table with a swipe towards the corresponding direction. The center and the edges of the screen were used as tangible references (according to our first experiment). Thus, a short swipe from the middle of the head towards the edge of the screen triggers a *Near Right/Left* signal and a swipe from edge to edge triggers a *Far Right/Left* signal. A similar Left/Right signal was also used before for guidance using a vibrotactile HMD (KERDEGARI; PRESCOTT; KIM, 2016).

6.2.2.1.4 Experimental Protocol

Each subject filled a demographic questionnaire and read instructions before starting the experiment. Then, each subject performed an Interpretation test, where the subject had to feel a vibrotactile signal and answer what is the meaning of that signal. Then, each subject had to perform an Articulation test, where the subject had to see an expression and do the correspondent gesture in the mounted screen. Both the interpretation and the articulation tasks served to reinforce the learning of the vibrotactile vocabulary.

Finally, subjects had to perform the collaborative task in dyads. Tests were done in a reserved room. Each subject sat in a swivel chair at one of the sides of the room. Each one of them was wearing a VR headset with the vibrotactile headband, the articulatory screen, and a Leap Motion mounted on the VR headset. Every subject had ten ingredients to take in a given order. They could not see each other, but they both saw the table from the same perspective. They could select ingredients by gazing towards the object and grabbing with a pinch gesture in front of the Leap Motion (see Figure 6.9 (right)). A small reticle was added in the center of the field of view to provide a reference. They performed a practice session to understand the elements of the virtual scene. Then they performed the complete collaborative task. Subjects had an environmental sound played on their Oculus headphones and were instructed to not talk to each other.

After the task, subjects had to fill out a SEQ (SAURO; DUMAS, 2009), a Mutual Understanding questionnaire (BIOCCA; HARMS; GREGG, 2001), and a SUS questionnaire (BROOKE, 2013). The whole experiment took on average 30 minutes.

6.2.2.1.5 Subjects

Twenty four subjects participated voluntarily in the study (14 males and 10 females). They participated in couples and all couples knew each other from before the experiment. Their ages ranged from 19 to 33 years (M = 25, SD = 2.7). All subjects read and agreed with an Informed Consent Form before the experiment as required by the Helsinki declaration.

Handedness was assessed with an Edinburgh Handedness Inventory (DRAGOVIC, 2004) and fourteen subjects were shown to be right-handed while the remaining were marked as mixed-handed. Twelve subjects reported having some visual problem, namely nine cases of Myopia, three cases of Astigmatism, one with Hypermetropy and one with strabismus on the left eye. Four subjects reported never had used a VR headset before. Eight subjects had participated in the Experiment I. We found no correlation between these individual differences and their performance during the experiment.

6.2.2.2 Results

6.2.2.2.1 Interpretation

Table 6.3 shows the confusion matrix according to the interpretation of the tactile cues. The diagonal of the table shows the interpretation accuracy for each tactile signal.

Table 6.3 Signal Interpretation Confusion Matrix, N = 5 [Response (%)]

	Dir.	Pos.	Neg.	N.R/L	F.R/L	“ ”
Direction	**95.00**	1.25	0.00	1.25	2.08	0.42
Positive	0.83	**95.00**	0.00	0.00	0.00	4.17
Negative	1.67	2.50	**95.00**	0.00%	0.00	0.83
Near R/L	3.33	0.00	0.83	**83.33**	9.17	3.33
Far R/L	1.67	0.83	0.00	5.83	**89.17**	2.50

There was a significant effect of the tactile signal [F(4,715) = 3.0698, p = 0.0159] on reaction times. Post-hoc comparisons indicated that the mean reaction time for the *Near*

R/L signal (M = 4119.7ms, SD = 5665.2, $p < 0.05$) was higher (slower) than signals for *Positive* (M = 2824.1ms, SD = 2531) and *Negative* (M = 2877.9ms, SD = 2045). Signals indicating Direction took on average 4041.4ms (SD = 3525.2), while the *Far R/L* signal took 3311.2ms (SD = 2756).

6.2.2.2.2 Articulation

Table 6.4 shows the confusion matrix according to the articulation of tactile cues. The diagonal of the table shows the accuracy in articulating each tactile signal.

Table 6.4 Signal Articulation Confusion Matrix, N = 5 [Response (%)]

	Long Tap	Tap	2 Taps	Short Swipe	Long Swipe
Direction	**73.73**	20.34	1.69	1.69	2.54
Positive	0.84	**94.12**	3.36	1.68	0.00
Negative	2.56	35.90	**58.97**	1.71	0.85
Near R/L	20.34	35.59	1.69	**39.83**	2.54
Far R/L	5.04	15.97	1.68	13.45	**63.87**

Accuracy for articulation (M = 64%, SD = 15.9) was lower than for interpretation of the tactile cues (91.6%, SD = 7.2) [$F(1,46) = 60.1545$, $p < 0.0001$]. No difference was found between reaction times though. Interpretation for each tactile cue took on average 3406ms (SD = 716.7), while articulation took 3675ms (SD = 1378) on average.

There was a significant effect of the tactile signal [$F(4,586) = 6.0435$, $p = 0.0002$] on reaction times. This time, the mean reaction time for the *Far R/L* signal (M = 4972.8ms, SD = 6351.4, <0.01) was higher than signals for *Positive* (M = 2928.7ms, SD = 5813.2) and *Negative* (M = 2444.7ms, SD = 3785.9). In addition, reaction times for *Direction* (M = 4641.9ms, SD = 4216) were higher than the signals for *Positive* (<0.05) and *Negative* (<0.01). Long tap and swipe across the whole screen were naturally longer to articulate than the others. Signals indicating Direction took on average 4041.4ms (SD = 3525.2), while the *Far R/L* signal took 3311.2ms (SD = 2756). The signal for *Near R/L* took on average 3654.5ms to articulate (SD = 2769.8).

Figure 6.20 shows a Multidimensional Scaling (MDS) from the results of the Interpretation and Articulation tests.

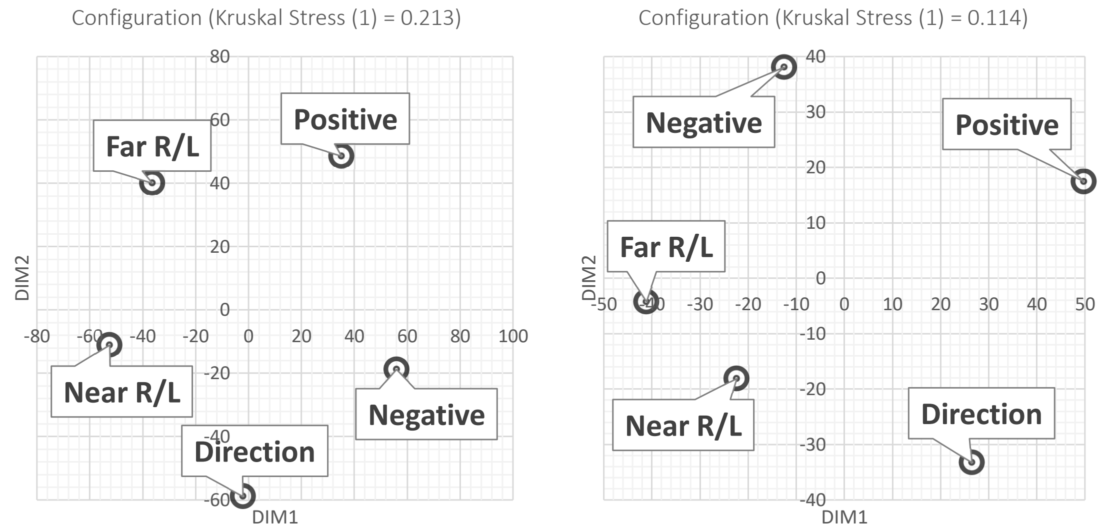
While the vibrotactile signals have shown to be very distinct from each other (Figure 6.20 (left)), the signals for *Far R/L* and *Near R/L* are closer from each other concerning their articulation (Figure 6.20 (right)). It is possible that signals for *Far R/L* and *Near R/L* are going to be articulated indiscriminately in the collaborative task, only to convey information about right and left in the scene (no matter if it is far or close).

6.2.2.2.3 Tactile Intercommunication

Subjects took on average 11m19s (SD = 02m58s) to perform the collaborative task. Mean errors were about 10.7 (SD = 8.1) and dyads exchanged 170 tactile signals on average during the task (SD = 101.3).

There was a significant difference between the usage of each tactile signal during the collaborative task [$F(4,55) = 7.8662$, $p = 0.0001$]. As shown in Figure 6.21 (left), the *Positive* signal was the most used during the tactile dialog overall ($p < 0.01$). However, even though the signals for positive and negative were basic to the task, some participants

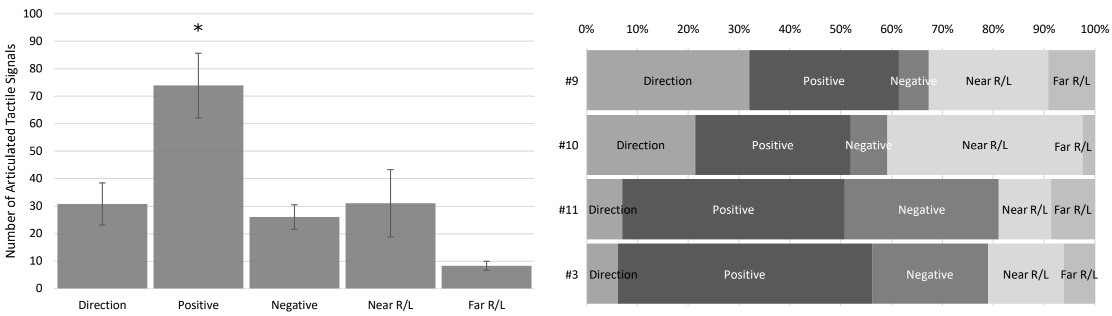
Figure 6.20 - MDS solutions for the Interpretation (left) and Articulation test (right) at 2 dimensions (MACLEAN; ENRIQUEZ, 2003; TERNES; MACLEAN, 2008)



Source: the author.

reported to have exchanged the use of *Negative* signal by pointing the direction of the correct ingredient when their partners took a different ingredient by mistake.

Figure 6.21 - (left) *Positive* signal (M = 73.8, SD = 40.9) was used more often than *Negative* (M = 26.0, SD = 15.4), *Direction* (M = 30.8, SD = 26.4), *Near R/L* (M = 31.0, SD = 42.2), and *Far R/L* (M = 8.4, SD = 5.7). (right) Dyad #9 and dyad #10 expressed 64.7% and 62.2% of direction signals, and 35.2% and 37.7% of confirmation signals, respectively. On the other hand, dyad #11 and dyad #3 expressed 25.9% and 27.1% of direction signals, and 74% and 72.8% of confirmation signals, respectively



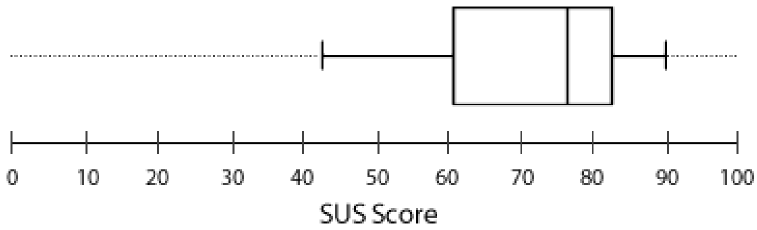
Source: the author.

Figure 6.21 (right) shows the usage of each tactile signal during the conversation by four dyads. Dyads #9 and #10 are examples of subjects that used a direction signal (i.e. *Near R/L*, *Far R/L*) instead of the *Negative* signal. On the other hand, Dyads #3 and #11 used mostly confirmation signals (i.e. *Negative* and *Positive*).

6.2.2.2.4 Usability and Subjective Measures

As shown in Figure 6.22, mean SUS scores ranged from 42.5 to 90.0 (M = 72.1, SD = 13.4). According to surveys that compare SUS scores for different systems, an average score of 72 receives a grade "B" and is considered a "Good" system (BROOKE, 2013; BANGOR; KORTUM; MILLER, 2009).

Figure 6.22 - Mean SUS score for all subjects (M = 72.1, SD = 13.4)

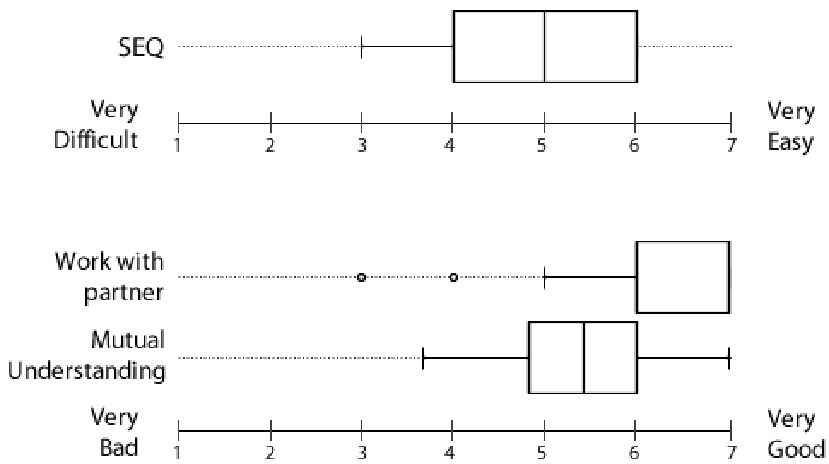


Source: the author.

Figure 6.23 shows the summary of the results for the post-task questionnaires. SEQ scores yielded 4.8 on average (SD = 1), while the answer for "How good it was to work with your partner" yielded 5.9 (SD = 1.1).

Mutual understanding (BIOCCA; HARMS; GREGG, 2001) was measured by six items (three matched pairs): "My opinions were clear to the other" and "The opinions of the other were clear", "My thoughts were clear to my partner" and "The other individual's thoughts were clear to me", and "The other understood what I meant" and "I understood what the other meant". Overall, mutual understanding was good with 5.3 (SD = 0.8).

Figure 6.23 - SEQ (M = 4.8, SD = 1), How good it was to work with your partner (M = 5.9, SD = 1.1), and Mutual Understanding (M = 5.3, SD = 0.8)



Source: the author.

6.2.2.3 Discussion and Conclusion

6.2.2.3.1 Interpretation vs. Articulation

Regarding the Interpretation task, every signal in the set of tactile cues yielded high accuracy. However, subjects took more time overall to interpret the signal for *Near R/L*.

Since *Near R/L* is composed of a short and fast sequence, differentiating it from a longer sequence might be the cause for the delay in answering its meaning. Yet, the set of vibrotactile signals was refined during pre-test. Thus, taking the results from the interpretation of the signals, an MDS analysis was able to show that the vibrotactile cues were very distinct from each other. In fact, interpretation of the tactile cues yielded higher accuracy than the articulation of the same cues.

The confusion matrix for articulation on Table 6.4 shows that most of the errors happened by doing a tap instead of the correct gesture. It happened mostly due to hesitation during the trials when subjects touched the screen by mistake while trying to reach the screen. That "slip of the finger" effect seemed to be much more frequent when subjects were preparing themselves to perform swipes. This is also an issue reported for other wearable touch interfaces (e.g. Google Pixel Buds [2]), when users grab the device and end up by triggering some function with a tap gesture. The amount of Positive signals shown in Figure 6.21 is still a remainder of such "slip of the finger" effect. Thus, one general guideline that can be drawn from such effects is to avoid the use of single taps to trigger primary actions in any touch interface.

6.2.2.3.2 Tactile Intercommunication

All subjects were able to guide their partners to find the proper ingredients receiving instructions only by vibrotactile messages. Regardless of the impossibility of seeing each other and without being able to talk to each other, subjects could rapidly agree on a strategy and co-regulate their actions. Dyads could either decide to work on all the ingredients of one partner first or take time doing one ingredient for a subject at a time. Subjects could eventually articulate vibrotactile cues at the same time. However, every time a subject articulates a signal, both subjects feel that signal on their heads. Thus, the "talker" can "hear" their own words. Then, after articulating a couple of signals at the same time, one subject would stop and wait for the partner to adjust the conversational flow. In addition, even if someone committed a mistake (e.g. a "slip of the finger"), it could be worked around with the context, just like in a natural voice-based talk.

Another strategy observed concerned the strategy to solve the problem. Some dyads would perform the task in a very similar way to an exhaustive search. A subject would grab an ingredient and wait for a confirmation signal. If the ingredient was not correct, the subject would grab a different ingredient without waiting for a directional signal. In many occurrences, subjects would take more time than necessary to perform a long press when they wanted to point an ingredient. If their partners grabbed an ingredient in the mean time, they would drop the long press to confirm or not the object that was taken by their partners. Other dyads would optimize the conversation by dropping the use of the Negative signal. Instead of saying that their partners took the wrong ingredient, they just conveyed the direction of the proper ingredient. Then, the conversation would happen like this:
- User 1: *Far Right*.
- User 2 grabbed a Red Potion
- User 1: *Far Right*.
- User 2 grabbed a Pumpkin
- User 1: *Positive*.
- User 2 answered Pumpkin. Right answer.

[2]https://store.google.com/us/product/google_pixel_buds

That is the transcription of a short dialog between a dyad during the collaborative task. It shows that our system allowed subjects not only to communicate through vibration but also to perform communicative decisions about how to use the available vibrotactile vocabulary. Different from previous work where subjects could also build new signals during conversation (JESUS OLIVEIRA; NEDEL; MACIEL, 2016), we built a fixed vibrotactile vocabulary that subjects could use as common code and we focused only on their articulatory process. Future work should also assess the differences in the freedom of articulation and its implications to the communicative process.

To communicate only through tactile feedback is not a trivial task. As pointed out by MacLean (MACLEAN; HAYWARD, 2008), our subjects have been using vision for the kinds of tasks we test since early childhood, and they have been using the tactile version for only a short training period. Thus, the comparison between an unconventional modality such as vibrotactile intercommunication with a conventional talk would not be fair. With that in mind, our aim was not at accessing how vibrotactile communication outplays oral communication. Instead, our aim was at understanding how subjects communicate when they only have the tactile channel available. Still, our tactile task was rated mostly as being easy to perform.

6.2.2.3.3 Guidelines for Articulation

Knowing about the capabilities of the technique should allow developers to produce more usable interfaces and a better experience when interacting with this display.

Based on our experimental results from gesture reproduction with our back-of-HMD interface, we came up with a set of guidelines to orient the implementation of an articulatory screen for tactile intercommunication. They are:

- Regardless of actuator density in a tactile display, less than ten targets should be presented to the user to support better accuracy in target selection when tapping;

- For swipe gestures, accuracy and precision increase with a tangible reference. Thus, the touch surface should present borders or markers to serve as anchor points;

- Subjects are not precise when reproducing interval duration, thus gestures (such as double taps) should not demand precision in interval reproduction;

- Subjects reproduce the duration of taps with more precision for longer duration times (e.g. 800ms). Thus, when using rhythm to encode tactile information, short vibration bursts should be avoided.

6.2.2.3.4 Applications

In this work, we provide a way for subjects to articulate vibrotactile cues using a horizontal array of tactors around the head. Even thought tactors are placed very close to each other, people can reproduce basic gestures to express different tactile messages in a vibrotactile array. Since arrays of actuators are easy to embed in other wearable pieces, it increases the possibilities for applying this setup in other contexts and devices. Some smart glasses (e.g. Google Glass, Vuzix) and VR headsets (e.g. Samsung Gear VR) already present lateral trackpads for interaction with the virtual content. They could be used for tactile articulation as well. The articulatory screen could be used for touch intercommunication, but also for object selection with gaze tracking, and for navigating GUIs.

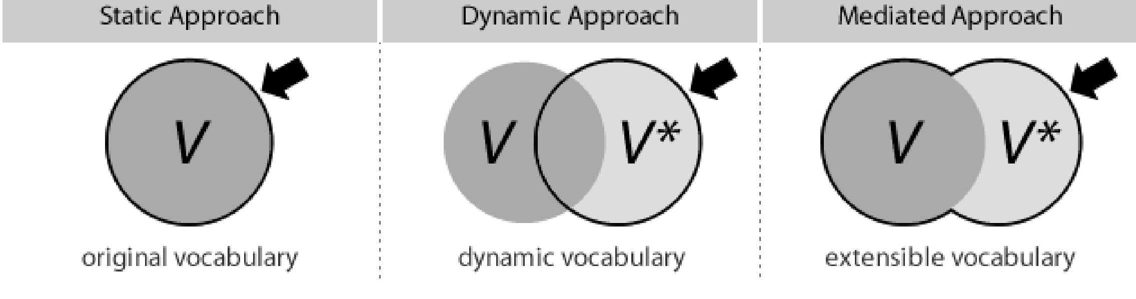
Applications for tactile feedback in collaborative work and intercommunication are many and it could also support remote guidance, entertainment, and training in both virtual and physical environments. For instance, if the display is removed, it is possible to create a headpiece that can be attached to hats and helmets for vibrotactile output only. Thus, since tactile feedback is used as a means to convey information in a non-obtrusive way, interaction by touch would provide a compatible input. Just by touching your wearable device, you can send a tactile message to a person next to you or even at a remote venue. Without looking at a screen, the person would receive and understand your message, in a silent conversation. It can be applied to tactical communication and to guide miner works and firefighters from a distance, for instance.

6.3 Assessing Articulatory Modalities for Intercommunication

In this final iteration we used the same collaborative task and apparatus from the previous study (Section 6.2) to assess how the translation between articulatory gestures and tactile signals should be performed.

In previous works, users could trigger tactile cues by pressing buttons, performing specific gestures, or even selecting graphical icons on a display (CHAN; MACLEAN; MCGRENERE, 2008; BROWN; WILLIAMSON, 2007; CHANG et al., 2002; ISRAR; ZHAO; SCHNEIDER, 2015). However, since the interface delimitates the articulation of the signals, it hinders the users' autonomy. As a consequence, the given tactile vocabulary may become stagnant and restrictive in two-way interactions (this can be called a *static approach*). Instead, users can have more freedom to articulate tactile cues by receiving more access to the hardware parameters. Such approach increases user's autonomy and allows users to adapt the tactile signals according to their communication needs (JESUS OLIVEIRA; NEDEL; MACIEL, 2016) (this can be called a *dynamic approach*). However, variability in articulation might produce tactile signals that are not perceptually suitable, hindering mutual understanding during intercommunication. Here, we propose a *mediated approach* in which small variations of articulatory gestures are suppressed to not affect the corresponding tactile signals, but completely new articulations still can produce new tactile signals (see Figure 6.24).

Figure 6.24 - A Static approach preserves the original tactile vocabulary (V), while a Dynamic approach allows interlocutors to express it in different ways and even to include new signals to it (V*). A Mediated approach though can preserve the given vocabulary and still allows the addition of new signals



Source: the author.

In this study, we explore the trade-off between freedom of articulation and mutual understanding by comparing three articulatory approaches: static, dynamic, and mediated articulation. Each articulatory condition varies in how much the articulatory gesture affects the final tactile signal. First, we designed and assessed a set of vibrotactile signals to support tactile guidance. Then, subjects were paired to perform a collaborative task in an immersive virtual setup using a vibrotactile HMD and the given tactile vocabulary to guide each other. We assessed their performance during the task as a function of each articulatory condition. In addition, we assessed subjective measures, such as workload, easiness, and mutual understanding during the task for each condition.

6.3.1 Materials and Methods

6.3.1.1 Subjects

Twenty subjects participated voluntarily in the study (14 males and 6 females). Their ages ranged from 17 to 26 years (M = 21, SD = 2.5). They participated in pairs (i.e. 10 dyads) and each pair knew each other before the experiment. All subjects read and agreed with an Informed Consent Form before the experiment as required by the Helsinki declaration.

Handedness was assessed with an Edinburgh Handedness Inventory (DRAGOVIC, 2004) and fifteen subjects were shown to be right-handed, while the remaining were marked as mixed-handed. Three subjects reported that they never used a VR headset or any tracking device before. In addition, eleven subjects reported having some visual problem, namely eight cases of Myopia (one of them also presented Keratoconus) and three cases of Astigmatism (one of them with Hyperopia). No correlation was found between these individual differences and their performance during the experiment.

6.3.1.2 Stimuli Set and Conditions

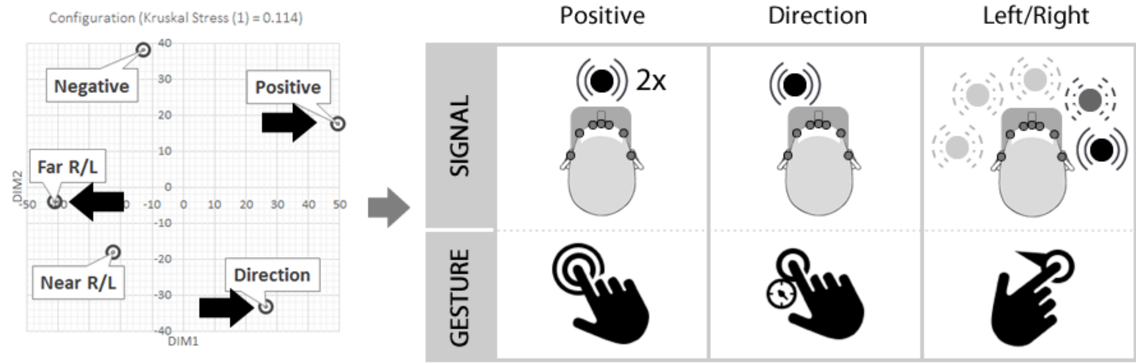
After a perceptual adjustment, the final vibrotactile vocabulary was composed of only three sets of signals: Positive signal, Direction signals, and Right/Left signals (see Figure 6.25).

The *Direction* of an ingredient is given from an egocentric perspective. If the subject performs a long tap anywhere on the screen while facing an ingredient, the tactor facing the ingredient position starts to vibrate indicating its position. The other subject feels a vibration and turns the face towards the target felt until the vibration is perceived on the center of the forehead, indicating that the subject is now facing the proper ingredient. Such stimulus is conventionally used for guidance (JESUS OLIVEIRA et al., 2016b). When a subject grabs an ingredient, the partner can confirm the selection with a *Positive* signal using a double tap. The subject can also say that an ingredient is more on the left or more on the right of the table with a swipe towards the correspondent direction. This *Left/Right* signal was also used before for guidance using a vibrotactile HMD (KERDEGARI; PRESCOTT; KIM, 2016). The burst duration for all signals has 200*ms* as well as the interval between two bursts. Sequences are activated without interval between bursts. To make sure subjects are aware of the stimuli they produce on their team partners, they also receive the same vibrating feedback.

In the *Static articulation*, the system only recognizes the three predefined gestures (double tap, long tap, and swipe). Even swipe gestures of different lengths always trigger the same Left/Right signal. Any other gesture (e.g. short taps) are suppressed[3]. In the

[3] Suppressed signals are not rendered and the person who articulated the gesture is aware that the gesture

Figure 6.25 - (left) MDS solution for the adjustment of an initial vocabulary in 2 dimensions. The stress is a measure of the fitness of the space's dimension based on perceived distances between stimuli (TERNES; MACLEAN, 2008); (right) Gestures and resulting vibrotactile feedback



Source: the author.

Dynamic articulation, every signal is produced according to the articulated gesture, and it can change in position and duration. Thus, the position of vibration, length of a sequence, and burst/interburst duration are modified as a function of the articulatory gesture (e.g. a slow swipe will result in a slow sequence of actuation). When it comes to the *Mediated condition*, the system also recognizes variations of the three predefined gestures. However, other gestures are not suppressed (e.g. a slow swipe will not slow down the sequence of actuation, but short taps are triggered according to the tapped position).

6.3.1.3 Experimental Protocol

Each subject filled out a demographic questionnaire and read instructions before starting the experiment. Then, each subject had to perform an Interpretation test, where the subject had to feel a vibrotactile signal and answer what is the meaning of that signal. Ten signals were presented in a randomized order. Subjects did not practice before the task, so it served to reinforce the learning of the vibrotactile vocabulary as well.

Finally, subjects had to perform the collaborative task in dyads. Tests were done in a dedicated room. Each subject was set in a swivel chair at one of the sides of the room. Each one of them was wearing a VR headset with the vibrotactile headband, the articulatory screen, and a Leap Motion mounted on the headset. Subjects had an ambient sound (music) played on their Oculus headphones and were instructed to not talk to each other.

Every subject had ten ingredients each (total of twenty) to select in a given order. The selection order was randomized across sessions. They could not see each other, but they viewed the table from the same perspective. They selected ingredients by gazing towards the object and grabbing with a pinch gesture (captured by the Leap Motion, as shown in Figure 6.9 (right)). A small reticle was shown at the center of the field of view to provide a reference for selection. Subjects performed a practice session to understand the elements of the virtual scene. Then they performed three sessions of the collaborative task. Each session corresponded to an articulatory condition and the sessions were counterbalanced across dyads. The whole experiment took on average 50 minutes.

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was not recognized by the system.

The performance was assessed as the number of correct ingredients selected during the task, duration, and use of tactile signals. After each session, subjects filled out a Mutual Understanding questionnaire (BIOCCA; HARMS; GREGG, 2001) and a SEQ (SAURO; DUMAS, 2009) as usability measure. Subjects also had to fill out a NASA-TLX questionnaire (HART, 2006) to self-judge their task load.

6.3.2 Results

6.3.2.1 Interpretation of Tactile Signals

Table 6.5 shows the confusion matrix for the interpretation task. Without having experienced the stimuli before, subjects were able to properly interpret the meaning of more than 80% of each tactile signal. The Direction Signal, which corresponds to a long vibration towards a given direction, was the most mistaken with 83% of right answers. In this case, 10% of the trials were marked as a Left/Right signal that corresponds to a sequence of actuation moving to the left or to the right.

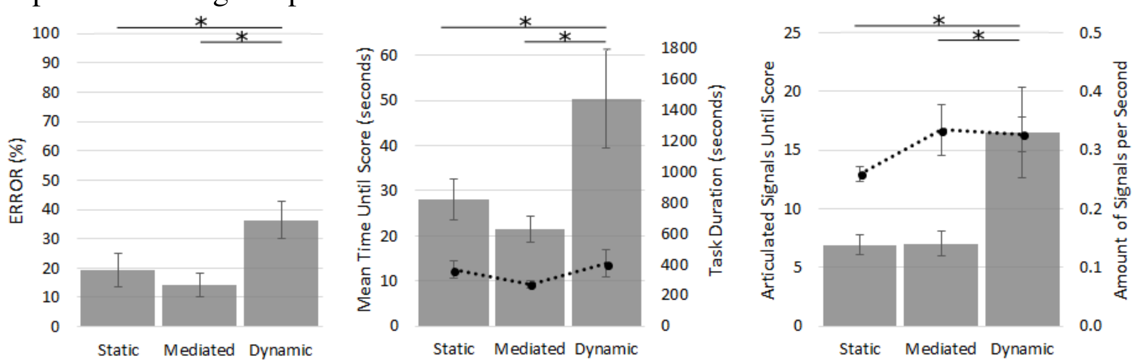
Table 6.5 Signal Interpretation Confusion Matrix, N = 3 [Response (%)]

	"Positive"	"Direction"	"Left/Right"	" "
Positive Signal	**96.67**	0.00	0.00	3.33
Direction Signal	3.33	**83.33**	10.00	3.33
Left/Right Signal	0.00	3.75	**92.50**	3.75

6.3.2.2 Performance and Behavior

Figure 6.26 shows the average performance of dyads for each articulatory condition.

Figure 6.26 - Bar plots represent left axis and line plots represent right axis. (left) Dynamic articulation yields more errors (M = 36%; SE = 6.3) than Static (M = 19%; SE = 5.5) and Mediated (M = 14%; SE = 4.1); (center) It takes more time to select a correct item with Dynamic articulation (M = 50s; SE = 10.8) compared to Static (M = 28s; SE = 4.5) and Mediated (M = 21s; SE = 2.8). Mean time for each task was of 348s; (right) It takes more signals to indicate the correct item with Dynamic articulation (M = 16; SE = 3.8) compared to Static (M = 6; SE = 0.9) and Mediated (M = 7; SE = 1.1). Subjects expressed less signals per second with Static condition



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A One-Way ANOVA test shows that the articulatory modality has an effect on the amount of items selected by mistake during the task [F(2,27) = 4.7339, p = 0.017] (see

Figure 6.26 (left)). Post-hoc comparisons with Student's t-test indicated that with the Dynamic articulation dyads mistake more items compared to the use of Static ($p < 0.05$) and Mediated articulation ($p < 0.01$).

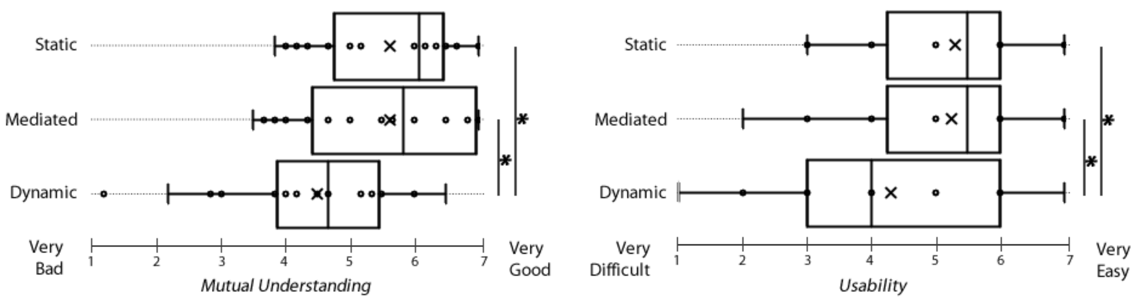
When it comes to the total time for performing each task, there was no significant difference between conditions (see Figure 6.26 (center-second axis)). However, the articulatory conditions presented an effect on the time it took to select the correct item [F(2,27) = 4.7588, p = 0.0166] (see Figure 6.26 (center-first axis)). When using the Dynamic condition, dyads take more time to find the correct item compared to Static ($p < 0.05$) and Mediated modalities ($p < 0.01$).

On average, dyads exchange more tactile signals per second using Mediated and Dynamic articulation than the Static modality, with no significant difference between the amount of articulated signals for each condition (see Figure 6.26 (right-second axis)). Yet, there is an effect of the articulatory modality on the amount of signals exchanged to select an item correctly [F(2,27) = 5.3676, p = 0.0109] (see Figure 6.26 (right-first axis)). Post-hoc comparisons indicated that, to choose the correct item, dyads have to articulate more signals with the Dynamic modality compared to both Static and Mediated modalities ($p < 0.01$).

6.3.2.3 User Experience

Figure 6.27 shows the subjects' evaluation for mutual understanding and usability during the collaborative task for each articulatory condition.

Figure 6.27 - (left) Mutual Understanding was better for Static (M = 5.6; SE = 0.3) and Mediated (M = 5.6; SE = 0.4) compared to Dynamic articulation (M = 4.5; SE = 0.4); (right) It was also easier to perform the task with Static (M = 5.3; SE = 0.4) and Mediated (M = 5.3; SE = 0.4) conditions compared to Dynamic (M = 4.3; SE = 0.5) condition according to the SEQ scale



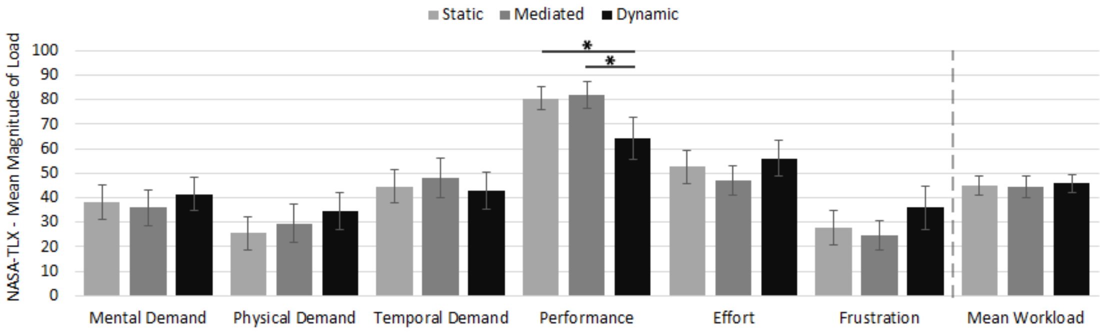
Source: the author.

Figure 6.27 (left) shows that the articulatory modality has an effect on mutual understanding [F(2,57) = 5.6857, p = 0.0059]. Post-hoc comparisons indicated that understanding a partner during the collaborative task is more difficult when using the Dynamic modality compared to the remaining modalities ($p < 0.01$).

Figure 6.27 (right) shows that there is also an effect of the articulatory modality on usability [F(2,57) = 3.1708, p = 0.0481]. It is harder to perform the task using the Dynamic modality over both Static and Mediated modalities ($p < 0.05$).

The overall workload did not vary significantly across conditions (see Figure 6.28). However, articulatory conditions had an effect on the Performance dimension for the NASA-TLX [F(2,57) = 4.7991, p = 0.0118]. The perceived performance when using the Dynamic articulation was more affected than the performance for Static ($p < 0.05$) and Mediated modalities ($p < 0.01$).

Figure 6.28 - Mean scores from NASA-TLX. Mean workload did not vary significantly between Static (M = 44.7; SE = 3.8), Mediated (M = 44.5; SE = 4.4), and Dynamic (M = 45.8; SE = 3.6) conditions. The perceived performance, though, was worse for Dynamic condition (M = 64; SE = 8.5) compared to Static (M = 80; SE = 4.6) and Mediated (M = 82; SE = 5.5)



Source: the author.

6.3.3 Discussion and Conclusion

In this study, we show that a dynamic vocabulary, that has position and duration transformed according to the articulatory gesture, is more difficult to understand during a collaborative task. The changes in the given stimuli set affect communication, and therefore the performance of the dyad during the task. Like in any conversation, the participants try to establish whether what has been said has been understood (in a grounding process (CLARK; BRENNAN et al., 1991)). For the tactile intercommunication, the grounding process can be expressed in terms of the time and the number of signals necessary to establish what is a correct item to be selected. Thus, the Dynamic condition was shown to take more time and more signals in the grounding process. It was also more difficult to understand and to perform when using such modality.

Previous work has shown that interlocutors are able to modify a tactile vocabulary according to their needs using a dynamic approach (JESUS OLIVEIRA; NEDEL; MACIEL, 2016). With the Dynamic approach, subjects might reproduce signals in different ways or even create new ones. Thus, the tactile vocabulary that emerges during the tactile communication might differ from the original. However, in our experiment, dyads did not have the time or the complementary channels to agree with variations of a given signal or to the addition of new signals.

Tactile feedback is especially useful when other senses are overloaded or unavailable. With the ability to articulate tactile signals, subjects can receive feedback from peers (e.g. a specialist from distance) instead of receiving feedback only from a machine. For that, a Static articulation is well suited. Yet, results show that a Mediated condition did not vary significantly in performance, usability, and mutual understanding compared to the Static condition. Moreover, the Mediated condition allowed subjects to vary a few parameters and to express more signals than the given stimuli set. Therefore, it is reasonable to assume that there is an advantage in preserving the given vocabulary to some extent and still allow users to extrapolate the given vocabulary to some extent to provide flexibility during the conversation.

6.4 Summary

In this last phase of our Thesis, we have applied the Tactile Fovea technique (presented at Chapter 4) to design a vibrotactile HMD for VR interaction. In addition, we applied the Proactive Haptics paradigm (presented at Chapter 5) to design an articulatory interface for the same vibrotactile HMD. The contributions of this final phase of our study include:

- The design of a usable vibrotactile display for spatial awareness in 3D spaces;
- The assessment of different frequency modalities for encoding vibrotactile information;
- The design and assessment of a usable articulatory interface for vibrotactile intercommunication;
- The assessment of different gestures for tactile articulation using back-of-HMD interaction;
- The refinement of a vibrotactile vocabulary for intercommunication and guidance;
- The assessment of different approaches for mapping tactile articulation and cueing during intercommunication.

7 CONCLUSION

In this Thesis, our goal was to study and develop effective tactile interfaces for communication. More than that, our goal was to provide more autonomy and control to the user in order to participate proactively in the communication flow. Therefore, we took into account different tasks, contexts, and user profiles and also the intercommunication process to propose and assess new interfaces and techniques.

Our approach facing this research was an experiment-guided study aiming at converging to effective tactile interfaces and approaches for tactile communication and intercommunication in physical and virtual environments. As reported, we proceeded in three phases:

1. First, we explored different body sites, assessing performance during target localization, perception to vibrotactile cues, different tasks, and user profiles. During that phase, we designed and fully assessed a tactile display to be used around the head;

2. Then, we explored tactile communication from a different angle, focusing on intercommunication and allowing users to use touch and a channel for expressive communication with others;

3. Finally, we applied the knowledge and technology produced in the first two phases to design and assess a vibrotactile HMD for communication and intercommunication in virtual environments.

7.1 Thesis Contributions

7.1.1 Head Stimulation

The study of the head as loci for vibrotactile stimulation is one of the main contributions of this work. Wearable vibrotactile displays are fashioned in different ways, but the most conventional form is the vibrotactile belt e the vibrotactile vests to render vibrotactile cues on the user's trunk. The main advantage of trunk stimulation is to receive directional cues from egocentric perspective to support navigation and wayfinding tasks. In our work we explored the head, demonstrating that, more than navigation, the head stimulation can also support spatial awareness and attention redirection.

Our vibrotactile headpiece was the result of a thorough study assessing perception, usability, and performance in different tasks including multiple users. The subjects in our experiments were composed by blind and sighted subjects from different ages. That only reinforces the versatility of our display and techniques. Some general guidelines that can be drawn from our results on head stimulation include:

- Precision for spatial discrimination around the head is higher on the forehead;
- Precision for spatial discrimination around the head decreases according to skin type (hairy or glabrous) and its distance from the head midline;
- The distance between tactors should be kept above 15*mm* (edge-to-edge) if the response time of the application is crucial (e.g. for emergency signals and alert);
- A regular tactor coverage of 45° allows the user to be fast but not accurate, nor precise in a localization task;
- By reducing tactor coverage to 15° allows the user to be precise but not fast in a localization task;
- Increasing actuator density on the forehead is enough to increase precision and accuracy in an active detection task;
- Even during active exploration, users can localize targets with 99.5% of accuracy using the Tactile Fovea configuration;
- Deviation errors during a straight walk task can be reduced in average 11% from the baseline veering when using the vibrotactile HMD;
- The veering tendency can be significantly reduced with vibration for both blind and blindfolded subjects.

By the time we performed our first studies with head stimulation, there were not many previous applications to serve as a baseline for comparison. Nowadays, head stimulation has been implemented with different actuators, including thermal technologies. Our studies are also being used as a reference for new studies, some of which even adapted the Tactile Fovea technique proposed in this thesis for building different tactile displays mounted on the head (CHEN; PEIRIS; MINAMIZAWA, 2017a; LANGE et al., 2017; PEIRIS et al., 2017; RANTALA; KANGAS; RAISAMO, 2017).

7.1.2 Tactile Communication

One of the main contributions of this research is the proposal and study of a different approach for tactile communication. With Proactive Haptics we allow users to act as interlocutors, using tactile cues for interpersonal communication. In our studies, tactile icons were not used as a gimmick or complementary cues during conventional communication but rather the main channel for communication. A vibrotactile vocabulary was given as the main language, shared by the interlocutors. Yet, with the freedom to articulate vibrotactile signals, the interlocutors could have autonomy to build their tactile dialogues. More than that, according to the mapping or articulatory approach, interlocutors could even build their own signals to better convey some information during the dialogue.

We also demonstrated and assessed different aspects from tactile intercommunication proposing ways for users to integrate proprioception and cutaneous feedback. Such interaction allows for a better metaphor for the ability to touch and be touched in computer-mediated interactions. Some general guidelines that can be drawn from our results on tactile intercommunication include:

- Tactile articulation allows the users to express themselves through tactile cues;

- The design of tactile interfaces for intercommunication should consider not only tactile perception but also tactile articulation;
- Users can communicate through vibrotactile feedback with almost the same time and performance of users that use speech;
- Providing more freedom for articulation, interlocutors can adapt the given vocabulary by doing both syntactic and semantic neologisms;
- A tactile conversational flow is allowed by tactile articulation and might be affected by the same phenomena related to speech;

Our concept for Proactive Haptics respects the conventional structure of natural communication and speech. Therefore, it is expected that the tactile communication is affected by the same phenomena that affect speech communication when interlocutors express themselves through tactile signals. The theoretical foundation of Proactive Haptics should support new techniques and interfaces for haptic interaction in computer-mediated communication.

7.1.3 Virtual Reality

Finally, another contribution of our research is the design and assessment of an interface for multisensory interaction with VR. In our research, after studying head stimulation and tactile intercommunication, we applied our results to the design of a vibrotactile HMD to support spatial awareness in 3D spaces and also intercommunication in collaborative virtual environments.

The vibrotactile HMD is composed by a graphical display and a vibrotactile headband implementing the Tactile Fovea. It serves as a model for a single apparatus that is capable of rendering tactile information about objects around users and even placed outside their field of view. By modulating vibration parameters, we can convey information about the position of objects keeping few actuators in the display. This low-density tactile display can then be easily implemented in different commercial HMDs for VR/AR interaction.

The vibrotactile HMD also implements Proactive Haptics with a touch interface made for the articulation of tactile cues. After assessing perception, performance, usability, and mutual understanding in collaborative tasks, we demonstrate that such interface allows intercommunication and mutual guidance in immersive setups. To the extent of our knowledge, no other device exists that allows both tactile communication and intercommunication in VR and that was thoroughly assessed for perception and articulation of tactile signals.

Some general guidelines that can be drawn from our results include:

- Tactile feedback can be rendered in virtual headsets using the Tactile Fovea;
- A quadratic function is better to modulate frequencies in an active pointing task;
- Targets should not be placed bellow -22.5° in elevation around the user;
- Users are able to integrate location and frequency modulation during guidance;
- The visual aspect of the virtual scene is not likely to affect the user performance during tactile exploration;

- Back-of-device interaction should use simple 1D gestures (e.g. taps, and swipes);
- Matching the articulatory gestures to the tactile signals makes it easy to learn the vocabulary;
- Regardless of actuator density in a tactile display, less than ten targets should be presented to the user to support better accuracy in target selection when tapping;
- For swipe gestures, accuracy and precision increase with a tangible reference;
- Subjects are not precise when reproducing interval duration;
- Subjects reproduce the duration of taps with more precision for longer duration times (e.g. 800ms);
- Back-of-device touch interfaces should avoid triggering actions with single taps;
- If it the designer of the haptic interface opts for a static tactile vocabulary, a static articulatory method can be adopted to allow intercommunication;
- If it the designer of the haptic interface opts for a dynamic tactile vocabulary, a mediated articulatory method can be adopted to provide certain freedom to the user while preserving part of the given vocabulary.

7.2 Perspectives

Limitations of this study include the assessment of the external validity of our vibrotactile interfaces and techniques. Due to the controlled variables and conditions, our techniques have not been tested outdoors for navigation in the street nor for unassisted interaction with virtual environments. Further studies would be fundamental to assess final devices and prototypes outside the lab for daily tasks. Further studies should also address the tasks and contexts in which trunk or head might be better suitable for tactile stimulation.

Regarding Proactive Haptics, further studies could demonstrate its application to other aspects of collaborative work. For instance, how to design haptic interfaces that allow awareness of both the shared workspace and the peers in a collaborative setup. In addition, even though we proposed the concept of Haptic Articulation, we actually assessed mostly tactile articulation and perception. Other actuators should be tested in order to better understand how other parameters from other stimuli and technologies (e.g. force-feedback, thermal feedback, pain, pressure, etc.) can fit our concept.

Looking farther in the future, we imagine having more effective tactile interfaces inserted ubiquitously in our spaces, portable devices, and clothes. When we first started our studies with tactile interaction, we were looking towards a reality in which our own clothes would be smart and able to render extra and useful information on our skin at any time. Nowadays, commercial projects, such as the Jaquard [1] in which Google and Levi's collaborate creating smart fabric and clothes, reinforces the proximity to such reality, in which tactile interaction would be pervasive. Meanwhile, our techniques can be implemented with extra sensors and applied to conventional clothing for effective tactile interaction with physical and virtual environments, and for communication and intercommunication with computer agents and between individuals.

[1] https://atap.google.com/jacquard/

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APPENDIX A INTERFACES HÁPTICAS E SUA APLICAÇÃO EM COMUNICAÇÃO TÁTIL MEDIADA POR COMPUTADOR

Resumo da Tese em Português

Feedback háptico é geralmente renderizado de forma reativa pelo sistema. Em geral, o sistema adquire as informações sobre o ambiente (por meio de sensores ou algoritmos predefinidos) e aciona o feedback tátil. No entanto, uma parte importante da interação social é perceber as necessidades e intenções dos outros e agir proativamente sobre essas percepções. Assim, em ambientes virtuais como na vida real, o toque também deve ser processado proativamente. Algumas interfaces hápticas afetivas permitem que os usuários troquem proativamente sinais táteis simples para expressar emoções, mas tais sinais não suportam a troca de conteúdo informativo. Mesmo em sistemas informativos táteis, os interlocutores devem ser capazes de se expressar através de sinais táteis.

Portanto, como na linguagem falada onde nossa enunciação está relacionada ao nosso controle sobre o aparato vocal, nós propomos que a articulação háptica esteja relacionada ao nosso controle sobre os parâmetros hápticos. A possibilidade de acessar diferentes conjuntos de parâmetros hápticos dá ao usuário a capacidade de articular tato proativamente. Desta forma, a intercomunicação tátil não deve ser apenas proativa, mas expressiva, dinâmica e direta, como a articulação da fala.

A capacidade de articular sinais hápticos mecânicos deve fornecer um meio para os indivíduos se expressarem através de háptica em cenários mediados por computador. Ao invés de aprender um determinado vocabulário háptico e apenas percebê-lo passivamente durante uma tarefa, os usuários também podem agir em seu ambiente usando o canal háptico, aplicando ou mesmo modificando o vocabulário háptico fornecido. Assim, as contribuições de uma pesquisa sobre a articulação háptica podem ser aplicadas a diversas aplicações. Entre as possíveis aplicações, podemos citar o uso da articulação háptica como um canal alternativo para comunicação, como sentido suplementar durante a comunicação, e para o design de vocabulário háptico centrado no usuário.

Portanto, o objetivo geral desta pesquisa foi desenvolver interfaces táteis efetivas para comunicação, levando em consideração seu uso para intercomunicação entre indivíduos e elementos relacionados à articulação pró-ativa de sinais táteis.

Para desenvolver esta tese, nos concentramos em um estudo guiado por experimentos visando convergir para interfaces tátil eficazes e abordagens para comunicação tátil e intercomunicação em ambientes físicos e virtuais. Tal estudo foi feito em três fases incrementais: estudo e projeto de um display tátil de uso geral, proposta de novo paradigma para interação tátil, e estudo e projeto de um display tátil para comunicação e intercomunicação em ambientes virtuais imersivos.

A.1 Estudo e Projeto de um Display Tátil Montado na Cabeça

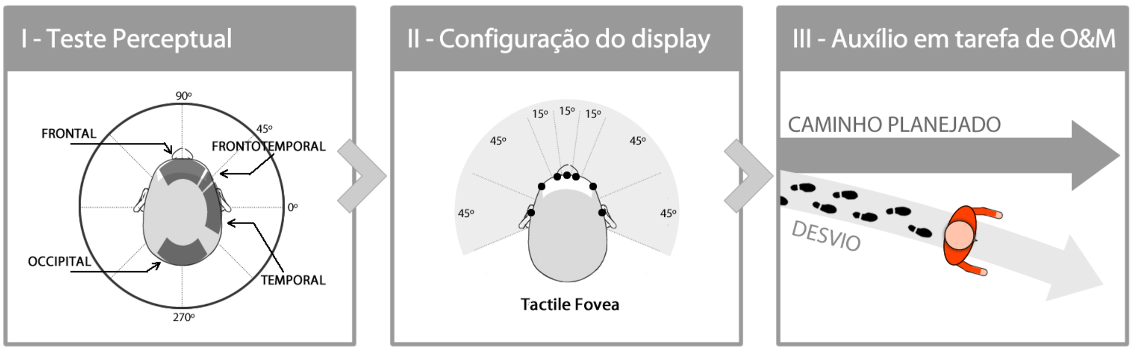
Na primeira fase do nosso estudo, foram exploradas diferentes variáveis relacionadas ao projeto de representações hápticas para podermos projetar uma interface tátil mais versátil. A partir de um estudo preliminar, avaliou-se a agradabilidade e a confortabilidade de vibrações na cabeça, pescoço e tronco como alternativas para a indicação direcional a partir de uma perspectiva egocêntrica.

Confirmamos que a localização de estímulos táteis ao redor do pescoço é uma tarefa difícil de realizar, conforme relatado anteriormente por Morrow et al. (2016). No entanto, percebemos também que a cabeça poderia ser uma alternativa adequada para a navegação egocêntrica junto com o tronco.

A pele na cabeça é conhecida por ser uma das regiões do corpo humano mais sensíveis à estimulação mecânica. Há estudos em que atuadores vibratórios são acoplados a óculos, capacetes e faixas de cabeça para serem usados como Displays Táteis Montados na Cabeça (Head-Mounted Displays - HMDs) (RASH et al., 2009; NUKARINEN et al., 2015; KERDEGARI; KIM; PRESCOTT, 2015). Assim, a estimulação da cabeça é uma alternativa, especialmente para aplicações que usam capacetes de realidade virtual onde a interação é principalmente impulsionada pelos movimentos da cabeça.

Desse modo, realizamos um conjunto abrangente de experimentos para dar suporte ao design de HMDs vibrotáteis para aplicações relacionadas à conscientização espacial, navegação, e orientação em ambientes físicos e virtuais (ver Figura A.1).

Figure A.1 - Primeira série de estudos para projetar e avaliar uma interface tátil montada na cabeça do usuário



Source: the author.

Nossa abordagem para desenvolver esta tese começa com o estudo e o projeto de uma tela vibrotátil e versátil e eficaz. Para tanto, experimentos perceptuas, bem como experimentos de desempenho, foram feitos para apoiar a avaliação de diferentes aplicações e perfis de usuários. As contribuições dos estudos apresentados nesta primeira estapa estão descritas no Capítulo 4 e incluem:

- A prospecção de diferentes partes do corpo para comunicação tátil;
- A avaliação da acuidade da cabeça para estimulação vibrotátil;

- A avaliação de diferentes configurações para sinalização tátil ao redor da cabeça;
- O design de uma faixa de cabeça vibrotátil usando a técnica de Fovea Tátil;
- A demonstração do uso prático de nosso display vibrotátil em uma tarefa clássica de Orientação & Mobilidade.

Diferentemente do cinto vibrotátil projetado em nossos estudos anteriores, a faixa de cabeça vibrotátil é projetada para suportar não apenas a navegação, mas também o reconhecimento espacial e o redirecionamento de atenção em espaços virtuais e reais. No entanto, o paradigma de interação tátil com este dispositivo ainda é o mesmo dos nossos estudos anteriores, tendo os sinais táteis renderizados pelo computador e fornecendo apenas uma comunicação unidirecional com o usuário. Portanto, damos continuidade ao nosso estudo avaliando um paradigma diferente para comunicação, permitindo aos usuários intercomunicarem-se usando sinais vibrotáteis mais expressivos.

A.2 Háptica Proativa para Intercomunicação

Em uma segunda etapa de nossa pesquisa, for desenvolvida e testada uma aplicação para intercomunicação entre indivíduos (ver Figura A.2). Nessa aplicação, os interlocutores podiam se expressar livremente através do tato. Para isso, um usuário poderia tocar em seu corpo para estimular a área correspondente no corpo do seu parceiro em uma tarefa colaborativa.

Figure A.2 - Interface para a livre articulação tátil

Source: the author.

Embora o uso de sinais de vibração seja incomum na intercomunicação, os resultados mostraram que o desempenho dos sujeitos que o utilizaram predominantemente a vibração não foi significativamente afetado. Além disso, um estudo de caso mostrou que alguns dos usuários usaram a liberdade de expressão através de sinais táteis para adaptar o vocabulário proposto, fazendo neologismos sintáticos e semânticos.

Nesta fase, nossa contribuição não diz respeito a uma nova tecnologia para atuação ou a um novo método para a construção de padrões táteis, mas a uma nova abordagem para projetar a intercomunicação tátil de modo adaptativo baseada no conceito de articulação tátil. Assim, a adaptação dinâmica do vocabulário tátil tornou-se possível devido à capacidade de pronunciar proativamente sinais táteis. As contribuições deste estudo são apresentados no Capítulo 5 juntamente à formalização do conceito de articulação tátil.

Uma série de novos estudos com usuários foram projetados para validar os fatores que julgamos estar relacionados à dinamicidade da articulação tátil. Nosso objetivo neste estudo foi investigar se as mudanças no desempenho seriam significativamente maiores para outras tarefas em ambientes e cenários virtuais colaborativos. Nosso primeiro passo foi projetar um HMD vibrotátil para interação com ambientes virtuais, aplicando o conhecimento desta fase e da fase anterior. Em seguida, o objetivo foi implementar e avaliar interfaces e métodos articulatórios neste novo HMD vibrotátil.

A.3 Interação Tátil em Ambientes Virtuais Imersivos

Nesta fase final do desenvolvimento da Tese, aplicamos os resultados apresentados no Capítulo 4 e no Capítulo 5 ao projeto e avaliação de um HMD vibrotátil para interação com ambientes virtuais.

Nesta etapa, realizamos o projeto e a avaliação de um HMD vibrotátil feito para renderizar a posição de objetos em um espaço 3D (ou seja, codificando azimute e elevação). A seguir, realizamos o projeto e a avaliação de uma interface articulatória incorporada ao vibrotátil HMD para suportar intercomunicação tátil em ambientes virtuais imersivos. E finalmente, avaliamos diferentes abordagens de articulação tátil para entender o trade-off entre liberdade de articulação e compreensão mútua (ver Figura A.3).

Figure A.3 - Última série de estudos para projetar e avaliar uma interface tátil montada na cabeça do usuário para comunicação e intercomunicação em ambiente virtual

Source: the author.

As contribuições desta fase final do nosso estudo estão descritas no Capítulo 6 e incluem:

- O design de um display vibrotátil utilizável para a consciência espacial em espaços 3D;
- Avaliação de diferentes modalidades de frequência para codificação de informações vibrotáteis;
- Design e avaliação de uma interface articulatória utilizável para intercomunicação vibrotátil;
- Avaliação de diferentes gestos para articulação tátil utilizando a interação back-of-HMD;
- O refinamento de um vocabulário vibrotátil para intercomunicação e orientação;
- Avaliação de diferentes abordagens para mapeamento de articulação gestual e sinais de vibração durante a intercomunicação.

A.4 Conclusão

Nesta Tese, nosso objetivo foi estudar e desenvolver interfaces táteis eficazes para comunicação. Mais do que isso, nosso objetivo era proporcionar mais autonomia e controle ao usuário, a fim de permitir que o usuário participe de forma proativa no fluxo de comunicação. Portanto, levamos em conta diferentes tarefas, contextos e perfis de usuários e também o processo de intercomunicação para propor e avaliar novas interfaces e técnicas.

Nossa abordagem frente a essa pesquisa foi um estudo conduzido por experimentos com o objetivo de convergir para interfaces tátil eficazes e abordagens para comunicação tátil e intercomunicação em ambientes físicos e virtuais. Conforme relatado, procedemos em três fases:

1. Primeiramente, exploramos diferentes locais do corpo, avaliando o desempenho durante a localização do alvo, a percepção de sinais vibrotáteis, diferentes tarefas e perfis de usuário. Durante essa fase, projetamos e avaliamos uma tela tátil para ser usada ao redor da cabeça;

2. Em seguida, exploramos a comunicação tátil de um ângulo diferente, focando na intercomunicação e permitindo que os usuários usem o tato como um canal para comunicação expressiva com outros;

3. Finalmente, aplicamos o conhecimento e a tecnologia produzidos nas primeiras fases para projetar e avaliar um HMD vibrotátil para comunicação e intercomunicação em ambientes virtuais.

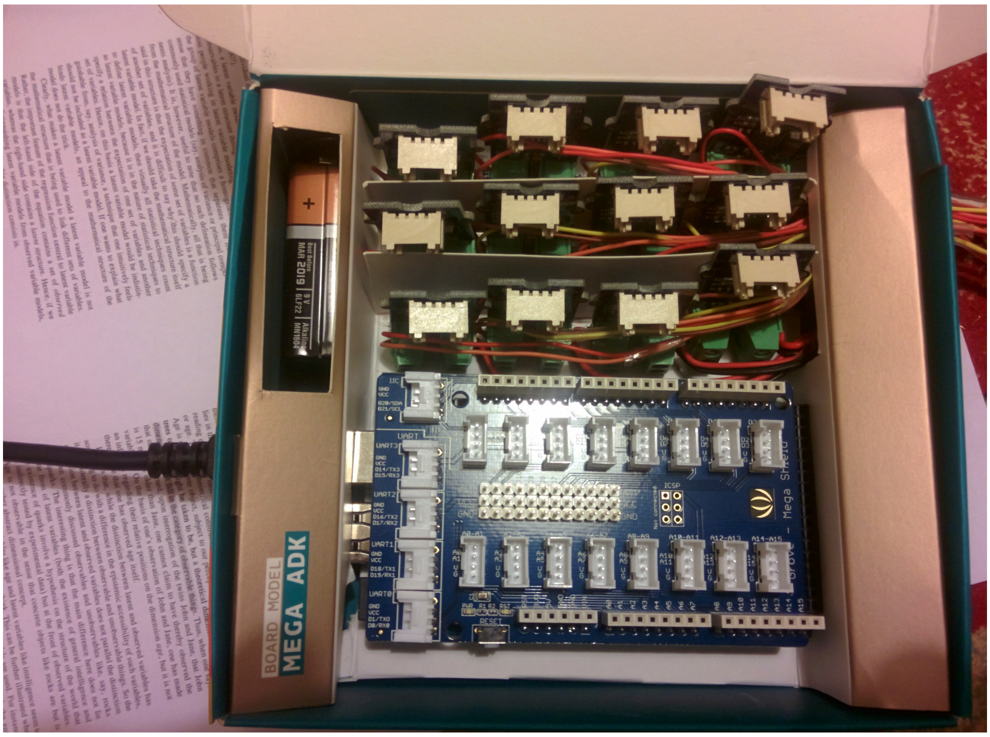
APPENDIX B VIBROTACTILE DISPLAY PROTOTYPE

Vibrotactile Headband with ERM motors
Components:

- Arduino MEGA ADK microcontroller board
- 12 Grove – MOSFET
- 12 motors 10mm shaftless, 3:4mm button type (310-101 Precision Microdrives)
- Grove - Mega Shield 1.0

Assembly:

Figure B.1 - Board and MOSFETs

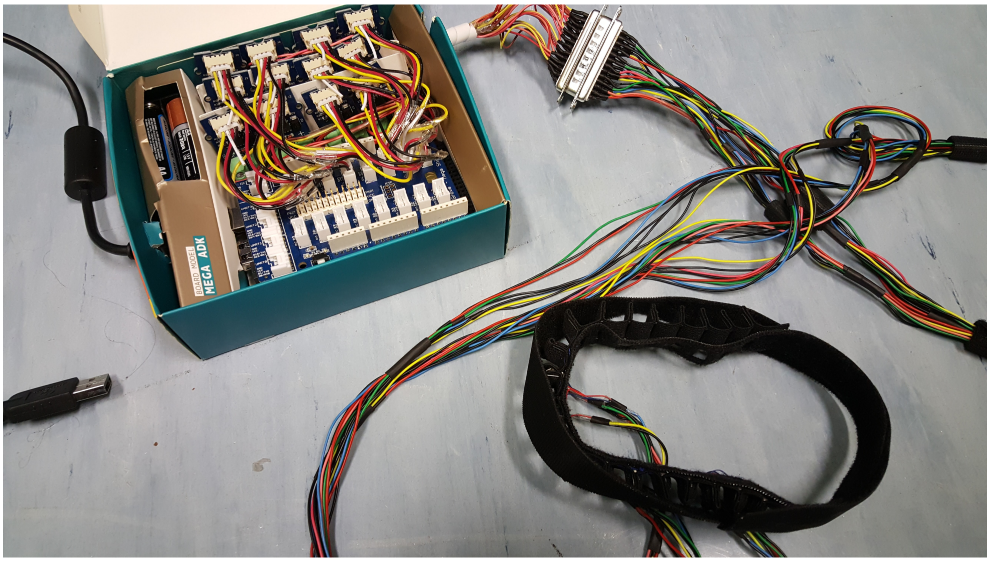


Source: the author.

Vibrotactile Headband with LRA motors
Components:

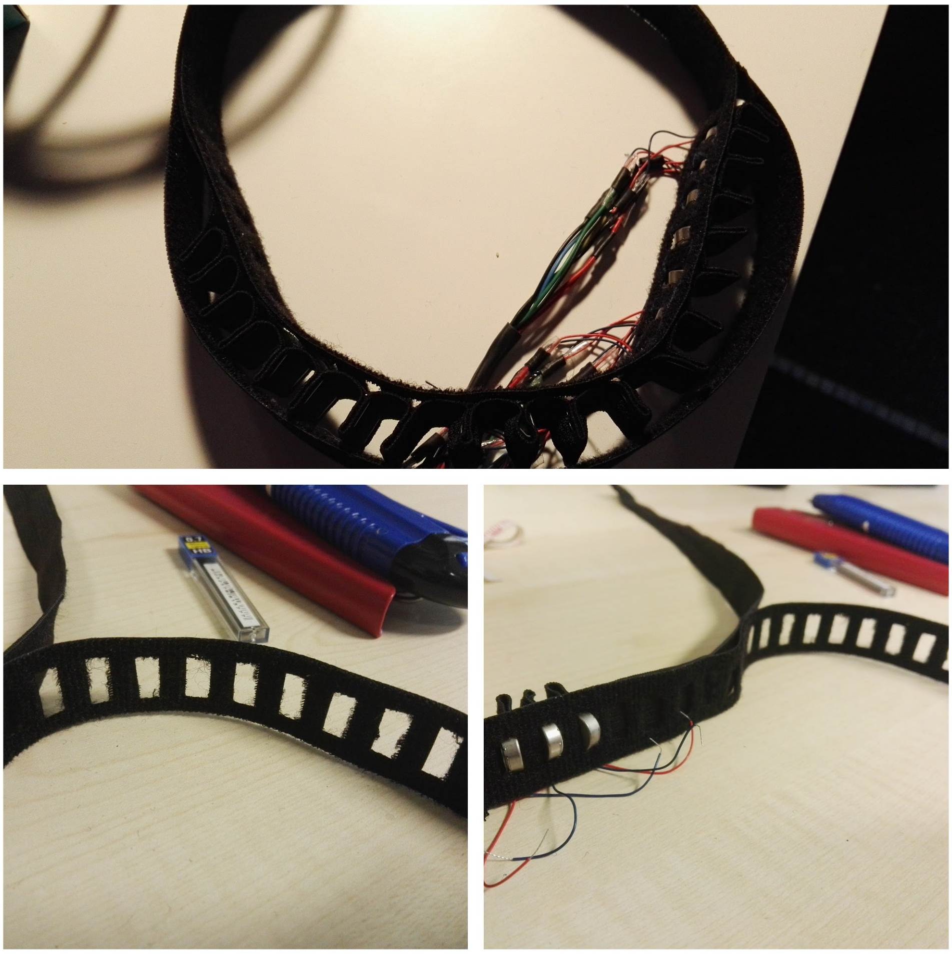
- Arduino MEGA ADK microcontroller board

Figure B.2 - Connections



Source: the author.

Figure B.3 - Headband



Source: the author.

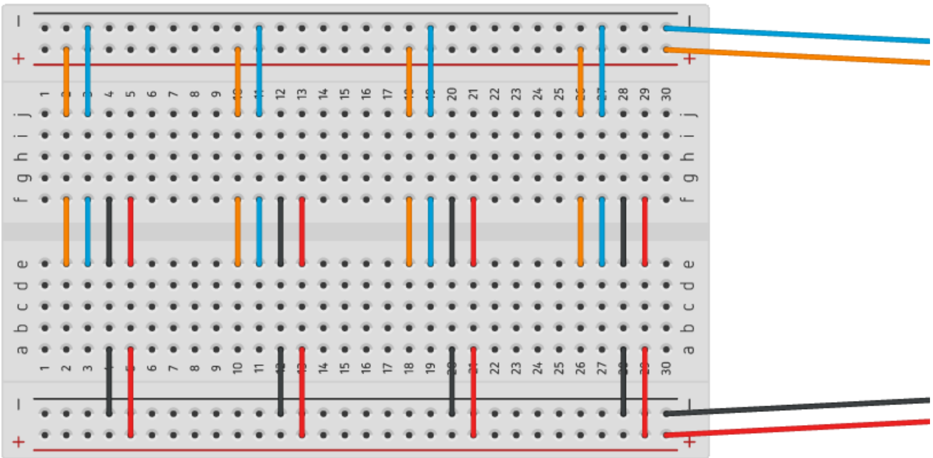
- Adafruit DRV2605L Haptic Motor Controller
- 10mm Linear Resonant Actuators 4mm type (C10-100 Precision Microdrives)
- Adafruit Perma-Proto Half-sized Breadboard

Assembly:

B.0.0.1 Circuit

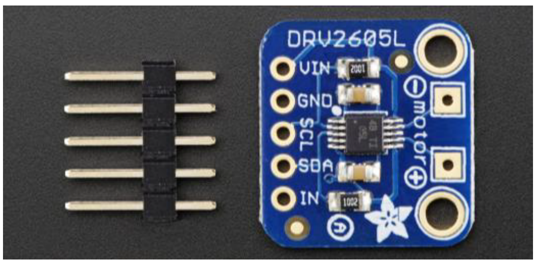
The circuit was built on a breadboard to receive the Haptic Driver component which has the inputs VIN, GND, SCL, SDA, and IN. VIN and GND appear in red and black, while SCL and SDA are blue and orange.

Figure B.4 - Preparing the breadboard



Source: the author.

Figure B.5 - Haptic Driver



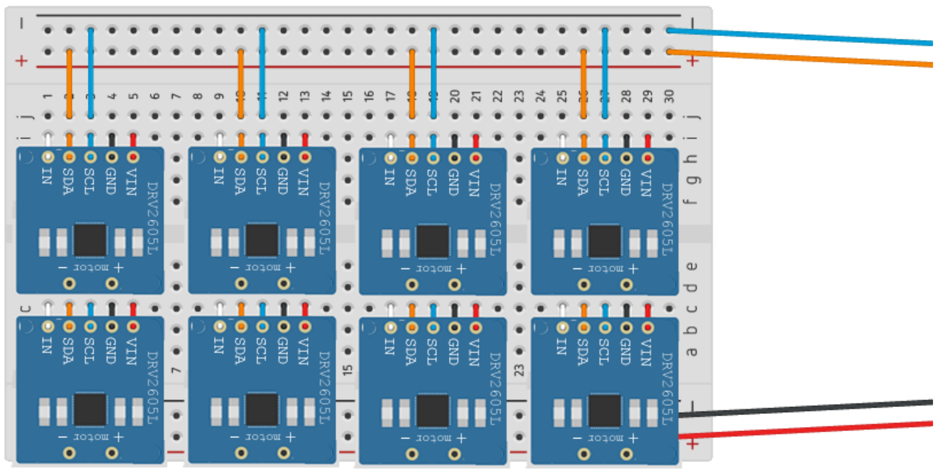
Source: the author.

Then, eight Haptic Drivers must be added to the board to control eight vibrating motors.

The VIN inputs on the haptic drivers are used to control the motor by PWM signal. They were connected to the Arduino board from the pins 2 to 9. Then, the SDA was connected to the pin 20 and the SCL to the pin 21 (those pins work for the Arduino Mega SDK, but differs for other boards). The GND was connected to the ground pin and the VIN pin was connected to the 3V pin.

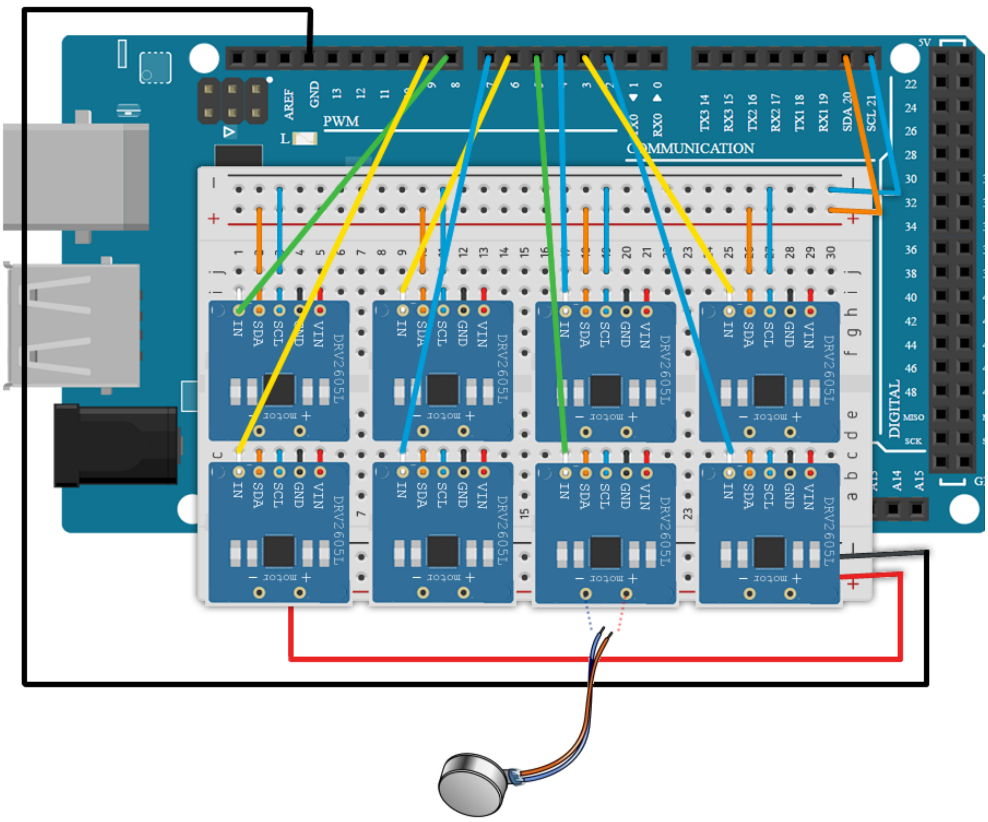
Then, the eight motors were connected to the drivers with cables of 1 meter each. The final board was placed on a container with the space for the Arduino and open spaces for the cables.

Figure B.6 - Adding the haptic drivers



Source: the author.

Figure B.7 - Connecting the breadboard to the Arduino

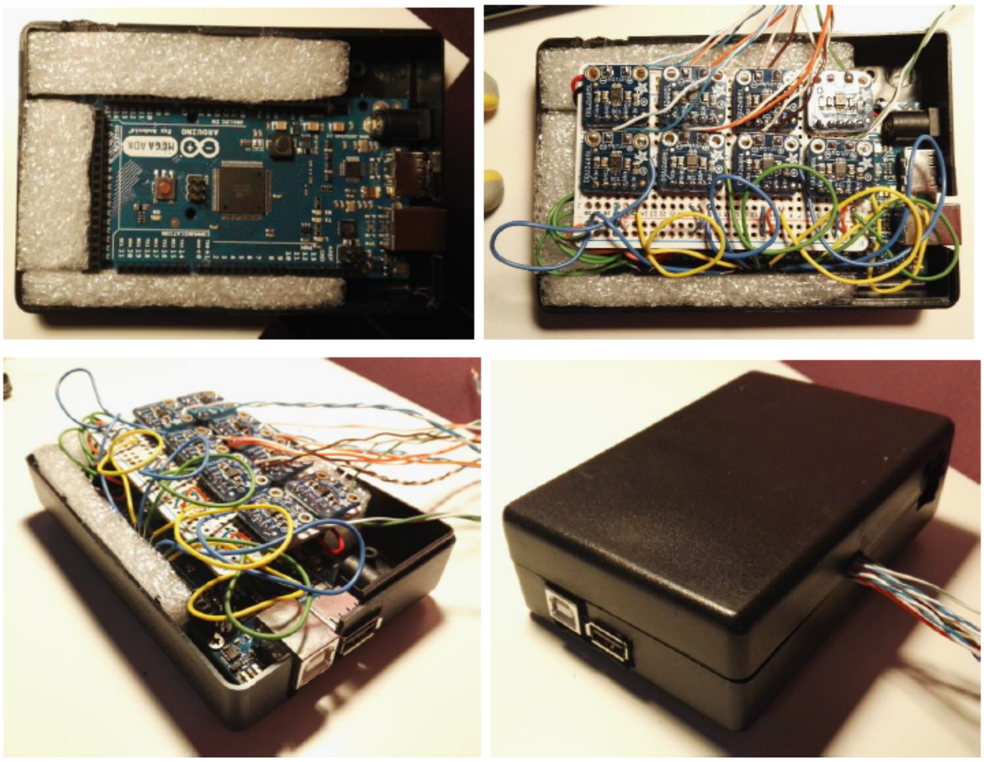


Source: the author.

B.0.0.2 Headband

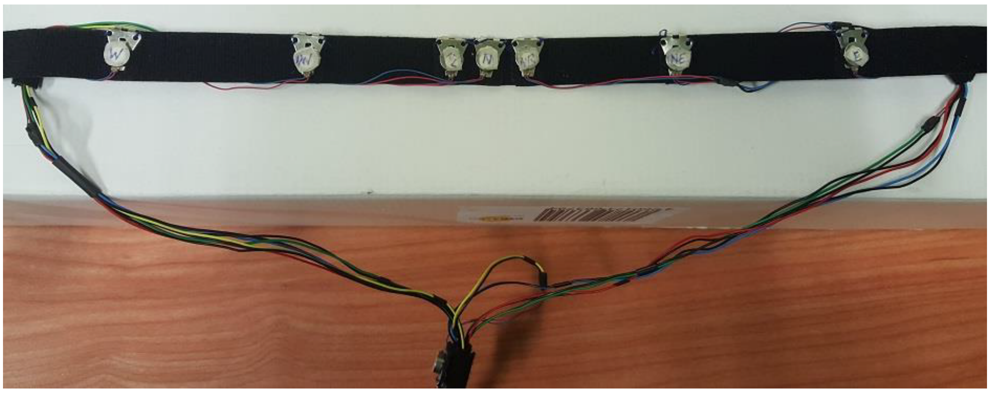
The eight motors were simply attached to pieces of Velcro to be easily repositioned on a larger strap of Velcro. Motors in cardinal and collateral positions are placed 7.5 centimeters apart. Two other motors were placed 0.5 centimeters apart from the central one.

Figure B.8 - Images from setup



Source: the author.

Figure B.9 - Headband



Source: the author.

B.0.0.3 Software

To set the headband it is necessary to load an Arduino piece of software.

- First, install the Arduino IDE
- Then, download and install the Adafruit_DRV2605 Library

Finally, create a new project in Arduino with the following code:

```
#include <Wire.h>
#include "Adafruit_DRV2605.h"
Adafruit_DRV2605 drv;
```

```
int digOut = 8; // Number of digital outputs
int PWM = 255; // 100% duty cicle
int PIN = 0;

void setup() {
    Serial.begin(57600);

    // DRIVER
    drv.begin();
    drv.useLRA();
    drv.setMode(DRV2605_MODE_PWMANALOG);
    drv.selectLibrary(6);
    drv.writeRegister8(0x01, 3);
    drv.writeRegister8(0x03, 6);
    drv.writeRegister8(0x20, 0);
    drv.writeRegister8(0x1D, 0);

    // OUTPUT: Motors
    for (int i = 0; i < digOut; i++) {
        pinMode(i+2, OUTPUT);
        analogWrite(i+2, 0);
    }
}

void activateMotor(){
    analogWrite(PIN, PWM);
    delay(500);
    analogWrite(PIN, 0);
}

void loop () {
    // Activate each motor on the order it was in the previous array
    PIN = 2; activateMotor();
    PIN = 7; activateMotor();
    PIN = 8; activateMotor();
    PIN = 5; activateMotor();
    PIN = 3; activateMotor();
    PIN = 6; activateMotor();
    PIN = 9; activateMotor();
    PIN = 4; activateMotor();
    delay(5000);
}
```

APPENDIX C CONSENT INFORM QUESTIONNAIRE

Figure C.1 - Consent Inform Questionnaire at Google Docs (PT-BR)

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO

Você está sendo convidado(a) a participar de uma pesquisa sobre interação. Leia este documento atentamente e esclareça todas as dúvidas antes de consentir na sua participação.

OBJETIVO: Essa pesquisa tem como objetivo avaliar o uso de uma dispositivo criado para que duas pessoas possam se comunicar em um ambiente imersivo usando apenas o tato.

PROCEDIMENTOS: O participante deverá usar um par de óculos de realidade virtual com uma superfície para entrada de dados (como um trackpad) na frente dos óculos. Essa superfície servirá para que o participante envie sinais de vibração para seu companheiro durante um jogo. Desse modo, quando o participante tocar no óculus, o seu companheiro sentirá um toque correspondente em forma de vibração. Ao final de cada fase do jogo, o participante deverá preencher questionários de usabilidade.

Os dados obtidos ao longo do experimento (imagens e dados) serão utilizados apenas neste estudo de forma totalmente anônima. O tempo total do experimento será de cerca de 40 minutos. Os participantes podem, sem nenhum prejuízo e a qualquer tempo, interromper o teste, se assim o desejarem.

RISCOS E BENEFÍCIOS: O presente estudo pode causar alguns sintomas como náusea e/ou enjoo devido ao uso do óculus e de vibrações. Os benefícios para o participante são a oportunidade de experimentar um novo protótipo para articulação de sinais de vibração e poder contribuir para uma pesquisa científica sobre a articulação de sinais de entrada em um dispositivo vestível a ser usado em ambientes virtuais.

Marque a opção abaixo se você está de acordo com o termo *

○ Aceito participar do experimento. Fui devidamente informado(a) e esclarecido(a) pelo pesquisador sobre a pesquisa, os procedimentos nela envolvidos, assim como os possíveis riscos e benefícios decorrentes de minha participação. Foi-me garantido o sigilo das informações e que posso retirar meu consentimento a qualquer momento.

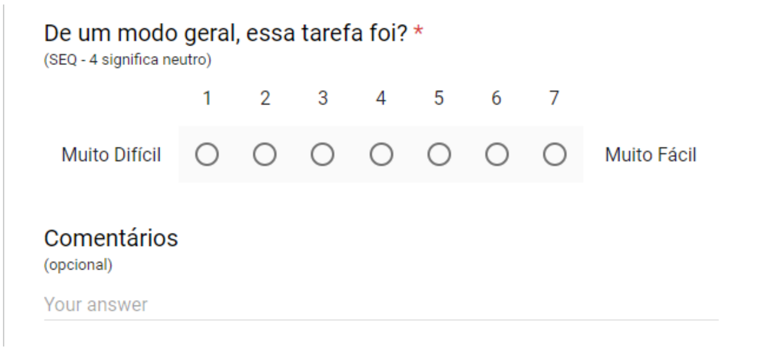
BACK NEXT

Never submit passwords through Google Forms.

Source: the author.

APPENDIX D POST-TASK USABILITY QUESTIONNAIRE

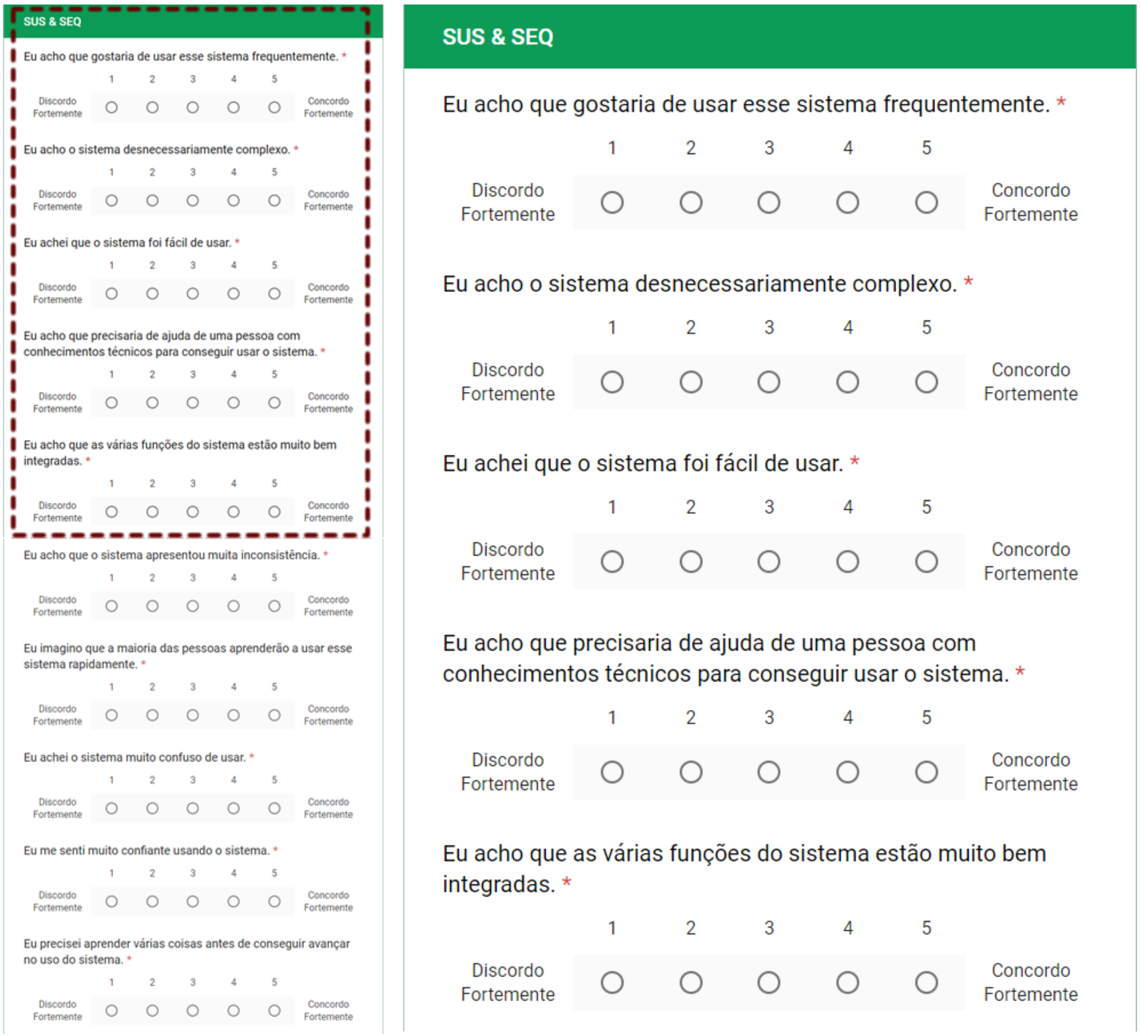
Figure D.1 - Single Easy Question (SEQ)



Source: Adapted from (SAURO; DUMAS, 2009).

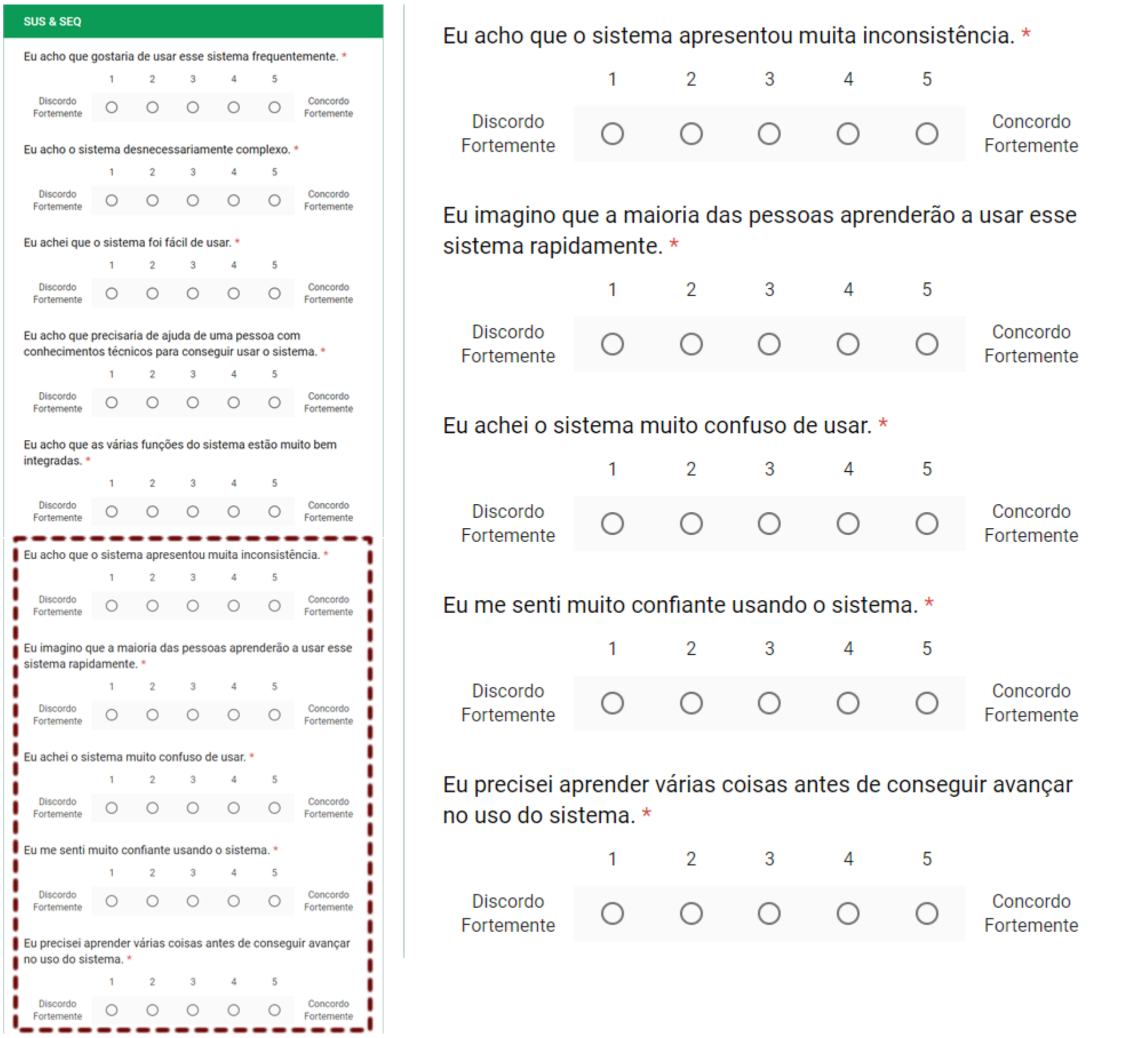
APPENDIX E SYSTEM USABILITY QUESTIONNAIRE

Figure E.1 - System Usability Scale (SUS) [first part]



Source: Adapted from (BROOKE, 2013).

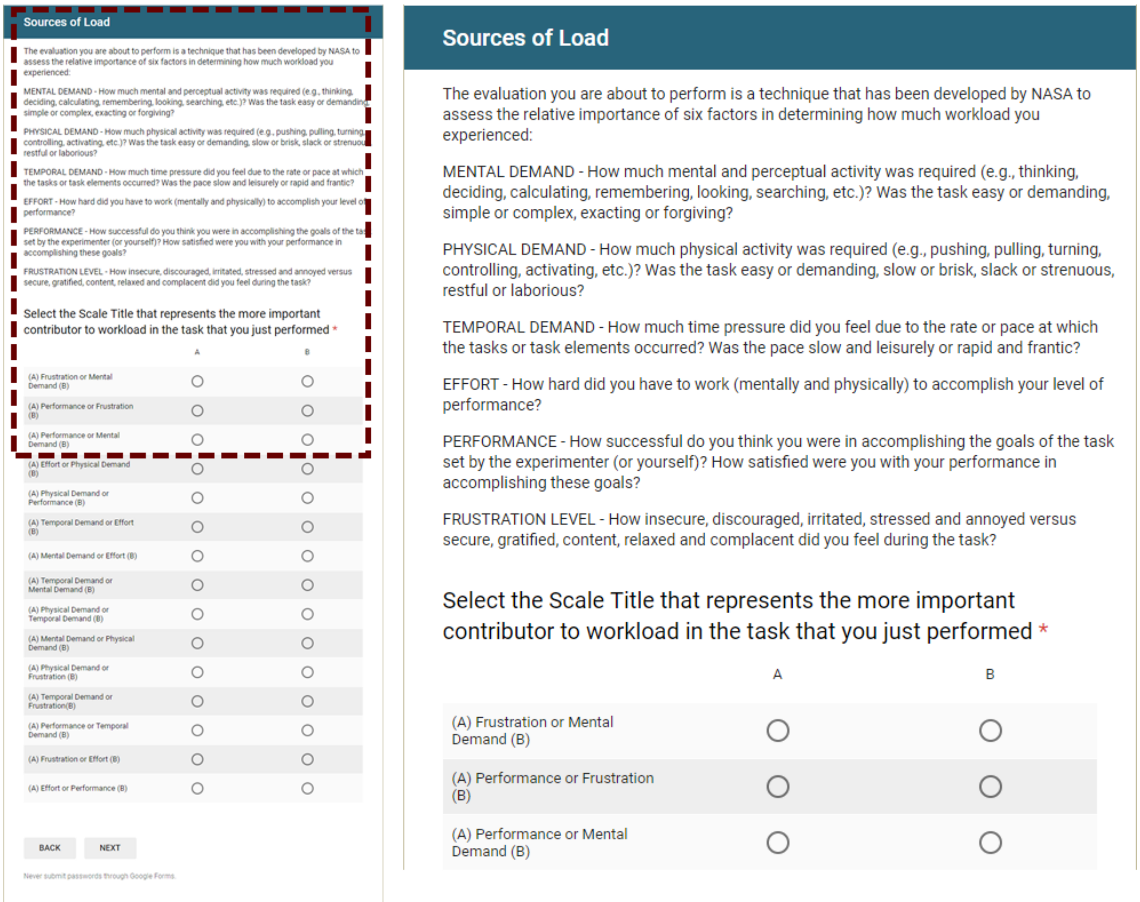
Figure E.2 - System Usability Scale (SUS) [second part]



Source: Adapted from (BROOKE, 2013).

APPENDIX F WORKLOAD QUESTIONNAIRE

Figure F.1 - NASA-TLX - Sources of Load [first part]



Sources of Load

The evaluation you are about to perform is a technique that has been developed by NASA to assess the relative importance of six factors in determining how much workload you experienced:

MENTAL DEMAND - How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

PHYSICAL DEMAND - How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

TEMPORAL DEMAND - How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

EFFORT - How hard did you have to work (mentally and physically) to accomplish your level of performance?

PERFORMANCE - How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

FRUSTRATION LEVEL - How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Select the Scale Title that represents the more important contributor to workload in the task that you just performed *

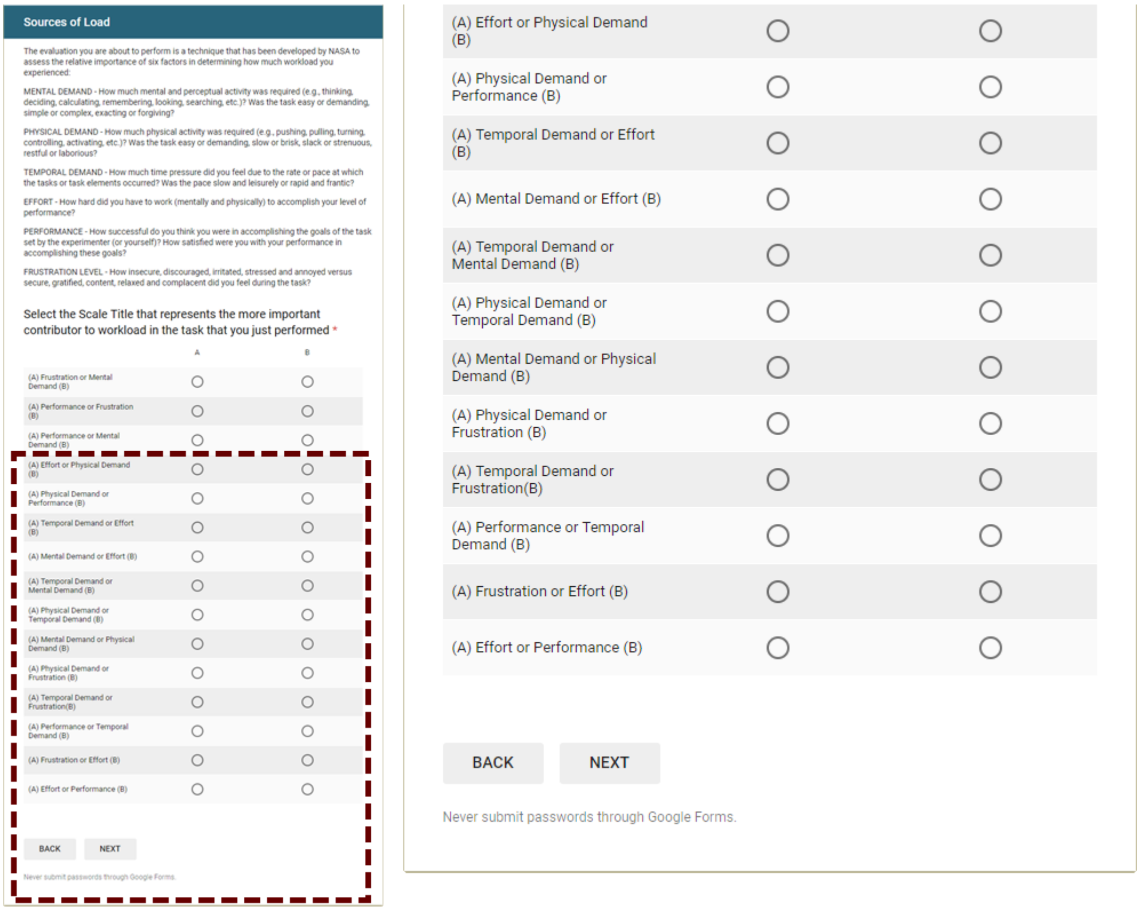
	A	B
(A) Frustration or Mental Demand (B)	○	○
(A) Performance or Frustration (B)	○	○
(A) Performance or Mental Demand (B)	○	○
(A) Effort or Physical Demand (B)	○	○
(A) Physical Demand or Performance (B)	○	○
(A) Temporal Demand or Effort (B)	○	○
(A) Mental Demand or Effort (B)	○	○
(A) Temporal Demand or Mental Demand (B)	○	○
(A) Physical Demand or Temporal Demand (B)	○	○
(A) Mental Demand or Physical Demand (B)	○	○
(A) Physical Demand or Frustration (B)	○	○
(A) Temporal Demand or Frustration(B)	○	○
(A) Performance or Temporal Demand (B)	○	○
(A) Frustration or Effort (B)	○	○
(A) Effort or Performance (B)	○	○

BACK NEXT

Never submit passwords through Google Forms.

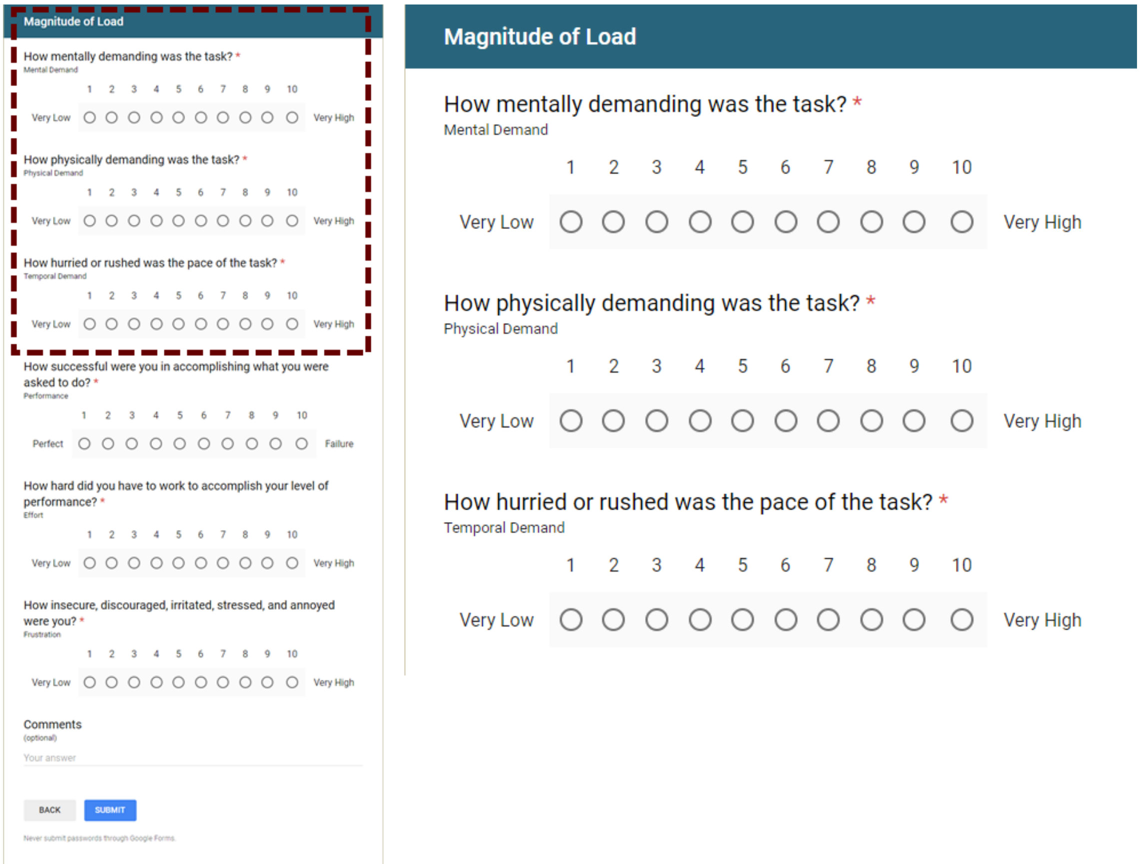
Source: Adapted from (HART, 2006)

Figure F.2 - NASA-TLX - Sources of Load [second part]



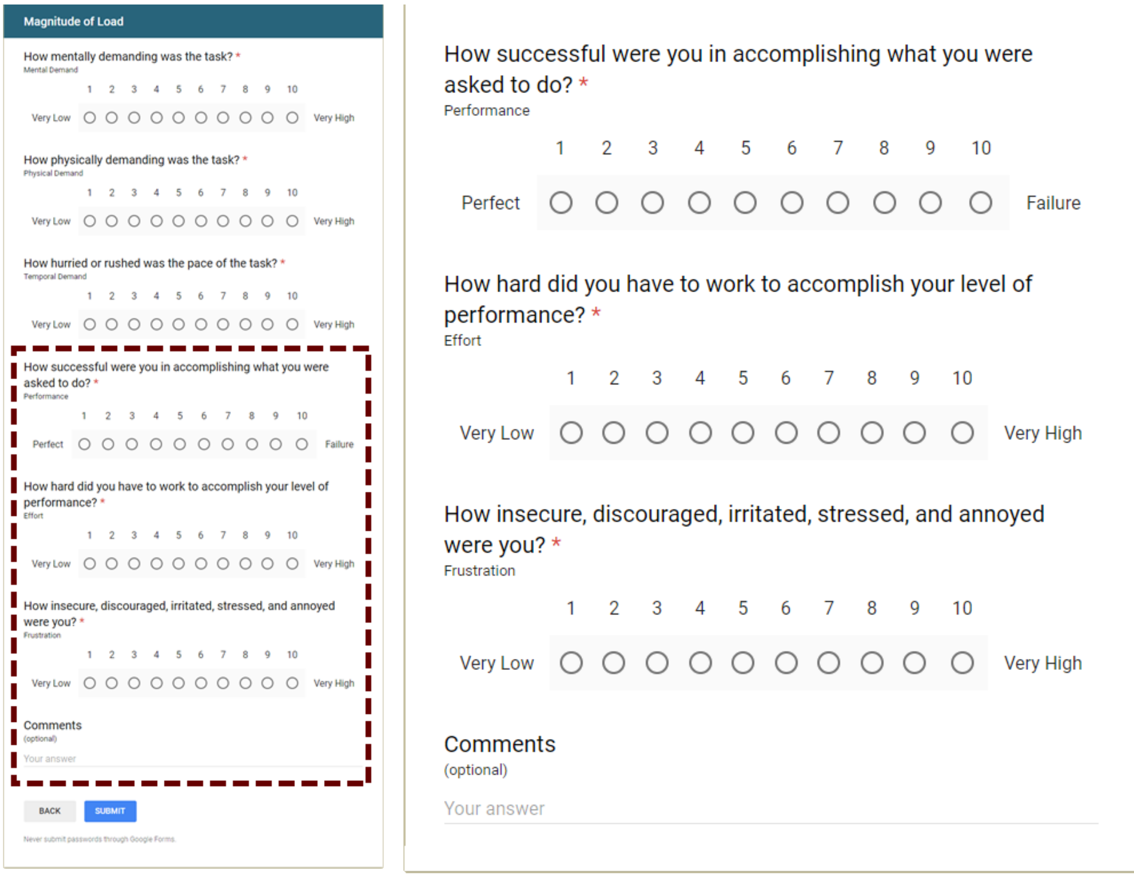
Source: Adapted from (HART, 2006)

Figure F.3 - NASA-TLX - Scale [first part]



Source: Adapted from (HART, 2006)

Figure F.4 - NASA-TLX - Scale [second part]


Magnitude of Load

How mentally demanding was the task? *
Mental Demand
	1	2	3	4	5	6	7	8	9	10	
Very Low	○	○	○	○	○	○	○	○	○	○	Very High

How physically demanding was the task? *
Physical Demand
	1	2	3	4	5	6	7	8	9	10	
Very Low	○	○	○	○	○	○	○	○	○	○	Very High

How hurried or rushed was the pace of the task? *
Temporal Demand
	1	2	3	4	5	6	7	8	9	10	
Very Low	○	○	○	○	○	○	○	○	○	○	Very High

How successful were you in accomplishing what you were asked to do? *
Performance
	1	2	3	4	5	6	7	8	9	10	
Perfect	○	○	○	○	○	○	○	○	○	○	Failure

How hard did you have to work to accomplish your level of performance? *
Effort
	1	2	3	4	5	6	7	8	9	10	
Very Low	○	○	○	○	○	○	○	○	○	○	Very High

How insecure, discouraged, irritated, stressed, and annoyed were you? *
Frustration
	1	2	3	4	5	6	7	8	9	10	
Very Low	○	○	○	○	○	○	○	○	○	○	Very High

Comments
(optional)
Your answer

BACK SUBMIT

Never submit passwords through Google Forms.

How successful were you in accomplishing what you were asked to do? *
Performance
1 2 3 4 5 6 7 8 9 10
Perfect ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ Failure

How hard did you have to work to accomplish your level of performance? *
Effort
1 2 3 4 5 6 7 8 9 10
Very Low ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ Very High

How insecure, discouraged, irritated, stressed, and annoyed were you? *
Frustration
1 2 3 4 5 6 7 8 9 10
Very Low ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ Very High

Comments
(optional)
Your answer

Source: Adapted from (HART, 2006)

APPENDIX G ANXIETY QUESTIONNAIRE

Figure G.1 - State-Trait Anxiety Inventory (STAI-6)

Spielberger State-Trait Anxiety Inventory (STAI: Y-6 item)

Published:

Marteau TM and Bekker H. The development of a six-item short-form of the state scale of the Spielberger State-Trait Anxiety Inventory (STAI). *British Journal of Clinical Psychology*. 1992;**31**:301-306.

Measure:

Name ………………………………………………………………..   *Date* ……………

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the most appropriate number to the right of the statement to indicate how you ***feel right now, at this moment****. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.*

	Not at all	Somewhat	Moderately	Very much
1. I feel calm	1	2	3	4
2. I am tense	1	2	3	4
3. I feel upset	1	2	3	4
4. I am relaxed	1	2	3	4
5. I feel content	1	2	3	4
6. I am worried	1	2	3	4

Calculation:

To calculate the total STAI score (range 20 - 80):

- reverse scoring of the positive items (calm, relaxed, content) so 1=4, 2=3, 3=2 and 4=1;
- sum all six scores;
- multiply total score by 20/6;
- refer to Spielberger's manuals to interpret scores (a 'normal' score is approx. 34 - 36) or **Bekker HL**, Legare F, Stacey D, O'Connor A, Lemyre L. *Is anxiety an appropriate measure of decision aid effectiveness: a systematic review?* Patient Education and Counselling. 2003; 50: 255-262.

Source: Adapted from (MARTEAU; BEKKER, 1992)

APPENDIX H MUTUAL UNDERSTANDING QUESTIONNAIRE

Figure H.1 - Mutual Understanding Scale

Marque o quanto você concorda com as afirmações abaixo: *

	Discordo Fortemente (1)	-------------- -------------- (2)	-------------- -------------- (3)	- Neutro - -------------- (4)	-------------- -------------- (5)	-------------- -------------- (6)	Concordo Fortemente (7)
Minhas opiniões eram claras para meu parceiro.	○	○	○	○	○	○	○
As opiniões do meu parceiro eram claras.	○	○	○	○	○	○	○
Meus pensamentos eram claros para meu parceiro.	○	○	○	○	○	○	○
Os pensamentos do meu parceiro eram claros para mim.	○	○	○	○	○	○	○
Meu parceiro entendeu o que eu queria dizer.	○	○	○	○	○	○	○
Eu entendi o que meu parceiro queria dizer.	○	○	○	○	○	○	○

Source: Adapted from (BIOCCA; HARMS; GREGG, 2001)

APPENDIX I LIST OF PUBLICATIONS

Several articles with distinct contributions on Human-Computer Interaction, Virtual Reality and Psychophysics were submitted throughout our research. The following is a complete list of our publications up to this time:

Journal Papers:

- ***Assessment of an Articulatory Interface for Tactile Intercommunication in Immersive Virtual Environments***.
  OLIVEIRA, V. A. de J., NEDEL, L., MACIEL, A.
  2018, Computers & Graphics (to appear).

- ***Designing a Vibrotactile Head-mounted Display for Spatial Awareness in 3D Spaces***.
  OLIVEIRA, V. A. de J., BRAYDA, L, NEDEL, L., MACIEL, A.
  2017, IEEE TVCG.

- ***Construction and Study of Validity Evidence of the Teaching Assessment Scale***.
  da SILVA, M. A., MACHADO, W. L., PILOTTO, L. M., BACKES, B., ZANON, R. B., MACHADO, P. V., ZOLTOWSKI, A., VIEIRA, R. V. A., ENDRES, R. G., FRANCALANCI, M., **OLIVEIRA, V. A. de J.**, KRUG, J. S., BANDEIRA, D. R.
  2017, Revista Brasileira de Educação (vol.22 no.70).

Conference Papers:

- ***Assessing Articulatory Modalities for Intercommunication Using Vibrotactile HMDs***.
  OLIVEIRA, V. A. de J., NEDEL, L., MACIEL, A.
  2018, EUROHAPTICS Conference.

- ***Anti-Veering Vibrotactile HMD for Assistance of Blind Pedestrians***.
  OLIVEIRA, V. A. de J., NEDEL, L., MACIEL, A., BRAYDA, L.
  2018, EUROHAPTICS Conference.

- ***Tactile Treasure Map: Integrating Allocentric and Egocentric Information for Tactile Guidance***.
  MEMEO, M., **OLIVEIRA, V. A. de J.**, NEDEL, L., MACIEL, A., BRAYDA, L.
  2016, ASIAHAPTICS Conference.

- ***Localized Magnification in Vibrotactile HMDs for Accurate Spatial Awareness***.
  OLIVEIRA, V. A. de J., NEDEL, L., MACIEL, A., BRAYDA, L.
  2016, EUROHAPTICS Conference.

- ***Spatial Discrimination of Vibrotactile Stimuli Around the Head***.
  OLIVEIRA, V. A. de J., NEDEL, L., MACIEL, A., BRAYDA, L.
  2016, HAPTICS Symposium.

- ***Proactive Haptic Articulation for Intercommunication in Collaborative Virtual Environments***. **OLIVEIRA, V. A. de J.**, NEDEL, L., MACIEL, A.
  2016, IEEE Symposium on 3D User Interfaces - 3DUI.

- ***Tactile Interface for Navigation in Underground Mines***.
  OLIVEIRA, V. A. de J., MARQUES, E., PERONI, R. de L., MACIEL, A.
  2014, Symposium on Virtual and Augmented Reality - SVR.

- ***Assessment of Tactile Languages as Navigation Aid in 3D Environments***.
  OLIVEIRA, V. A. de J., MACIEL, A.
  2014, EUROHAPTICS Conference.

- ***Introducing the Modifier Tactile Pattern for Vibrotactile Communication***.
  OLIVEIRA, V. A. de J., MACIEL, A.
  2014, EUROHAPTICS Conference.

Posters:

- ***Speaking Haptics: Proactive Haptic Articulation for Intercommunication in Virtual Environments***. **OLIVEIRA, V. A. de J.**, NEDEL, L., MACIEL, A.
  2016, IEEE Virtual Reality - VR.

- ***Does Vibrotactile Intercommunication Increase Collaboration?*** **OLIVEIRA, V. A. de J.**, SARMIENTO, W. J., MACIEL, A., NEDEL, L., COLLAZOS, C. A.
  2015, IEEE Virtual Reality - VR.

- ***Applying Tactile Languages for 3D Navigation***.
  OLIVEIRA, V. A. de J., MACIEL, A.
  2014, IEEE Symposium on 3D User Interfaces - 3DUI.

Demonstrations:

- ***ULTRAHAPTICS Student Challenge: ULTRAMOTION***. VILLA SALAZAR, D. S., **OLIVEIRA, V. A. de J.**, NEDEL, L., MACIEL, A.
  2018, EUROHAPTICS Conference.

- ***The Invisible Enemy: Playing with Vibrotactile Guidance on a Head-mounted Display***. **OLIVEIRA, V. A. de J.**, BRAYDA, L, NEDEL, L., MACIEL, A.
  2016, Symposium on Virtual and Augmented Reality - SVR.

- ***Do Not Guess It, Just Feel It: Experiencing Vibrotactile Guidance on a Head-mounted Display***. **OLIVEIRA, V. A.**, NEDEL, L., MACIEL, A., BRAYDA, L.
  2016, EUROHAPTICS Conference.

- ***Tactile Treasure Map: Integrating Allocentric and Egocentric Information for Tactile Guidance***. MEMEO, M., **OLIVEIRA, V. A. de J.**, NEDEL, L., MACIEL, A., BRAYDA, L. 2017, ASIAHAPTICS Conference.