UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE INFORMÁTICA
PROGRAMA DE PÓS-GRADUAÇÃO EM COMPUTAÇÃO

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# Designing Tactile Vocabularies for Human-Computer Interaction

Thesis presented in partial fulfillment
of the requirements for the degree of
Master of Computer Science

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Advisor

Porto Alegre, February 2014

*"I have no special talent.
I am only passionately curious."*
— SIR ALBERT EINSTEIN

# ACKNOWLEDGMENTS

**Designing Tactile Vocabularies for Human-Computer Interaction**

# ABSTRACT

This thesis presents a study about tactile languages in human-computer interaction and a novel approach for vibrotactile prefixation. We intended to analyse how the choices made during the design process of tactile vocabularies would affect the user performance on an interactive task. Therefore, we have designed and tested different sets of tactile signals for aid navigation in virtual environments. It leaded us to fashion the concept of Modifier Tactile Pattern for vibrotactile communication which was tested through user experiments. In the assessment of the modifier-based vocabularies we attempted to effects of multisensory stimulation, factors related to the processing of tactile sequences and masking caused by multiple stimuli delivered in a same time. Results show that those participants who used modifier-based vocabularies performed better the navigation task. That and others results related to perception, learning and interpretation of our tactile vocabularies show the validity of the use of modifiers on tactile languages. The statements made from this work will be useful for designing usable tactile interfaces that demand expressive vocabularies.

**Projetando Vocabulários Táteis para Interação Humano-Computador**

# RESUMO

Esta dissertação apresenta um estudo sobre linguagens táteis em interação humano-computador e uma nova abordagem de prefixação vibrotátil. Nós pretendemos analisar como as escolhas feitas durante o processo de concepção de vocabulários táteis afetam o desempenho do usuário em uma tarefa interativa. Por isso desenvolvemos e testamos diferentes conjuntos de sinais táteis para suporte à navegação em ambientes virtuais. Isso nos levou a esboçar o conceito de Padrão Tátil Modificador para comunicação vibrotátil que foi testado por meio de experimentos com usuários. Na avaliação dos vocabulários táteis construídos com padrões modificadores foram considerados os efeitos de estimulação multisensorial, fatores relacionados ao processamento de seqüências táteis e o mascaramento causado pela exibição de múltiplos estímulos ao mesmo tempo. Resultados mostram que os participantes que usaram vocabulários construídos com padrões modificadores obtiveram desempenho melhor na tarefa de navegação. Esse e outros resultados relacionados à percepção, aprendizagem e interpretação dos nossos vocabulários atestam a validade do uso de modificadores na construção de linguagens táteis. As conclusões extraídas deste trabalho se mostram úteis no auxílio à concepção de interfaces táteis que sejam usáveis e que demandem expressividade de seus vocabulários.

**Palavras-chave:** Interação háptica, comunicação vibrotátil, realidade virtual, navegação.

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GUI    Graphical User Interface

BMW   Bayerische Motoren Werke

# CONTENTS

# 1 INTRODUCTION

The development of software and hardware components for displaying information in visual and aural ways is extremely common. Nonetheless, conveying information by the sense of touch has gained popularity. It can be found in joypads and smartphones that use different tactile parameters for convey information through touch. Tact is a mean by which we acquire several information about the environment that surrounds us and there are surveys that present it as a channel of communication as efficient as vision and hearing (CONWAY, 2001).

The sense of touch is more complex than vision and hearing. It 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 (proprioception). Such sense is provided by joints and muscle receptors. Moreover, more recent research has considered sense of position and sense of movement as two different senses (PROSKE; GANDEVIA, 2009). Cutaneous stimuli on the other hand are sensed through mechanoreceptors in the skin layers (taction). 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).

Basically, there are two areas where the cutaneous stimuli have been explored: the development and improvement of techniques for simulation of texture and other tactile sensations, and 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 (1991) as the discovery of a set of tactile patterns that, as speech sounds or letters, are clearly discriminated, rapidly processed and easily learned.

## 1.1 Problem

Mechanisms for tactile communication exist that are made to support orientation, locomotion, postural correction and even musical instrument teaching (LINDEN et al., 2011). In most of them, the set of tactile patterns is iconic, following an approach known as "tap-on-shoulders" (ERP et al., 2005). This approach can be exemplified by a tactile sensation printed on the side of the user body that is facing a particular target or obstacle, for example. The set of tactile patterns in "tap-on-shoulders" approach is easy to understand but also limited, providing a relatively small amount of information to the user. A more expressive language would be more efficient in assisting users in their tasks by transmitting them all necessary information to achieve their goals.

Different kinds of information can be expressed by the use of different parameters, as

for example, variation of intensity and frequency of vibrators in a vibrotactile display. The meaning for each parameter is assigned arbitrarily. The addition of a small set of arbitrary elements may increase the complexity of the language, but also allows the transmission of a greater amount of information. The present work focuses on the study of how to use and combine such elements. We aimed to discover how to increase the expressiveness of a tactile language, keeping it as easy as possible to learn and to understand. Therefore, we explored design approaches for tactile languages and proposed a *novel approach for prefixation*.

The proposed approach was used to design vibrotactile patterns for aid navigation tasks and it was tested in navigation on virtual environments. The messages transmitted to support navigation in virtual environments should also be used for navigation in physical environments. Therefore, it is expected that the same vibrotactile language could be applied with few adjustments to several applications, such as gaming, robot-teleoperation systems, pedestrian orientation and so on. The development of the tactile language and the research on vibrotactile prefixation was conducted through an iterative and incremental process. So, we present our finds from the perspective of a cyclic set of steps of (re)design, prototyping, user experiments and analysis of different tactile vocabulary designs.

## 1.2 Overview

In the remainder of this thesis, we present on Chapter 2 a literature review and background for vibrotactile communication, haptic interaction design and tactile navigation. The section aforementioned contains contributions from the field of Human-Computer Interaction as well as from Virtual Reality, Linguistics and Psychophysics. On Chapter 3 the proposed prefixation approach is presented and discussed. Then, the remaining chapters will present phases of design, prototyping and user experiments related to an iterative development of a vibrotactile language for navigation. Chapter 4 presents the design and evaluation of a primary vocabulary for navigation; Chapter 5 presents an improvement of such vocabulary and a new prototype; and Chapter 6 presents the last phase with the redesign of the tactile language and an application test. Finally, a summary about all the findings can be found on Chapter 7 in conclusion of this thesis.

# 2  REVIEW OF HAPTIC INTERACTION

The haptic sense comprises proprioception and taction. The latter is most used for communication due the facility on generating such kind of stimuli. Vibrating stimuli is broadly used when it comes to tactile communication systems (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 a same signal (or tactile icon). However, it is necessary to be attentive to perceptual, cognitive and motor attributes to ensure the effectiveness of the haptic interaction.

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 wore 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 to replace the senses, thinking about tactile devices as a good alternative for deaf and blind people. However, several more recent applications focus on complementing senses instead (CHANG et al., 2002). The haptic feedback as 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 at haptic interaction design.

In this section we present a background for vibrotactile communication and interaction design. Such studies should help in making decisions during the construction and evaluation of the tactile icons and display. We start presenting some example of devices made for vibrotactile communication and studies on tactile expressiveness. After a review on tactile icons, we also present studies on spatiotemporal processing, learning and memorizing of tactile sequences. Concerning interaction design, we present methodologies for construction of haptic interfaces and tactile icons, as well as factors related to multitask and multisensory applications. We close this section discussing some works related to navigation task.

## 2.1  Vibrotactile Communication

The sign as a linguistic unit contains a signifier (acoustic image) and a signified (concept) (SAUSSURE, 2006). A sign represents a denoted object and its meaning relates to an immaterial representation, while its signifier relates to a material representation of this object. Such dyadic relation also exists in haptic representations. The design of interfaces for haptic communication must look at both aspects of haptic representations: meaning and haptization. While *meaning* concerns the information conveyed by the haptic cue,

*haptization* concerns the haptic artifacts felt by the user. The term haptization means the haptic equivalent of visualization for sight (SWINDELLS; SMITH; MACLEAN, 2005). In this section we present concepts related to haptic representations, such as examples of displays for haptization, the expressiveness of tactile languages and how to design tactile icons. The design of tactile icons encompasses spatiotemporal factors and characteristics of processing, learning and memorizing of tactile sequences, also presented later in this section.

### 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 vibrators 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 vibrator matrix 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 vibrators locate 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: (a) The Optacon, as many early tactile displays, converted printed words into tactual stimuli; (b) MusicJacket deliver tactile signals on different parts of the body



(a)                                         (b)
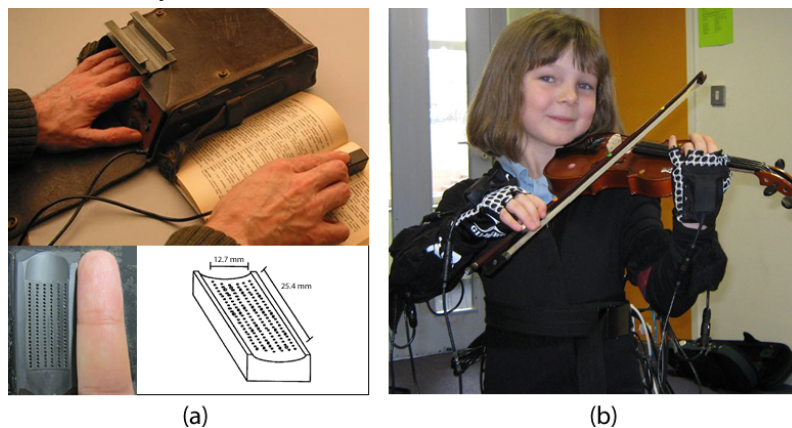
### 2.1.2 Expressive Capacity

Braille readers 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 aid in multitasking environments further than for assistive devices. In 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 limitations and expressive capacity.

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 informations that do not demand a cognitive component in the response (MACLEAN; HAYWARD, 2008).

Early research has applied the 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 in 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 focus on the use of prefixation signals to construct tactile vocabularies that can be either expressive and easy to learn and process.

### 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 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 with 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. They also classified tactons according to their construction mode.

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. It has been proposed that only nine different frequency levels should be used and only four in amplitude. Brewster and Brown (2004) defend that changes in amplitude influence the perception of frequency. Thus, there are conditions for variation of both parameters in a 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. A burst duration can be used to express proximity to an object and differentiate an attack (short burst with less than 0.1s) from other sentences. Groups of bursts with different durations can compose rhythmic units. Rhythm can address groups of events on the same area of the skin and it is good to inform temporal characteristics as proximity changes and pace velocity, for example. Rhythmic tactile sequences also can be constructed by prefixation or transformational approaches (TERNES; MACLEAN, 2008), which is discussed in more detail later.

In addition to hardware features and the type of information conveyed, spatiotemporal factors should be taken into consideration in the design of a vibrotactile device. 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).

Figure 2.2 - The motor and sensory homunculus
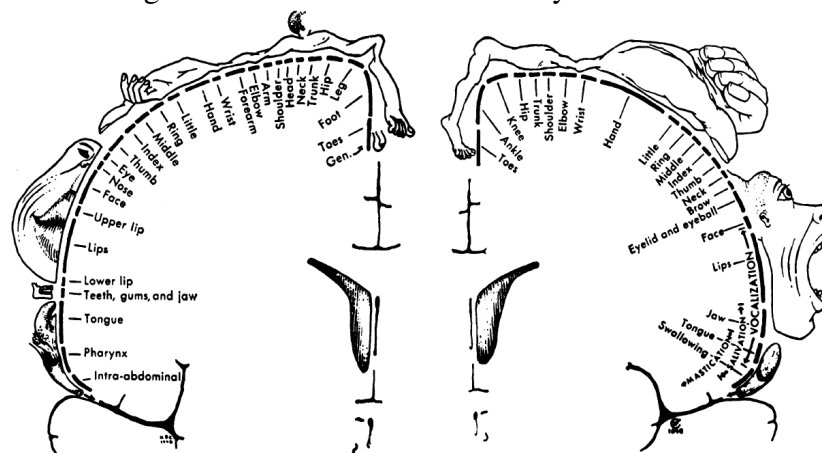


Source: Penfield and Rasmussen (1950).

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 reasons why many devices are built as displays for printing patterns on the palm of the user, for example. Furthermore, the 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. Most of these studies are interested primarily in the "low-level" aspects of temporal tactile perception and/or spatial tactile perception as opposed to more complex forms of learning. Few experiments have been conducted which examine the learning of temporal patterns or sequences containing complex sequential regularities (CONWAY, 2001).

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.

The acuity of several body parts were tested in processing tactile patterns. Among them: arm (CHOLEWIAK; COLLINS, 2003), forearm (OAKLEY et al., 2006) (BARGHOUT et al., 2009), the abdomen (CHOLEWIAK; COLLINS, 2000) and finger (GOBLE; COLLINS; CHOLEWIAK, 1996) by generating stimuli in different settings (SHERRICK; CHOLEWIAK; COLLINS, 1990) to identify the influence of body parts according to display size, arrangement of actuators, age of users and stimulus time.

Tactor position in the matrix is also an important factor. According to Weber, "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). Not only the location of the stimulus but also the size of the stimulated region influence the quality of tactile communication. These findings were observed in the current work where the tactile feedback were delivered in glabrous and hairy sites.

### 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, 2007a). In fact, several studies have demonstrated that attention dwells on a stimuli (visual, aural or tactile) for several hundreds of milliseconds. Therefore, it is common a person to wrongly report the existence or position of a 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 sequence of stimuli.

Analyzing these two processes and comparing different stimuli (visual, aural and haptic), some authors, in different studies and using different strategies, reached similar findings which prove that tact is more accurate than vision. However its accuracy is smaller than the hearing in simultaneity tests. As for the temporal order, many tests do not grant significant finds about difference in performance between different senses, while others show at least that the vision is also less accurate than touch (CONWAY, 2001).

### 2.2.3 Learning and Memorizing Tactile Sequences

Learning is strongly linked to memorizing. However, the relationship between memory and learning of tactile sequences is not completely known. Gilson and Baddeley (1969) as well as Sullivan and Turvey (1972) showed that memory for the tactile stimuli locations is best in the first 5 or 10 seconds after memorizing a tactile sequence. Gilson and Baddeley also noted that memory for touch declines when the training is stopped (CONWAY, 2001).

The rehearsal is important for memorizing tactile sequences. Its relevance was evidenced in studies by Watkins and Watkins (1974). They also 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 made in a way to respect such characteristics. A GUI was designed to guide the training step giving the user time to rehearsal. Also, a cylindrical keyboard was designed to match the position of the tactors on the user waist. Therefore, the user could encode the information in a more natural way.

A multisensory reinforcement training is advantageous even when the stimulus will

later be invoked purely through the haptic channel (MACLEAN; HAYWARD, 2008). Furthermore, the use of metaphors assists identification and memorisation of tactile patterns. It is a conventional approach to design tactile icons based on metaphors. The metaphors chosen by the designer can be teached 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, the users can also chose the stimulus-meaning associations themselves. There are studies that present good results (ENRIQUEZ; MACLEAN; CHITA, 2006; ENRIQUEZ; MACLEAN, 2008). In this work the metaphor and associations were chosen by the designer.

## 2.3 Haptic Interaction Design

A central concern of interaction design is to develop interactive products that are usable (ROGERS; SHARP; PREECE, 2002). It is not different in haptic interaction design. Haptic interfaces also must be designed to be easy to learn, effective to use, and provide an enjoyable user experience. The conventional practices for user interface design can be applied to the design of haptic interfaces as well. However, haptic design does differ in a significant way from visual and auditory design. In this section we present some conventional practices for user interfaces design. Also, some particular practices for haptic interaction design and tactile language design are presented.

### 2.3.1 Haptic Interaction Design Practices

A haptic 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 an unfamiliar modality has some challenges. People are not habituated to processing haptic representations of abstractions 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).

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 focus 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).

We present below some methodologies for design, implementation and evaluation of tactile signals.

Figure 2.3 - Possible Design Space of Haptic Components
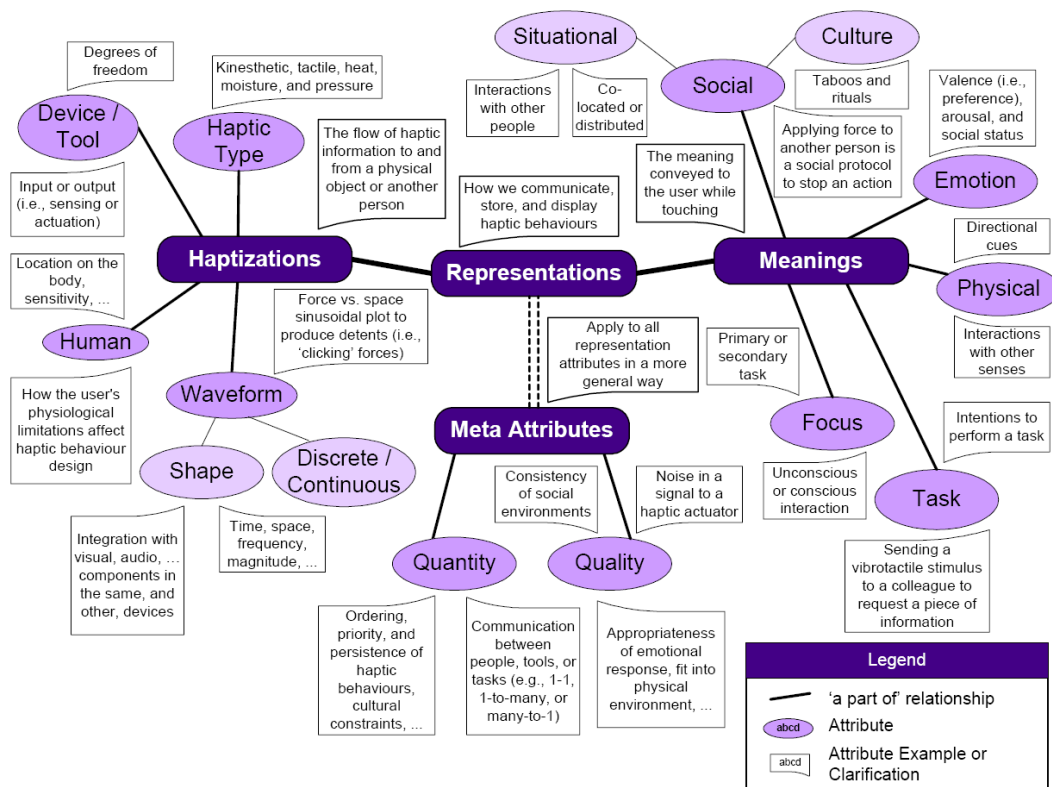


Source: Swindells, Smith and MacLean (2005).

### 2.3.2 Tacton Design Methodology

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).

*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 ad hoc. 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 (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 addition of qualifiers

Figure 2.4 - Tactile Language Design Methodology
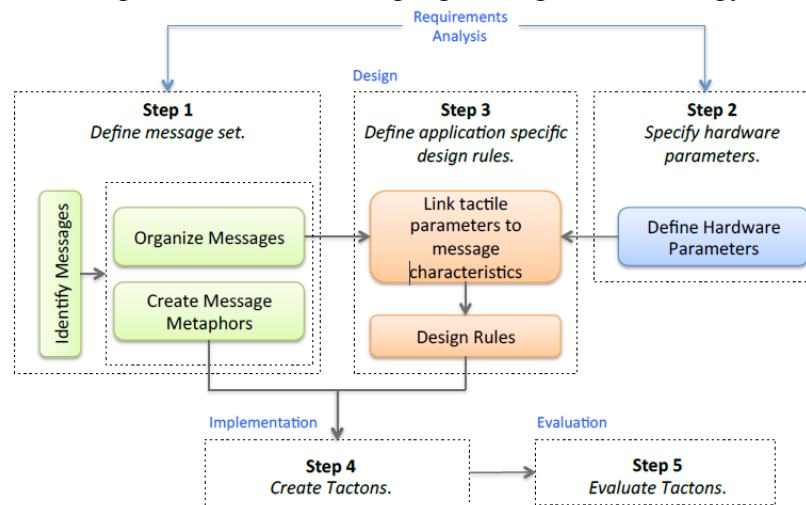


Source: Riddle and Chapman (2012).

Figure 2.5 - 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).

to other simple tactons. The qualifier gives details about the message. So, if 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). Finally, *Step 5* of the tactile language design is 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 stimulus with target meaning, individual stimulus salience, discernibility of items in the set, and maintenance of desired salience level under cognitive workload. Therefore, Chan proposes an iterative and user-centered four-step process to encompass those variables (Figure 2.6). 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 systematise this step. The progressive refining of the tactile icons is the main advantage of the 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.

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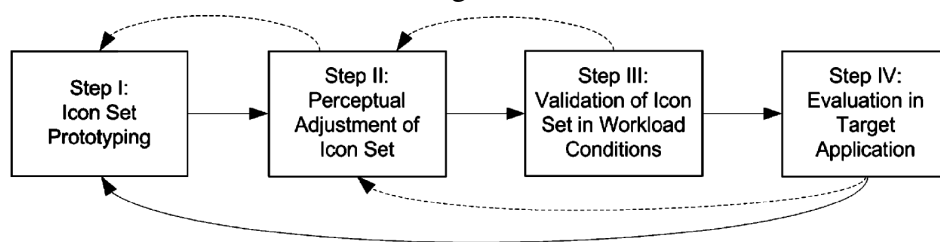


Source: Chan, MacLean and McGrenere (2008).

The work described in this thesis was not focused on a particular application for tactile navigation. Therefore, we did not follow the methods aforementioned in a way to design and test a single set of tactile icons. We aimed to explore prefixation approaches and to propose a novel one. So, we rather designed and tested several sets of stimuli to analyse the effects of our choices in the design process. However, we followed the Riddle's approach to design the sets of icons that we used for tactile navigation.

## 2.4   Tactile Aid for Navigation

Tactile stimuli have been used as a channel for rendering supplemental information when sight and hearing are unavailable or overloaded. Therefore, tactile displays are useful for navigational support in environments such as dark mines, closed forests or smoky areas. Commercially, the automotive industry has explored their potential. Tactile feedback can be delivered in a car through steering wheels (ANGELINI et al., 2013), gas pedal (ABBINK et al., 2011), seat (VAN ERP; VAN VEEN, 2001) and other locations in contact with the driver's body. The iDrive is an example of tactile application present in BMW vehicles. Also in human-machine interaction, tactile stimuli have been used to provide collision-proximity feedback and aid robot teleoperation (BARROS; LINDEMAN; WARD, 2011) and navigation in virtual environments (MOUSTAKAS et al., 2006; LINDEMAN et al., 2005).

Tactile displays are commonly made for a specific purpose. In mobility and navigation tasks, there are tactile vocabularies made to display instructions and directions for astronauts (ERP; VAN VEEN, 2003), militaries (JONES; KUNKEL; TORRES, 2007) and visually impaired pedestrians (DAKOPOULOS; BOURBAKIS, 2009). In all those works only one set of tactile icons was designed and refined to a specific application. In the work presented in this thesis, instead, many tactile vocabularies were designed through an iterative and incremental development.

The palm of the hand is a sensitive site of the human body. Many authors explored the construction of arbitrary signs in mobile devices (PIELOT; POPPINGA; BOLL, 2010) or in displays for tactile visualization (WALL; BREWSTER, 2005) to be perceived by the users with their hands. A system based on the hand for navigation in physical environments was presented by Yoon (2009). In Yoon's system, obstacles are recognized by ultrasound sensors and exhibited through a tactile display on the user's hand to replace vision. The information rendered about obstacles is in part iconic and in part arbitrary. Based on researches about construction of tactile icons (BREWSTER; BROWN, 2004; RIDDLE; CHAPMAN, 2012), we have also built a tactile display to support navigation by displaying obstacle information in a display for the hand. However, differently of the

display presented by Yoon (2009) and other similar displays (JACOB; MOONEY; WIN-STANLEY, 2011; PRADEEP; MEDIONI; WEILAND, 2010), we wish to additionally transmit as much information as necessary with the tactile display.

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 (CHOLEWIAK; BRILL; SCHWAB, 2004). Tasks that demand perception of three-dimensional space also require accurate localization of stimuli, and abdomen has a good performance in such aspect (KARUEI et al., 2011; ERP et al., 2005). In a study on vibrotactile localization at sites around the circumference of the abdomen, Cholewiak (2004) shows that the relative position of eight motors equally spaced around the torso is well perceived by a person. This occurs because, like touch, vibrating stimuli are best located when they are presented near anatomical points of reference, such as the navel and the spine. In a study about the perception of vibration across the body in mobile contexts, the stimuli delivered on the spine was the one with the best results (KARUEI et al., 2011). Other studies also presented vibrotactile displays made with eight motors for mobility and navigation tasks (ERP et al., 2005; BOLL; ASIF; HEUTEN, 2011). In the present work we also designed a vibrotactile display as a belt for navigation.

The navigation task usually involves the use of multiple senses. Some studies address issues related to multisensory stimulation and workload (CHAN; MACLEAN; MC-GRENERE, 2005; ERP; WERKHOVEN, 2006; GALLACE; TAN; SPENCE, 2007b; MENELAS et al., 2010). When navigating in a virtual environment, the user performance will be affected by the perception of the different stimuli presented. Thus, the vision competes with the sense of touch and affects the decision on navigating. Also the use of tactile *sequences* may represent a perceptual issue on the navigation as presented before. Our experiments were not made with blindfolded users as we did not want to explore sensory substitution. Therefore, we noted the effects of the multisensory stimulus on the navigation tasks.

## 2.5 Summary

Vibrating stimuli is most used for tactile communication due the facility to manipulate vibration parameters. It makes possible to encode additional meaning to a same signal and to design expressive tactile icons. Tactile displays are usually made by arranging arrays of actuators to produce what we can call haptic visualization (haptizations). The design of haptizations encompasses human factors, such as spatiotemporal factors and characteristics of processing, learning and memorizing of tactile sequences. All these factors were observed during the design process of our tactile vocabularies described later in this dissertation.

The design of tactile interfaces is still at a rather early stage. There is a need for standardization and for models to design such interfaces. Nevertheless, some of the conventional practices for user interface design can also be applied to the design of haptic interfaces. There are specific design practices for haptics and approaches for design of tactile icons that were presented in this work. Rather than applying those approaches and heuristics to design a set of tactons for a specific navigation task, we explored the elements involved in the construction of tactile icons and designed many vocabularies in this work. Differently of previous works, we also propose here a novel concept of *modifier signal* as an important breakthrough to increment the tactile language.

# 3   NOVEL APPROACH FOR CONSTRUCTION OF TAC-TILE MESSAGES

The parameters used in the construction of tactile patterns were presented earlier in the literature as haptic phonemes. According to Enriquez and Maclean (2006), they represent the smallest unit of a constructed haptic signal to which a meaning can be assigned. Once a meaning is assigned to a parameter or to a combination of parameters, they can be treated as morphemes instead. As morphemes, they constitute the *minimal meaningful unit* of a tacton and can be classified as free (e.g. roots) or bound (e.g. prefixes). This characteristic of a tactile pattern behavior as free or bound morpheme has not been emphasized before. However, prefixation is not a novel approach for tactile languages. In Braille, some signs are reserved to work as prefixes. Each prefix can be attached to a basic sign modifying its meaning. A modifier pattern however modifies the meaning of an entire tactile sequence or several sequences at once.

It is possible to expand the expressiveness of a tactile language varying the elements involved in the construction of the tactile patterns, such as body position, tactor position and parameters of vibration. Thereby, different kinds of information can be expressed by the use of different parameters, as for example, variation of intensity and frequency of vibrators in a vibrotactile display. The addition of a small set of arbitrary elements, such as vibrotactile parameters, can increase the complexity of the language, but also allows the transmission of a greater amount of information without being necessary to scale the tactile display resolution. So, it is important to study how to use and combine these parameters to discover how to increase the expressiveness of a tactile language keeping it as easy as possible to learn and to understand.

In order to reduce the number of chunks of a tactile language as we increase its expressiveness, we have found inspiration from morphology and formalized the concept of *Modifier Tactile Pattern* for vibrotactile displays. Arbitrary variations may result in vocabularies that are difficult to memorize and process. The use of prefixation with modifiers could enhance the tactile vocabulary expressiveness keeping it easier to learn due the number of signals to recall. Hereinafter we present the concept of Modifier Tactile Pattern and means to design tactile icons with modifiers. Assessment of modifier-based vocabularies are presented later in chapters 4 and 5.

## 3.1   Modifier in Braille

The Braille code was invented by Louis Braille, who introduced this writing system *circa* 1824. It has evolved from the tactile "Ecriture Nocturne", code invented by Charles Barbier for sending military messages that could be read on the battlefield at night, with-

out light. Braille is written with up to six raised dots arranged in a grid of two columns and three rows. This combination enables the configuration of 63 simple signals, as well as a blank. Therefore, basic signs are concatenated to form composite signals (double, triple, etc.) and increase the capacity of graphical construction.

Some simple signals are reserved to serve as prefixes. So, from 63 possible signs, 6 are reserved as prefixes, remaining 57 basic signs and the blank. One or more prefixes form a compound with one basic sign. Thus, a composite signal is characterized only when a simple signal appears after the prefix, or the set of prefixes. Some prefixes also have the role of modifiers. As a modifier, they affect a sequence or several sequences of symbols. A prefix is bound to a word and has a full meaning only when it meets a simple sign, while a modifier qualifies the meaning of several signs at the same time.

On Braille, the *uppercase prefix* is made by two raised dots (see Figure 3.1). This prefix is bound to a word or letter to apprise that the next signal should be assumed as uppercase. If more letters must be interpreted as uppercase, it is necessary to concatenate the same prefix twice in a row, which will work as a modifier. As an *uppercase modifier*, it turns all letters of the next word to uppercase. The uppercase prefix repeated three times in sequence turns all words of the sentence to uppercase.

Figure 3.1 - Uppercase modifier in Braille formed by concatenating the uppercase prefix



Source: Compiled by author.

## 3.2   The Modifier Tactile Pattern

A *Modifier Tactile Pattern* is 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. In that case, the influence of the Modifier on a tactile sequence remains during the period of the pattern burst or continues until another flag appears. So, as a pair of parenthesis, a pattern can be used to interrupt the action of the Modifier.

The Modifier works differently for haptizations. Vibrotactile cues are dynamic and are composed by several parameters. In Braille, the modifier affects one or more patterns in sequence, while the Modifier affects patterns or vibrotactile parameters sequentially or simultaneously. The vibrotactile Modifier acts like a specializing flag. When it is activated the user is receiving the message that parameters should be understood differently. For

example, assuming a tactile language made for a desktop application. The tactile display could use *rhythm* to communicate distance of a cursor to a point, *relative position* of a tactor to communicate position of the current window and *amplitude* to differentiate alert situations. A *Modifier* can be added, previously or simultaneously, changing the type of information conveyed by the display at the moment. Thus, rhythm would now inform the remaining capacity of a folder, position of tactor would suggest position of files and amplitude would differentiate user permissions.

In this work, we do not intend to classify tactile languages according to some morphological typology as natural languages. We just focus on the potential of treat meaningful units of a tacton as morphemes. And mostly, on the tactile signal characteristic to be bound or free. A *simple Tacton* is like a stem word or a root and have a meaning which does not depend of other Tacton semantically. On the other hand, a modifier is a variation of an affix which is a bound pattern. As a bound pattern, it has a meaning but it cannot be written without a simple Tacton. A modifier, as well as any other bound pattern, is pointless when displayed alone. In order to make the concept clearer we exemplify the utilization of Modifiers for design vibrotactile vocabularies.

## 3.3 Design With Modifiers

According to Riddle and Chapman (2012), a base tacton is created at the moment when a tactile parameter is combined with a metaphor associated to the message. Complex tactons and complex messages are made up by addition of qualifiers to other simple tactons. The qualifier gives details about the message. So, if 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 and Brown (2004) presented three approaches to syntax development of Tactons: compound, hierarchical and transformational. Hereinafter, we use such approaches as an example of how to design Modifiers.

### 3.3.1 Compound Approach

The construction of the language can be given in many different ways according to this approach. The main characteristic here is the existence of a set of signals that can be concatenated in different ways to compose a new message or Tacton. In this case, the Modifier Pattern must be inserted into the set of Tactons and its combination is subject to the usage rules of Modifiers.

As an example to demonstrate the approach, consider the patterns depicted in Figure 3.2.

It is possible to use 'Delete' and 'Create' as prefixal patterns, because the informed action is expected to know which object should be the target of such action. Thus, according to the implementation, when receiving the 'Delete' information one might ask "'Delete' what?". As prefixes these patterns would complete the information with the next basic pattern. Sentences such as "Delete file", "Create folder" and "Create file", for example, could then be printed.

With this vocabulary, the tactile display could inform a list of items to be deleted by displaying: "Delete file" and "Delete folder". To avoid the prefix 'Delete' to be printed repeatedly for each possible deleted item, the pattern 'Delete' can be specialized to a Modifier. As a Modifier it should affect multiple items. The list could now be printed as "*Delete_* file folder". In the design, the modifier action on a sequence can be defined

Figure 3.2 - Compound approach. Four Tactons formed by different parameters being combined to construct sentences
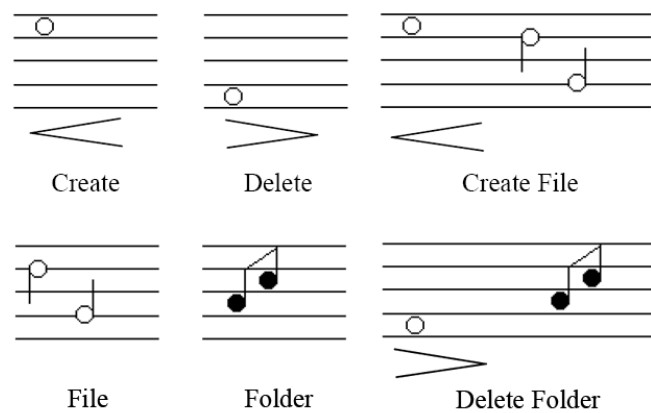


Source: Adapted from Brewster and Brown (2004).

to be valid until a blank (no motor active) or until the occurrence of another pattern that expresses the end of the modifier action.

The difference between the basic pattern and the modifier is a choice of the designer. The new modifier pattern '*Delete_*' can be created by concatenating the pattern 'Delete' twice. So, 'Delete' + 'Delete' = '*Delete_*'. Or the pattern can remain the same and be treated only as a modifier. For example, the sequence "Delete folder file" can be interpreted as two different expressions "Delete folder" and "file", or as the expression "Delete folder and file". The difference is in using the pattern 'Delete' as a prefix or as Modifier.

### 3.3.2 Transformational Approach

In transformational approach, each property of an entity is represented by a different tactile parameter. If a property of an object is represented by frequency, all objects that have the same property with the same value will be expressed with the same frequency. Besides, other property can not be expressed with frequency to avoid ambiguity. The different values of a property also need to be mapped to different values of the parameter chosen. For example, if frequency represents file type, each file type must be related to a single frequency value. Files of the same type are represented by the same frequency.

Modifiers can be created using a signal to inform that some parameters should be interpreted differently. A modifier may indicate, for instance, the change of the entity represented: instead of reporting about the desktop, the display passes to convey information about the hardware using the same parameters. What we want to promote is the reuse of parameters in a way to facilitate the learning of the tactile vocabulary. The forms of application are diverse and depend on the design strategy.

As we said in previous sections, prefixation is not a novel approach for tactile languages. Through the transformational approach or similar approaches, a set of tactile messages can be constructed by the junction of a base tacton with qualifiers. Ternes and MacLean (2008) called it "icon precursors in their tactile variant". However, the main difference between the transformational approach and the modifying approach is conceptual. A Modifier Tactile Pattern is not only an affix; it specifically changes the meaning of the remaining signals and parameters.

### 3.3.3 Hierarchical Approach

The main characteristic of the hierarchical approach is the structure of derivation used to define the construction of patterns. The hierarchical structure gives support to the design choices and manifests the characteristics inherited by each Tacton depending on the type of the transmitted information. Following the hierarchical structure, patterns can be constructed by transformational or composition methods. Figure 3.3 shows a literature example to explain the hierarchical approach.

Figure 3.3 - In a hierarchical way, each Tacton inherits properties from the levels above it
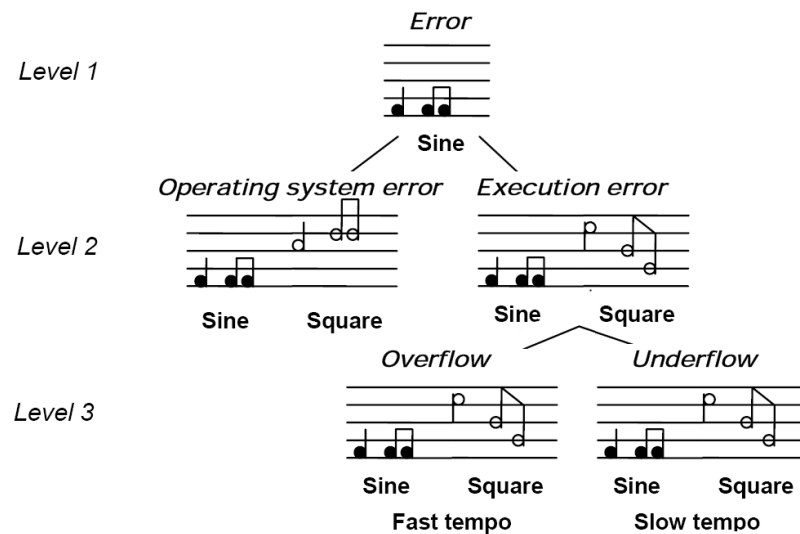


Source: Adapted from Brewster and Brown (2004).

Note that in Figure 3.3 some patterns are formed by *composition*; in Level 2 the rhythmic structure inherits the Tacton from Level 1 and adds to it a higher frequency Tacton played with a squarewave. The figure also shows that other patterns can be formed by *transformation* where different values of the same parameter represent different values of the same property; in Level 3 the parameter tempo of the two Tactons is changed. Therefore, in the hierarchical approach, the construction and use of modifiers occur as in the composition and transformational approaches, depending on the designer's choice. For instance, the "Error" signal could be repeated to compose a modifier and then reuse its parameters and meaning to create another Tacton.

## 3.4 Summary

We have explored the design of vibrotactile languages through a morphological point of view. Therefore, we have emphasized the use of a prefixation approach for construction of tactons. That way its possible to reuse the same patterns to convey different meanings, just by concatenating them with prefixal signals. So, based on Braille, we have defined the concept of Modifier Tactile Pattern as a tactile signal that modifies the interpretation of the remaining signals of a Tacton or tactile sequence. By reusing patterns we could get tactile vocabularies made by less signals to recall. Thus, the use of modifiers could enhance the tactile vocabulary expressiveness keeping it easy to learn. To evaluate such characteristic we have designed tactile vocabularies and performed user tests in virtual environments. Hereinafter we present the design and assessment of modifier-based vocabularies and the results of the user experiments.

# 4 INITIAL VOCABULARY FOR TACTILE NAVIGATION

We have created a vibrotactile language to characterize elements of a path, such as obstacles and routes to aid navigation. What we called *Initial Vocabulary* is actually the first iteration of our development process. As a means to ascertain the feasibility of designing such interface, we designed and tested this primary vocabulary. This vocabulary is basic and the construction of its signals took into consideration the use of a grid of tactors with limited parameters. The Modifier concept was not formalized yet. Although, it was applied experimentally in this initial design.

This section presents the development of both a vibrotactile language and a display. The tactile display was built for delivering tactile cues on the palm of the user's hand as tactile displays for tactile communication. As a large cortical area is devoted to it, the palm of the hand is a sensitive site of the human body skin. Either perception of the tactile cues and interpretation of the tactile icons were tested in user experiments. Even without acquaintance with this kind of interaction, all participants performed the task successfully, reaching the destination with the support of the tactile display.

## 4.1 Tactile Language Design

The methodology of Riddle and Chapman (2012) was used as an initial reference for the construction of patterns. We believe it is a good starting point as we are focused on pattern construction only, leaving the cognitive load issues for a future analysis. Researchers interested in evaluating the usage of the tactile language under workload should consider other methodologies that fit better, e.g. (CHAN; MACLEAN; MCGRENERE, 2008).

The construction of the language will be presented here in three steps: identification of the messages to be transmitted via cutaneous stimulation, the relationship between messages, metaphors and activation parameters, and finally the construction of tactons.

### 4.1.1 Set of Messages

To simplify the language, our set of transmitted messages include only information about *destination* and *obstacles* present in the route. In more elaborate environments and in a real situation, additional information may be necessary for the user to move around and orient him/herself without problems. However, in order to make inferences and test the effectiveness of the haptic language on locomotion, it may be interesting to perform such task first in a simpler and controlled environment. In a movie theater, a bank branch or an university campus, for example, to know the direction that must be followed and to recognize obstacles in the path until the destination seems to be enough information for

most users to locomote successfully.

The set of messages for this application can be defined as shown in Figure 4.1. The display should convey information about the destination and the obstacles immediately around the pedestrian. About destination, only its direction should be informed. Unlike destination, obstacles may exist or not in a path, so the user must be informed about the *existence* of obstacles. Messages about the position of the obstacle should be simple just presenting its direction in relation to the pedestrian.Thus, the messages about obstacles are informed through a collision-proximity feedback.

Figure 4.1 - Message set hierarchy
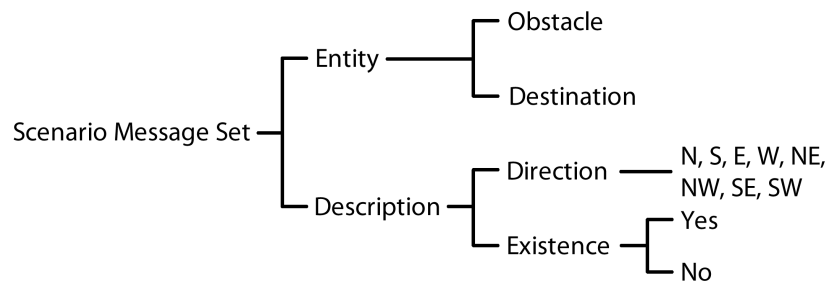


Source: Compiled by author.

### 4.1.2   Messages, Metaphors and Vibrotactile Parameters

To represent the direction, which is a spatial information, the *tactor position* can be used as a parameter. And to represent the existence of elements (destination or obstacle) on the route, the *duration of stimulus* can be used. The information about the existence of an element belongs to a binary domain (the answer may be "yes" or "no"), so duration of the stimuli can be null for the inexistence of obstacles and some non-zero value for its existence. The non-null value will match the lifetime of the obstacle around the pedestrian, so the vibration will extend while the obstacle remains close to the user (collision-proximity).

To distinguish entities (destination and obstacle) a reserved tactor can be used as a Modifier. The entities identified by the language are only "destination" and "obstacle"; in this case the same parameter used for existence of an entity can be used to distinguish entities. It means that, if this tactor is off the currently described elements do correspond to obstacles. When it is on, the meaning of the signals changes to identify the destination. As there will always be obstacles along the way, and information about the destination will be requested by the user only in a few moments, the destination is characterized as secondary information as it can be memorized. Thus, the reserved tactor may remain disabled until the information about the destination is requested.

### 4.1.3   Construction of Tactons

Using the Compass rose as a metaphor for orientation, we positioned eight vibrators at the cardinal and ordinal directions. This metaphor adds an iconic factor to the pattern. These eight tactors should be used to represent the existence and direction of whatever entity we want to display. Then, another arbitrary signal should be added in order to distinguish entities. We could choose one new pattern for each entity and then we would have two different patterns to memorize, as well as the meaning of the eight tactors afore-

mentioned (see Figure 4.2). Instead, as we differentiate the entities using just one pattern, the modifier, only one new pattern must be recalled.

Figure 4.2 - Tacton composition

Obstacles ← <ObstaclePattern> + <DirectionPattern>

Destination ← <DestinationPattern> + <DirectionPattern>

Source: Compiled by author.

So, considering a display composed by a 3x3 matrix of vibrating motors, the central one can be used as the reserved tactor to differentiate destination and obstacles. The messages were built from the junction of the basic Tactons by following the compound approach. However, instead of displaying modifier and position in sequence, we display them simultaneously as in Figure 4.3.

Figure 4.3 - The figure shows two Tactons: One (left) that informs the existence of an obstacle towards east and another one (right) that informs the direction of the destination towards east
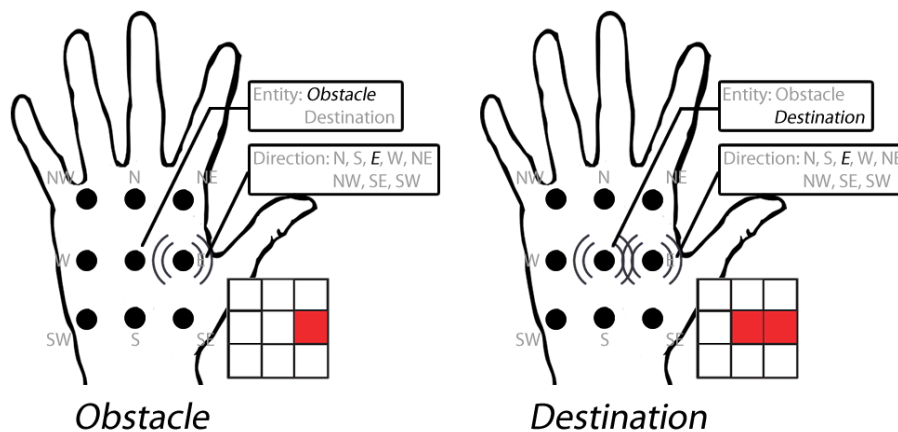


Source: Compiled by author.

Figure 4.3 shows an example of two tactons. One of them informs the existence of an obstacle towards east and the other one informs the direction of the destination towards east. However, the users do not have to retain the information of direction as a cardinal point in the environment as the motors are positioned perpendicularly to their bodies. That is how the positioning of the motors adds an iconic factor to the pattern. A signal in the left side evoques the existence of an entity in the left side. The same occurs with the remaining motors and positions.

## 4.2 Prototyping

As mentioned before, tactile displays are built in several formats: as belts, watches, waistcoats, etc. Based on the research related to proprioception, creating a tactile display that prints patterns on the user's hand is a smart choice. This is because the human hands are very sensitive and they have a good performance in processing multiple simultaneous stimuli (CHOLEWIAK, 1999). We tried the back of the hand (OLIVEIRA; MACIEL,

2012), but the cues were better perceived with the palm. Therefore, we created a tactile display for navigational aid in a virtual environment in the form of a matrix of vibrators for displaying patterns on the palm of the user's hand.

Nine tactors $ROB - 08449$ (Amplitude Vibration: $0.8G$; Voltage Range: $2.5V \sim 3.8V$), each with $3.4mm$, were attached to the surface of a plastic container. The vibrators were positioned at a distance of 2.3 cm apart horizontally and 2.5 cm vertically. The shape of the container used to build the display was chosen to facilitate the contact of the palm with the vibrators. An Arduino Mega board is used to control the vibrators. The communication between the board and the virtual environment is made through a serial port.

Due to vibrational resonance, in our first design none of vibrators could be discerned individually. That was because the vibrators were fixed on the surface of the container and the vibration of each one went through the whole display. As a solution, we placed small foam cubes under each vibrator in our final design. Thus, with the palm of the hand pressing the vibrators against the surface, or with the hand lightly touching them, it was possible to discriminate the vibration of each motor. Consequently, it allows to identify the combinations that make up each tacton. The final version of the display is shown in Figure 4.4.

Figure 4.4 - Final prototype of the hand-based vibrotactile display



Source: Compiled by author.

## 4.3 Evaluation

We performed user experiments to assess the effectiveness and usability of the display and the tactile language designed with the modifier pattern. In this section we present the planning of the user experiment. Initially, we present our hypotheses and then our experimental setup.

### 4.3.1 Hypotheses

We constructed some initial hypotheses to test vibrotactile display and language design:

- H1: the vibrotactile display allows the discrimination of different patterns. To convey meaning through a vibrotactile pattern is necessary for the users to have the capacity to differentiate such patterns. So, the design of the display should allow this;

- H2: the modifier clearly expresses whether the target direction or obstacle direction is being indicated;

- H3: patterns clearly state the direction of the target;

- H4: patterns clearly state the location of obstacles.

About the aimed support for user locomotion and orientation, we hypothesize that:

- H5: the combination of the designed display and language allows a person to navigate in an environment where obstacles are not visible and avoid collisions;

- H6: the combination of the designed display and language with the modifier allows a person to navigate to a destination in an environment where both obstacles and destination are not visible.

### 4.3.2 Experimental Setup

Each user was asked to perform four tasks and to fill out four forms. The overall experiment took between eighteen to thirty minutes for each participant. The tasks were categorized into two groups: tasks to verify perception of tactons and tasks to verify the usability of the language and display on navigation.

*Perception of Tactons*

*Task one - Identifying patterns:* In the first task, a set of vibrators was activated on the tactile display and the participants should feel it with their left hand and mark in a specific form how many and which vibrators were active. Fifteen randomly generated patterns were displayed (see Figure 4.5). Each micromotor was activated for one second and each pattern was displayed three times, with a delay of two seconds between them. After an interval of six seconds the next pattern was displayed. The whole task lasted exactly three minutes and fifteen seconds.

*Task two - Identifying information:* After the first task, the users were taught to interpret the tactile patterns as tactons. Then, in a second task, twelve patterns among those used in first task were printed in a different order. The participants read the pattern with their left hand and marked in the second form what information they believe the pattern conveys. They should answer if the printed pattern represented a destination or an obstacle, and mark the indicated direction. Each tacton was printed three times every six seconds. The whole task lasted exactly two minutes and fifty seconds.

*Tactile Navigation*

We would like to verify if the vibrotactile language built with a modifier could actually support the user in locomotion and orientation through a virtual environment. So, all the users also performed two navigation tasks. To perform such tasks, a virtual scenario was constructed consisting of a gallery full of obstacles.

Figure 4.5 - Graphical representation of the fifteen tactons used in task 1
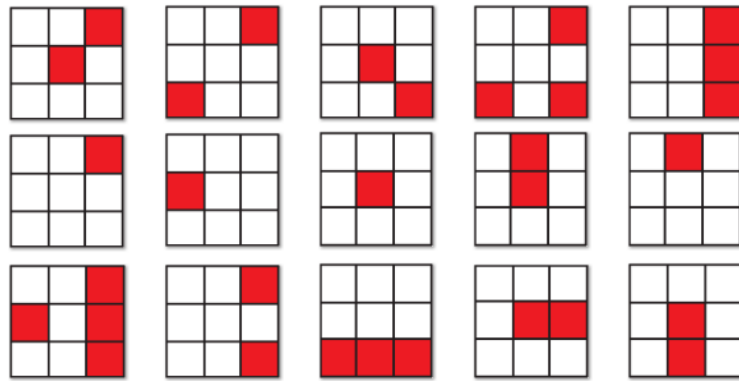


Source: Compiled by author.

*Task three - Gradual navigation:* In the first scenario, the character manipulated by the user (avatar) was initially positioned at the entrance of the gallery. The user moves through this gallery to reach the opposite side, indicated by a large and bright picture. The user was requested to avoid collision with obstacles along the way. The lighting along the path was uneven, decreasing light intensity as the avatar approaches the target. The haptic language is simplified to render only obstacles. It may not be useful or necessary in the first half of the task where the obstacles are visible. However, it is essential in the second half, where the user could not see the obstacles under a low illumination (see Figure 4.6).

Figure 4.6 - Testing locomotion using vibrotactile aid. The environment becomes darker as the user advances toward the target, gradually increasing the need for the haptic display to avoid the obstacles



Source: Compiled by author.

*Task four - Blind navigation:* Another test was performed rendering haptic information about both obstacles and destination. In this test, the character is placed from the beginning in a lounge with no light, thus having no visual information about the target destination. In this situation, the use of the tactile display becomes even more necessary for the user to acquire information about both the obstacles and the direction of the target destination.

## 4.4 Discussion and Results

*Fifteen* users have volunteered to participate in the tests; fourteen were male. The participants have a mean age of 24 years old and all of them are Computer Science students (six undergraduate, nine graduate). Four of them had previous experience with cutaneous stimuli by the use of another prototype made as a belt with vibrating motors. Three users present myopia and one of them also presents astigmatism. One user mentioned he suffers from hyperhidrosis, but this condition did not seem to affect his results.

Despite two participants are left handed, the tactile display was placed on the left side for all users because all of them state that they currently use the right hand to handle mouse and keyboard arrows (for navigation). They also used the right-hand with the pen to answer the survey (only cross marks). Testing was done in a private room where just remained the volunteer and the researcher to best avoid distractions.

### 4.4.1 Perception of Tactons

*Task one - Identifying patterns:*

With task one, we tested if each vibrator could be clearly perceived and if the users could identify the patterns. This task was devised to measure the user sensitivity free of bias. Therefore, it was performed without any previous training.

In a strict analysis, the user must check the *exact number of active motors* and *their exact position.* The average of correct answers was 8.13 ($\sigma = 2.82$), which represents 54.22% of the patterns (see Figure 4.7). Patterns made by the composition of three and four motors had a greater number of errors. However, the results show that the misinterpretations were not caused by the number of tactors but rather by their relative positions. In general, the users had a correct perception of the number of tactors, even though they did not report the correct positions for all micromotors in the display. Such result was expected as the hand is not the best location to deliver a great amount of stimuli due to masking. With such result we could know exactly the kind of patterns that are more difficult to process. If nothing else, in this test all users reported the correct position of the reserved motor.

Thus, we made a second analysis and this time we removed the patterns consisting of four motors simultaneously active. Besides, we consider as being correct the patterns in which the position of only one motor was swapped with a neighbor. In this relaxed analysis the mean score was 13.4 patterns ($\sigma = 0.9$), which represents 91% of them, as illustrated in Figure 4.7. This result was due to a large number of errors that have been caused by marking a neighboring location when more than one motor vibrate at the same time. We observed that, during a navigation task, the user can spend more time to feel the pattern and avoid this misunderstanding. So, when delivering vibration on the user's hand we must create tactons with a smaller number of motors to improve user processing.

Our vibrotactile display allows the discrimination of different patterns, as predicted by our first hypothesis. Even if the patterns composed by few motors are better discriminated than those with several motors vibrating simultaneously, the display is sufficiently effective to be used with a more elaborate task.

Figure 4.7 - Number of patterns properly recognized (y axis) by each user (x axis). Left: The dashed line marks the mean 8.13 and the dotted line marks the standard deviation. Right: The patterns made by four motors were removed. Also, the answers where the position of only one motor was swapped with a neighbor were considered correct. The dashed line marks the mean 13.4 and the dotted line marks the standard deviation
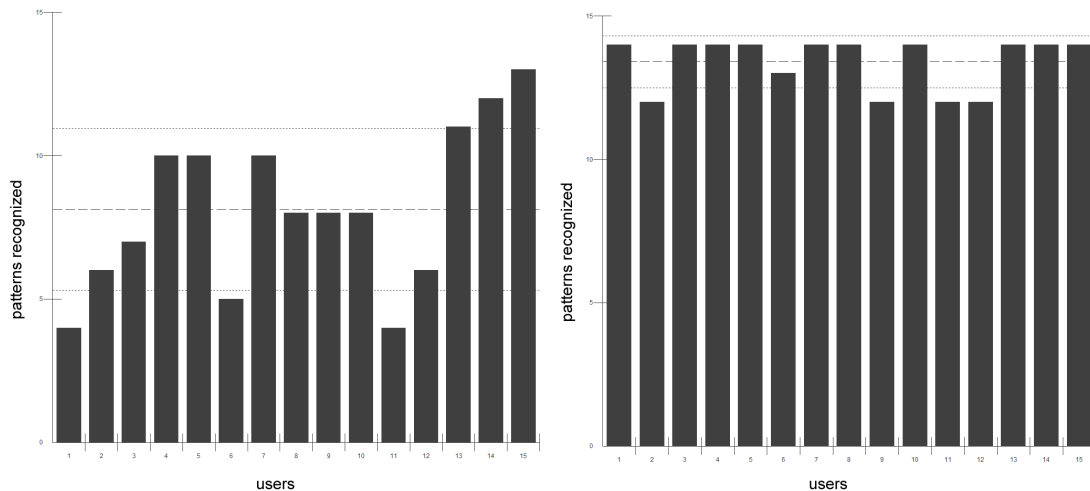


Source: Compiled by author.

*Task two - Identifying information:*

On task two, the tactile language design was tested. The users were taught to interpret the tactile patterns as tactons. The tactons were made to convey information about obstacles and destination. The central motor of the grid is used to differentiate those entities, and the peripheral motors vibrate to denote existence of obstacles around the user. If the central motor is turned on, the peripheral motors indicate the direction of destination instead. Therefore, the central vibration motor became the first to be processed by users in order to discern what kind of information the tactons were transmitting.

As in task one, the pattern of four motors simultaneously active achieved the worst results, so it was removed from this analysis. In this second task, the users hit the correct meaning conveyed by the modifier (destination or obstacle) in 95.75% of the displayed patterns (see details in Figure 4.8). This result satisfies the second hypothesis (H2). All users that failed in recognizing a pattern misinterpreted the pattern by only one motor. They thought that a neighbor motor was active instead of the central motor.

Also, when the central motor was activated alone there was a misinterpretation. Some users chose to mark the information as a "north signal" for example, assuming that the orientation was mandatory for any tacton. At the end, thirteen out of fifteen participants properly identified the information passed by the Modifier Pattern. Only two people were confused about the real position of the motor in the second test. They hit its position in the previous test, so this misinterpretation probably occurred due to a perception error or due to an interpretation that the modifier must necessarily be followed by at least one other active tacton.

In a strict analysis, the number of users that hit the exact position of the destination and the exact position of obstacles was respectively 73.3% and 64.7%. Although the motor placement and the use of a high number of motors still represent an issue in this design, there was an improvement in recognition of tactons compared to task one. Mainly,

Figure 4.8 - Number of correctly recognised modifier meanings for each user. The dashed line marks the mean 10.53 and the dotted line marks the standard deviation 0.7. Twelve patterns were displayed in this task
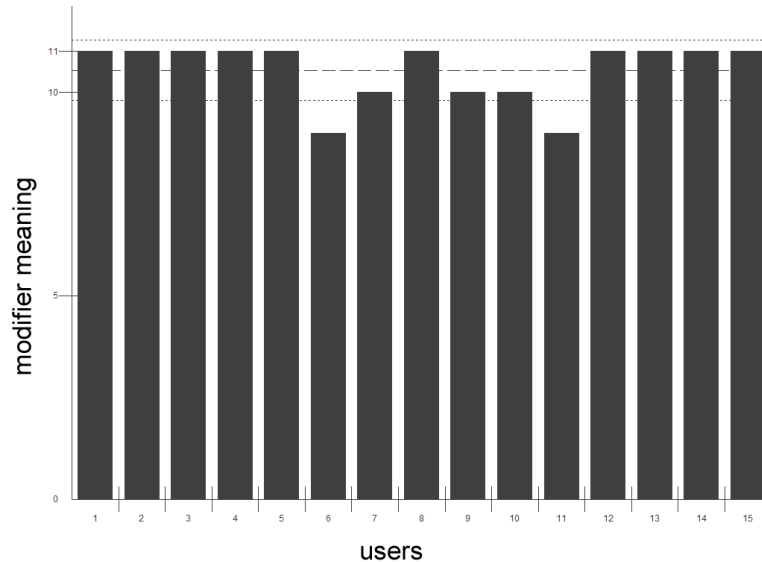


Source: Compiled by author.

the patterns that include activation of the central motor were better identified. Patterns clearly state the direction of the targets and obstacles (H3 and H4), which can be observed especially during the locomotion task. We summarize in Table 4.1 the values found in this session.

Table 4.1 - Summary of results of Task one and Task two

| Task | Condition | Avg. | % | Std. Dev. |
|------|-----------|------|------|-----------|
| Task one | Strict | 8.1 | 54.0 | 2.8 |
| | Relaxed | 13.4 | 91.0 | 0.9 |
| Task two | Meaning | 10.5 | 95.7 | 0.7 |
| | Exact dest. pos. | 3.0 | 73.3 | 0.7 |
| | Exact obst. pos. | 5.0 | 64.7 | 1.0 |

Source: Compiled by author.

## 4.4.2 Tactile Navigation

*Task three - Gradual navigation:*

In this task, each participant took an average of five minutes to complete the course. The fastest one completed in two minutes and the slower in fifteen. All users privileged the sense of sight in the more illuminated section of the path. In the middle of the scenario, where illumination became very low, some users still insisted in using vision. Only in the darker side of the scenario the participant switched their focus of attention to the aid of the tactile display. Figure 4.9 shows the route taken by one of the participants.

We also evaluated the collisions with obstacles (Figure 4.10). Three users have shown to be outliers and were removed for this analysis; they reported not to care about the num-

Figure 4.9 - Map of the scenario used in the experiment. The blue line indicates the route taken by one of the test participants. In this example the user completed the task without colliding
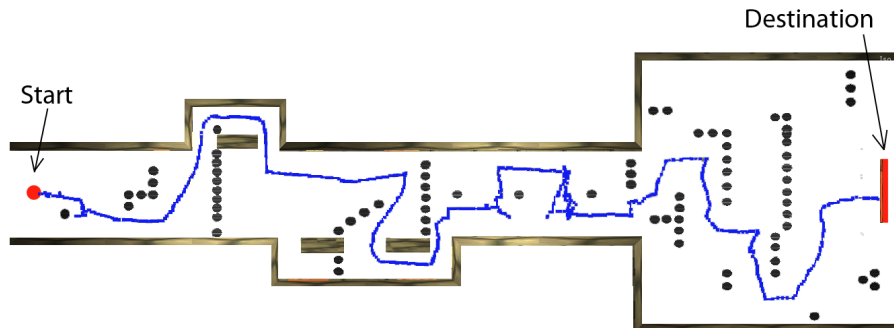


Source: Compiled by author.

ber of collisions as long as they reached to the destination. Figure 4.10 shows that their collision counts were much higher than the others. They collided around 2 deviations above the average that includes them (86), and near 10 deviations from the average excluding them (30). Although these collision numbers are meaningful for comparison, the absolute numbers are overshot. Our collision count method is time dependent and counts many collisions when an user remains in contact with an obstacle. Moreover, there was no feedback about collisions during the test, causing some people to remain in collision for a while. Then, 60 collisions may actually mean only 1, 2 or 3. Zero, nevertheless, means absolutely no collision.

Figure 4.10 - Number of collisions on task three (y axis) for each user (x axis). The dashed line marks the mean of 86 collisions including outliers. The dotted line marks the deviation. Only two users made no collisions, but absolute numbers are over counted as explained in the text
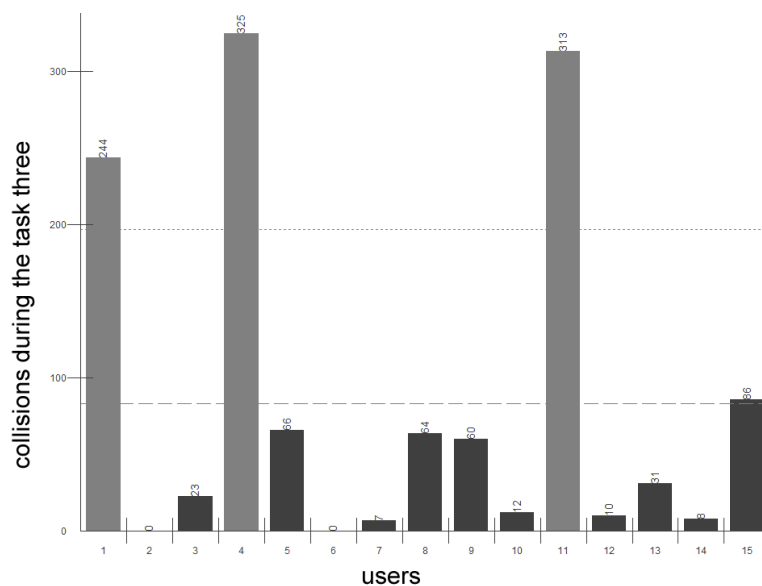


Source: Compiled by author.

After outlier removal, the remaining users achieved a mean of 30 collisions. Yet, most of the collisions have occurred in the darkest part of the environment where users saw the target but not the obstacles, creating a conflict between visual and tactile feedback. There, they could see the target very close ahead, which encouraged them to anxiously ignore the tactile feedback and collide. This confusion can be due to the hand-based design and must be further explored. However, despite the large variance in the number of collisions, two users completed the task without colliding. Considering that they received no training, this supports hypothesis H5, showing that a person can navigate in a virtual environment where obstacles are not visible using the proposed language and display and do not collide. We cannot claim this is a good result in terms of efficiency, but we are convinced that without the tactile aid it would not be possible in such a complex map (see Figure 4.9).

*Task four - Blind navigation:*

The second scenario, and last task of the whole test, took an average of eight minutes for each user to complete the course. The fastest user completed in two minutes and the slower took twenty-nine minutes to finish. All participants agreed that the second route was very difficult. Notice that no other orientation cue was given besides the haptic display and all participants are untrained. Nevertheless, all users performed the task successfully, reaching the destination. This shows that the combination of our display and language effectively allowed the users to navigate to the destination in an environment where both obstacles and destination were not visible, confirming H6.

There were many collisions in the task three that were due to the users preference to rely on vision instead of tactile feedback. In task four, instead, the users had only the tactile feedback to orient themselves. Therefore, those who made many collisions in task three committed three times fewer collisions on task four.

## 4.5 Summary

The user experiments have shown the usefulness of the created tactile vocabulary while aid for orientation and navigation tasks. Nonetheless, it has some issues that must be improved concerning its usability. The test results inspired new strategies to optimize the displaying of the tactile icons on the hand. The hand, although a sensitive loci, is less effective in receiving large amount of vibration. However, we noted that the hand perceives reasonably well about three vibrators at a time. We believe that the results could be improved by delivering less vibration to the hand. As the users move mostly forward on navigation, they use to keep their attention on the frontal motors. Turning the rear motors off automatically during the navigation we can mitigate the masking and enhance the interaction.

After ratifying the feasibility of the tactile navigation we went forward in the research. The concept of Tactile Modifier Pattern was shaped and the tactile vocabulary was increased in order to transmit more information during navigation. We also proceed exploring means to construct vocabularies with modifiers and analyzing how their design affects the user perception and the user performance in navigation. The following section presents the enhancement of the tactile language for navigation with a new prototyping and new user experiments.

# 5 ENHANCEMENT OF THE TACTILE LANGUAGE

In a second iteration we created an enlarged version of the tactile language for navigation. This version was intended to be more expressive. So, the message set was increased to transmit more informations during the navigation task. The tactile language was also intended to be suitable for navigation in virtual environments and also physical environments. Thus, the prototype of the tactile display was redesigned to make it wearable. As presented in previous sections, the perception we have about the location of our own body in the three-dimensional space is referenced to the location of the torso. Therefore, the new display was made as a belt. Such design proved to be more suitable as we wanted to free the hands for other tasks.

The tactile prefixation with modifier patterns can occur on differents ways. The modifier pattern can be displayed simultaneously (superposed) with the basic tacton or in sequence, following a compound approach, or can be attached at the beginning of the sequence as an ordinary prefix (juxtaposed). The choice of designing the tactile icons and messages by superposition or juxtaposition may affect the quality of the tactile language in different ways. The use of sequences may be simple to process in a simple task, but may demand a greater effort to process under heavy workload. Therefore, we designed *three vocabularies* and conducted an user study to assess the differences between tactile vocabularies made by a prefixation and a non-prefixation approach, and also the characteristics of prefixed messages by superposition and juxtaposition. Each vocabulary follows a different approach: a conventional one, based only on metaphors; a modifier-based vocabulary with patterns made by juxtaposition of tactons in sequence; and another modifier-based vocabulary with patterns made by superposition.

## 5.1 Vibrotactile Belt

Limbs are poor candidate sites for displaying tactile information to support orientation and mobility tasks. The initial tactile display made for the hand was good as it was fixed and positioned perpendicularly to the user's body. If the vibrating motors were attached on the hands, the cardinal references would be lost with the hand movement. The human torso is another sensitive loci and more suitable for tactile navigation. Previous works report that a belt made with eight motors is appropriate to work as a display (STELTENPOHL; BOUWER, 2013; BOLL; ASIF; HEUTEN, 2011; ROSEN-THAL et al., 2011; ERP et al., 2005). The waist location around the especially sensitive navel and spine sites, has been privileged by a number of authors (KARUEI et al., 2011; CHOLEWIAK; BRILL; SCHWAB, 2004). Also, some previous approaches arrange several motor arrays along the person's torso to display more information (MATEEVITSI et al., 2013; LINDEMAN et al., 2005). However, to focus on the expressiveness of the

tactile language, we choose to maintain the display small and manipulate the elements that compose the tactons instead.

Our belt was constructed with eight electromechanical tactors $ROB - 08449$ (Amplitude Vibration: $0.8G$; Voltage Range: $2.5V \sim 3.8V$), each with $3.4mm$. The vibrators were attached to pieces of Velcro and then positioned at equidistant locations. An Arduino Mega board was used to control the vibrators. The communication between the board and the virtual environment is made through a serial port (see in Figure 5.1).

Figure 5.1 - Final prototype of the vibrotactile display as a belt
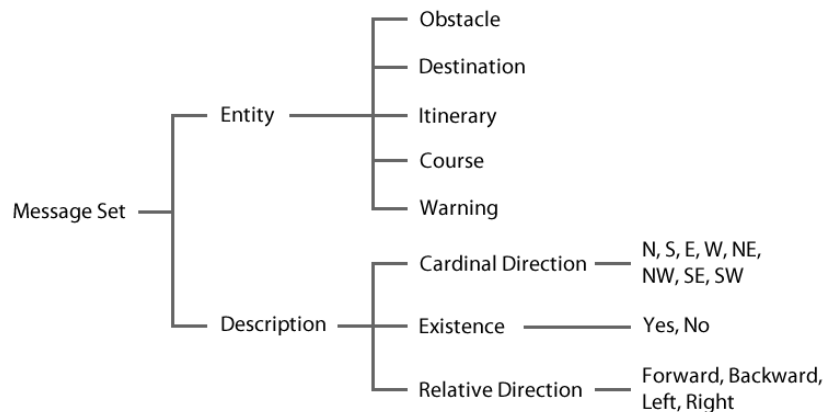


Source: Compiled by author.

## 5.2   Increasing the Tactile Vocabulary

A number of different messages may be helpful to aid a person in the navigation task. Some of them would rather be necessary to the task, such as destination loci. Others are unessential, but still helpful for route planning, such as minimum distance to a point. We designed a tactile language to transmit five different kinds of information. The number of five means a great amount of information and still a reasonable number of objects to memorize (Miller's Law). The evaluation of such amount of information allows us to observe to what measure they are essential for the navigation task and also how each information helps a person to follow a better route. The messages displayed via tactile stimuli indicate: Destination, Obstacle, Course, Warning and Itinerary (see Figure 5.2).

A navigation activity is basically defined as the problem of moving from an origin to a destination. The navigator must ascertain a position and then plan and follow a route. Therefore, the *Destination* is an imperative information for such task. A language could convey information about position, distance and other characteristics of the destination. Our language only conveys the direction of the destination in order to keep the set of messages simple. Another important information we also convey is the presence of *Obstacle* for collision-proximity detection. In Chapter 4 we demonstrated that a person in a completely dark environment could move to an unknown position without colliding with obstacles through the route just by using a vibrotactile display receiving Destination and Obstacle messages.

The tactile language designed also convey information about *Course* and *Warning*, similarly to a tactile paving (ISO 9001:2008). Both information are expected to help the

Figure 5.2 - Message set hierarchy



Source: Compiled by author.

user to feel predefined routes. Thereby, the user can receive information about flows that may lead to the destination (course message) and also be warned about stairs, ramps, and other elements that are not insurmountable obstacles but also demand attention (warning message). Finally, we also convey information about *Itinerary*. The itinerary messages guide the navigator to take a specific route (e.g., the shortest or the fastest), mostly like a GPS navigator. We display four distinct messages for itinerary, indicating that the navigator must go forward, backward, to the left or to the right. Such information would be also useful for drivers in the traffic.

### 5.2.1 Tactile Icons Design

The Compass rose is used as a metaphor for orientation. By placing eight actuators at the cardinal and the ordinal directions around the user waist we could point to directions from an egocentric perspective. This metaphor adds an iconic factor to the pattern, just as the "tap-on-shoulders" approach. These eight tactors are used to represent the position or direction of whatever entity we want to display. Then, other arbitrary patterns are added in order to distinguish and characterize different entities. The amount of arbitrary patterns and the way they are designed affect how they are learned. Therefore, different compositions should result in vocabularies with different qualities for 3D navigation. We have built three different set of tactons (or tactile vocabularies) so we could assess how the different choices affect the navigation task.

*First Vocabulary: Conventional Approach*

A non-prefixed approach was chosen to design the tactons in this vocabulary. By conventional we mean to create different vibrotactile patterns varying just the hardware parameters and the respective actuator position.

In Section 4, we noticed that users rarely pay attention to the back actuators. While navigating, they constantly move forward or rotate towards the destination, so there is no urge to perceive obstacles behind. Therefore, only the five frontal actuators are used to convey information about collision-proximity. The three rear motors are then free to render other information. In the present design we use two of them to convey information about course, while the remaining motor, on the spine, is used to display warning (see Figure 5.3).

Figure 5.3 - The tactor location is used to create patterns of Course, Warning and Obstacles
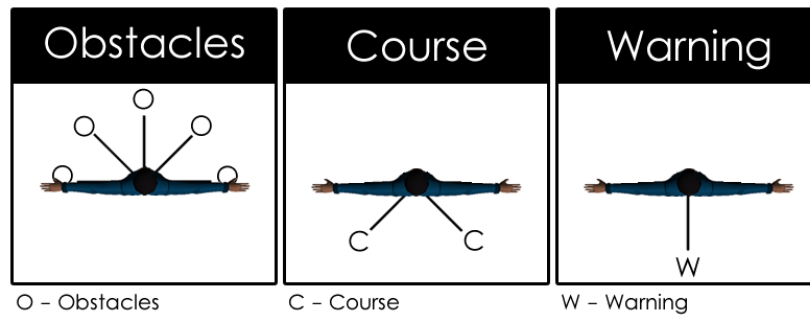


Source: Compiled by author.

As we reserved the tacton position to transmit information about obstacles, course and warnings, we had to choose other hardware parameters to transmit the remaining informations. To distinguish the destination from the obstacle position pattern, we use a change in frequency. For the itinerary, we render waves of bursts in sequence towards the direction suggested (see Figure 5.4).

Figure 5.4 - Frequency and shape were used to create patterns of Destination and Itinerary
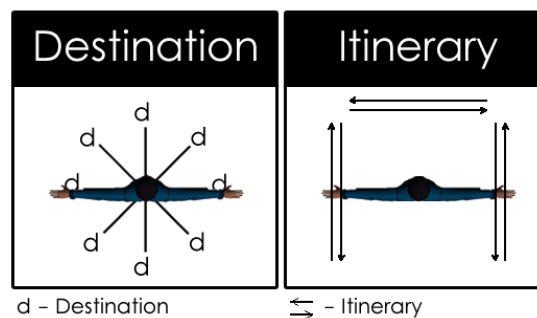


Source: Compiled by author.

*Second Vocabulary: Modifier-based by Juxtaposition*

In this vocabulary, we designed the tactons based on a prefixation approach. The frontal actuators are still used to convey information about obstacles, but the rear actuators now are used to compose modifier patterns. Each message is transmitted as a tactile sequence. First, the modifier pattern is displayed stating the entity. Then, the entity's direction or position is displayed by the activation of an actuator in the relative position on the user's waist.

Similarly to the conventional vocabulary, two rear motors were selected to print information about course. These two motors are activated to signalize that the display will now render course information instead of obstacles. The course was made by printing the two-rear-motors modifier plus the relative position of the course. As course and warning were both inspired by systems of textured ground surface, we use the same modifier to print the warning pattern. The warning sign is then made by printing the two-rear-motors modifier plus the spine motor.

The spine motor was, otherwise, used to mark the modifier sign for destination. First, the spine motor bursts. Then, one of the eight motors is activated to show the direction of the destination. To differentiate the itinerary pattern we created a compound modifier by printing the same modifier twice. So, when the pedestrian must move to the left, the spine motor is activated twice and then the left motor (see Figure 5.5).

Figure 5.5 - Modifier-based vocabulary. Three back motors were used to compose modifier patterns
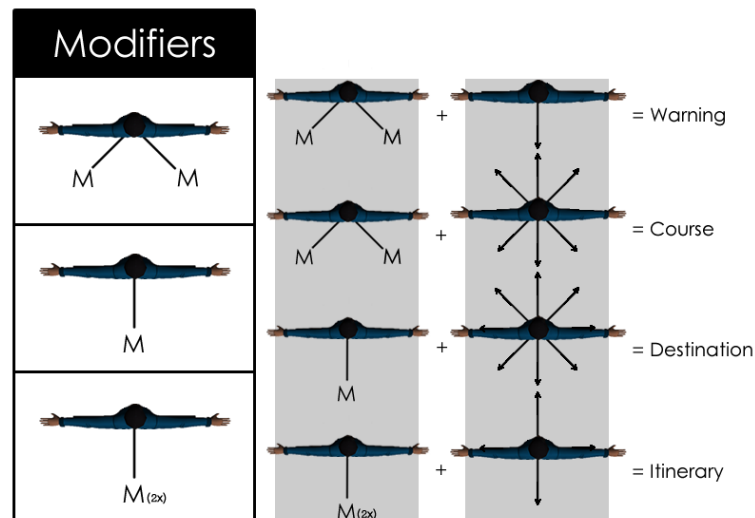


Source: Compiled by author.

*Third Vocabulary: Modifier-based by Superposition*

There are two mainly differences between the vocabulary presented in the previous section and the conventional one: the use of prefixes and sequences. So, we designed a third tactile vocabulary aiming to isolate *sequence* as an independent variable. As shown in Table 5.1, four messages in the conventional vocabulary are exhibited as a single pattern. The modifier-based vocabulary, in turn, was made only by patterns in sequence. We then designed another vocabulary based on modifiers but with four messages exhibited as a single pattern, without sequence (see Table 5.1).

Table 5.1 - Comparison between vocabularies. The first vocabulary has one message exhibited as a tactile sequence. The second vocabulary has many messages exhibited as sequences. The third vocabulary was done in an equivalent manner to the first one; the difference is that it is based on modifiers

| Message | Vocabulary | | |
|---|---|---|---|
| | First | Second | Third |
| Obstacles | Single pattern | Single pattern | Single pattern |
| Course | Single pattern | Sequence | Single pattern |
| Warning | Single pattern | Sequence | Single pattern |
| Destination | Single pattern | Sequence | Single pattern |
| Itinerary | Sequence | Sequence | Sequence |

Source: Compiled by author.

The modifier patterns are displayed simultaneously with the entity's direction or position, producing a single pattern (see Figure 5.6). In this vocabulary, the course was made by printing the two-rear-motors modifier and the relative position of the course at the same time. Also the warning was made by printing the two-rear-motors modifier and the spine motor simultaneously. The spine motor and one of the seven left motors burst to show the direction of the destination.

In the first vocabulary the itinerary is exhibited as a tactile sequence. So, we kept it as a sequence in this third vocabulary for normalization. At this time, when the indication is to move left, the spine motor is activated once and then the left motor.

Figure 5.6 - Modifier-based vocabulary with minimum sequence. The three back motors are used to compose modifier patterns that are printed simultaneously with direction/position information
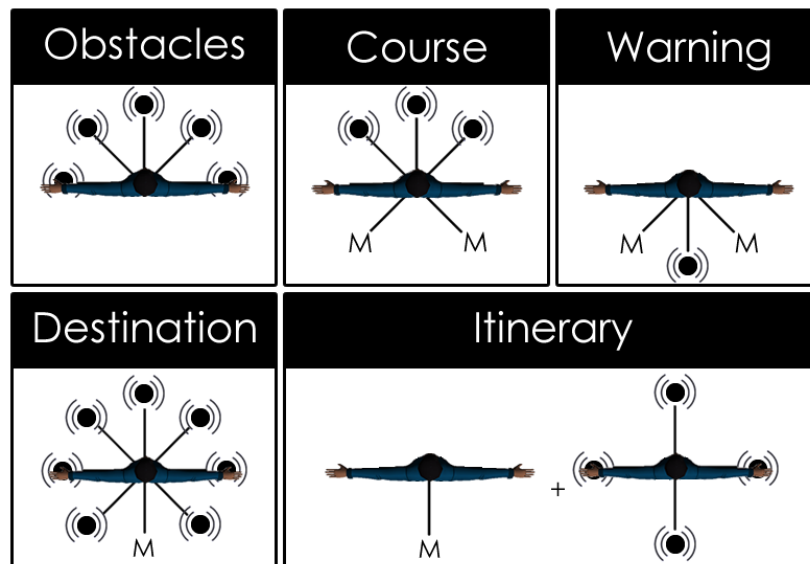


Source: Compiled by author.

## 5.3 Evaluation

A tactile vocabulary based on modifiers is more expressive than a similar vocabulary without modifiers as it uses less symbols to communicate the same information. On the other hand, learning the relations between symbols, e.g. prefixation or juxtaposition, may be more difficult than just memorize a greater number of symbols. We hypothesize, however, that modifier based vocabularies collaborate for a higher increase of user performance along time than a conventional vocabulary. At the same time, we wish to investigate how the use of sequential (prefixated) or simultaneous (juxtaposed) modifier patterns influence the user performance.

The study below compares the three vocabularies described in the previous session in many dimensions. Our main focus is to demonstrate that even with a minimal learning phase, modifier patterns can offer a gain in performance after a few trials. We also focus on determining the situations where patterns in sequence can perform better than simultaneous patterns.

### 5.3.1 Experimental Setup

For a between-groups experiment, we divided our population into three distinct user groups that will perform the same tasks but using a different vocabulary. First, each group was instructed on one of the three tactile vocabularies.

After filling a pre-test characterization form, each participant was invited to wear the tactile belt and use the tutorial app. The tutorial is a step-by-step visual description of the vibrotactile language. It also explains the experiment task and demonstrates how the belt works by activating it while a graphical representation is exhibited on the screen. Then, each individual was exposed to tasks that evaluated their perception of the motors and their interpretation of tactons displayed by the belt. Finally, each user navigates through four different scenarios using the tactile belt. At the end they filled an evaluation form to give their opinions on the tactile vocabulary. Hereinafter we describe the scenario of each task.

*Preliminary perception test*

In this first task, a set of vibrators is activated on the tactile display and the participants should sense it and answer how many and which vibrators were active. Fifteen randomly generated patterns were displayed. Each set of motors was activated for five seconds with a pause of two seconds between them. Before each new pattern be exhibited, the participant should mark the position of each motor activated by pressing buttons in a cylindrical keyboard we developed specifically for this task. This keyboard was made isomorphically to the belt, with eight buttons arranged in locations respective to the eight actuators. After pressing each button the corresponding motor is flagged on the screen (as seen in Figure 5.7) and stored before a new pattern starts. The whole task lasted exactly 1 minute and 45 seconds. This task is necessary to verify that the combination of motors type and position with the hardware and software implementation is able to render perceivable signals, independently of their meaning.

Figure 5.7 - Input device made as a cylindrical keyboard



Source: Compiled by author.

*Interpretation test*

In a second task, ten selected patterns are displayed through the belt. However, this time the participants are asked to inform the meaning the pattern conveys as a tacton. They should answer if the printed pattern represented a destination, an obstacle, a warning, an

itinerary or a course and then mark its direction Figure 5.8. Each tacton is printed during 11 seconds; the whole task lasts exactly 1 minute and 50 seconds. The same sequence of messages is displayed for all participants, but the vocabulary was different for each of the three groups.

Figure 5.8 - Screen for the interpretation of the vibrotactile messages
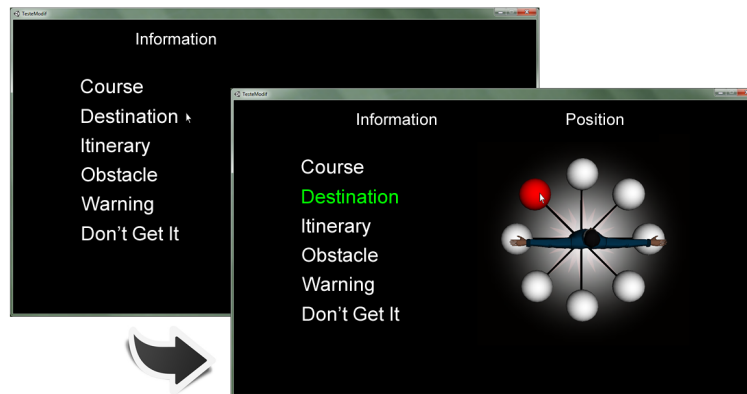


Source: Compiled by author.

*Navigation test*

This task was presented as a game composed by four different levels. The goal in each level is to reach the destination, an object lightened in red, using the information transmitted by the vibrotactile display. The first level is the same for the three groups and the belt only displayed information about obstacles. For the other levels, the scenario changes and the set of messages transmitted in each new level is increased by one additional type of information. The additional information is not always the same, being randomly selected for each user. At the last level, the complete set of messages of the respective vocabulary is exhibited to participants of each group.

The first scenario was the same used for navigation with the hand-based display presented in Chapter 4. The user should move through a gallery to reach the opposite side, indicated by a large and bright picture. The user was also requested to avoid collision with obstacles along the way. The lighting along the path was uneven, decreasing light intensity as the avatar approaches the target (see Figure 5.9).

Figure 5.9 - Testing navigation using vibrotactile aid
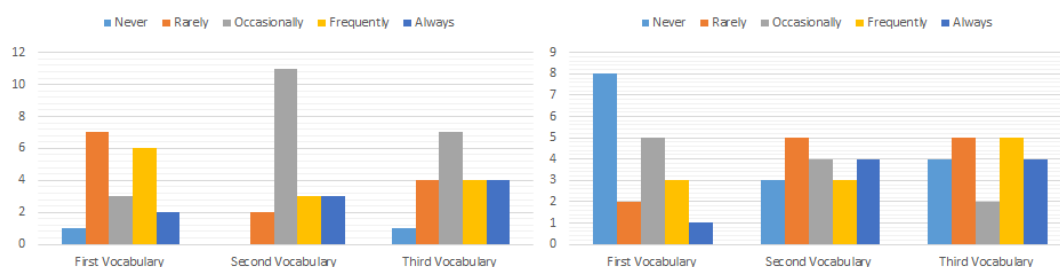


Source: Compiled by author.

In the first level, the destination is visible all the time. In the remaining levels, the users depend upon the information displayed by the tactile belt to find the destination location. They have to use the available tactile information, which vary as they progress between levels, to reach the goal while avoiding obstacles. Depending on the information available, some users may choose to follow the route suggested by the belt (itinerary), or to follow some course + destination while still avoiding obstacles through the way.

## 5.4   Discussion and Results

A population of 58 individuals have volunteered to participate in the tests; 47 are male and 11 females. The participants are students, covering an age range of 19 - 32 years. Twenty three users have some degree of myopia, astigmatism or hypermetropia. Testing was done in a dedicated room where just remained the volunteer and the researcher to best avoid distractions. A number of 20 participants learned and used the first vocabulary; 19 participants made their tasks using the second vocabulary and 19 participants used the third vocabulary. The overall experiment took between 18 to 30 minutes for each participant.

The volunteers reported in the pre-test questionnaire about their experience with games and their practice with joypads in the past six months. These questions are important because the participants had to use a joypad for the navigation task. The first group has a few more participants that rarely or never played games or used a joypad in the past 6 months. Although, the experience among the three groups was balanced. In all groups the majority of people have some practice in games, even though their playing habits are mostly occasional (see Figure 5.10). The number of users that occasionally, frequently or always play with joypads is barely the same for all three groups (see Figure 5.10).

Figure 5.10 - Participants background experience. (Left) Participants experience with 3D games. The responses are based on the past six months before the experiment. (Right) Participants experience with joypads. Some users reported to play 3D games frequently, but use keyboard and mouse instead of a joypad



Source: Compiled by author.

### 5.4.1   Preliminary perception test

The users from the three groups performed this task. First, we measured the user's torso and then we placed the motors at equidistant positions. The belt was placed 3cm above the navel of the participant, at the waist level. The torsos had an average of 80cm (65cm - 105cm). For this test, the patterns were activated in sets of one to three motors simultaneously. The results can be seen in the confusion matrix presented in Table 5.2. At the table, motors located at the cardinal positions are marked in bold, being the motor #2 placed at the central frontal position.

Table 5.2 - Stimulus/Response Localization Confusion Matrix from Experiment 1, N = 8

| Stimulus Site | Response (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | " " |
| 1 | 53.07 | 1.75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.44 | 8.77 | 35.96 |
| 2 | 2.34 | **67.25** | 1.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 29.24 |
| 3 | 0.75 | 2.26 | 52.38 | 9.52 | 1.00 | 0.00 | 0.25 | 0.00 | 33.83 |
| 4 | 0.00 | 0.00 | 4.09 | **46.78** | 8.77 | 0.00 | 0.00 | 0.00 | 40.35 |
| 5 | 0.00 | 0.00 | 0.58 | 9.36 | 43.27 | 1.17 | 0.00 | 0.00 | 45.61 |
| 6 | 0.00 | 0.00 | 0.00 | 0.00 | 3.51 | **83.63** | 6.43 | 1.17 | 5.26 |
| 7 | 1.32 | 0.00 | 0.00 | 0.00 | 1.75 | 0.44 | 68.86 | 8.77 | 18.86 |
| 8 | 7.89 | 1.75 | 0.00 | 0.00 | 1.75 | 0.00 | 16.67 | **67.54** | 4.39 |

Source: Compiled by author.

As expected, the locations around the navel and spine provided the best correspondences. The results near the spine were correctly marked in 83.63% of the cases. This result demonstrates the advantage of the motor on the back over the other motors. Such result also justifies the choice of the center-rear motor as an indicator of warning signals or pop-out signals.

The remaining rear motors also obtained a high number of correspondences. The left-rear motor (number 7) had the second highest number of correct hits, 68.86%. However, the right-rear motor (number 5) have not obtained the same level of perception, since in 43.27% of the times it was shown the response was left blank. Many occurrences have been left unanswered for those motors that were exhibited multiple times in sets of two and three motors. One-way ANOVA showed that there is a significant loss in the hits for patterns with many motors ($F(3.88)=27.99$, $p<0.00003$). It means that a higher number of motors causes more errors.

### 5.4.2 Interpretation test

The task was performed in a single trial. The same pattern sequence was displayed for all users with their respective vocabulary. The results have not presented significant difference between languages. However, the percentage of correct answers was lower for the second vocabulary (see Figure 5.11).

Figure 5.11 - Interpretation of messages by three different vocabularies
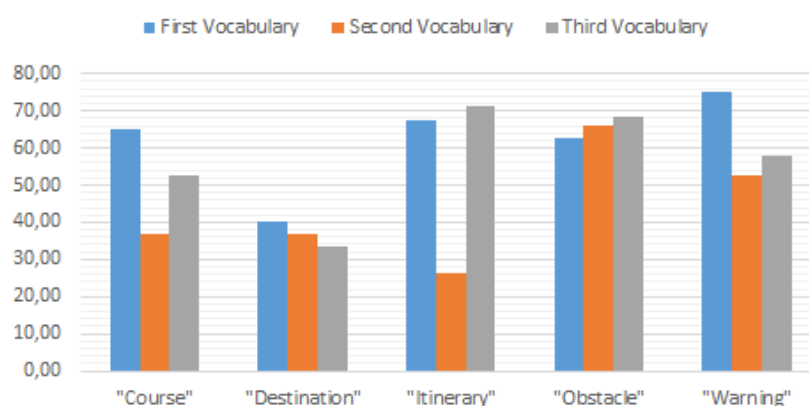


Source: Compiled by author.

With the second vocabulary, most of the users interpreted the Itinerary information as Destination. Destination and Itinerary activate the same motor to generate the modifier pattern, varying the number of successive activations. While the actuator vibrates once in the back to indicate destination and another to indicate its direction, for itinerary it vibrates twice in the back before displaying the direction of the itinerary. The third vocabulary also uses the same activation motor to generate the modifier pattern. However, as only the Itinerary is displayed using a sequence, we observed less confusion.

Confusion was also noticed in users that interpreted Warning information in the second vocabulary as Course, and vice versa. That can also be due to the similarity of the patterns. However, Course was confused less with Warning and more with Destination, which does not bring the same modifier pattern. This time the confusion is due the nomenclature used in the experiment. Many users had difficulty assimilating the differences between the terms Course, Destination and Itinerary in any of the vocabularies. Several errors also occurred in all vocabularies when the vibration was rendered at the spine to compose a Destination pattern.

We attribute most of the confusion and errors in this experiment to the total lack of training. At the same time, the task was very useful as it provided a standardized training for the navigation task that comes next.

### 5.4.3 Navigation test

Each user navigated through four distinct scenarios that worked as phases of a game. The participants took a mean of 20 minutes to complete the whole task. Eleven users have shown to be outliers and were removed for the analysis. Ten of them because they reported to have felt significant nausea and dizziness, spending more than 2 standard deviations above the average or not being able to complete the task. Actually, 8 among those 10 were not able to complete the navigation through the four scenarios. The 11th outlier is one that spent more than an hour to complete the experiment as he lost his way and wandered for a while before finding the target.

Figure 5.12 - Mean time to complete the navigation task with each vocabulary
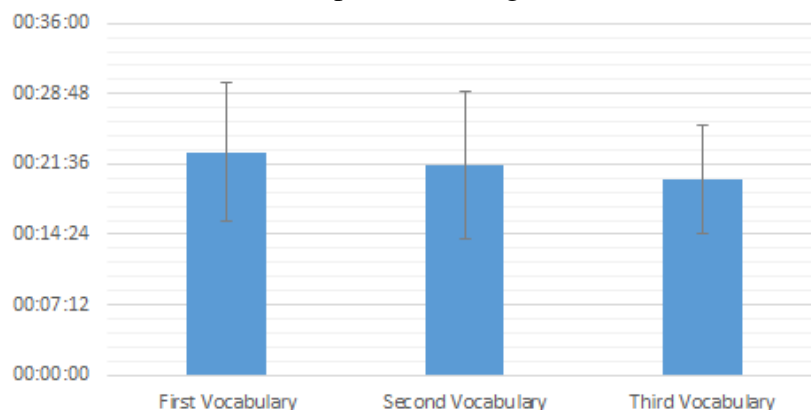


Source: Compiled by author.

Figure 5.12 shows the mean time of each group. The group of the third vocabulary was the faster, with a mean of 20min ($\sigma$ = 5:31min) to complete the whole task. The group of the second vocabulary took 21:32min ($\sigma$ = 7:35min); the third group was the slowest with 22:50min ($\sigma$ = 7:03min).

As presented in Chapter 4, during this experiment we also observed conflicts between visual and tactile feedback. Most of the collisions occurred in the darkest part of the first scenario where the users could see the target but not the obstacles; users could see the target very close ahead, which encouraged them to anxiously ignore the tactile feedback and collide. See the selected area in Figure 5.13. In this level the average collision were significantly higher than in the others (see Figure 5.14).

Figure 5.13 - Enlightened vision of the darkest part of the scene. The marked region shows the place where most of the collisions occurred



Source: Compiled by author.

Figure 5.14 - Number of collisions in each level/scenario
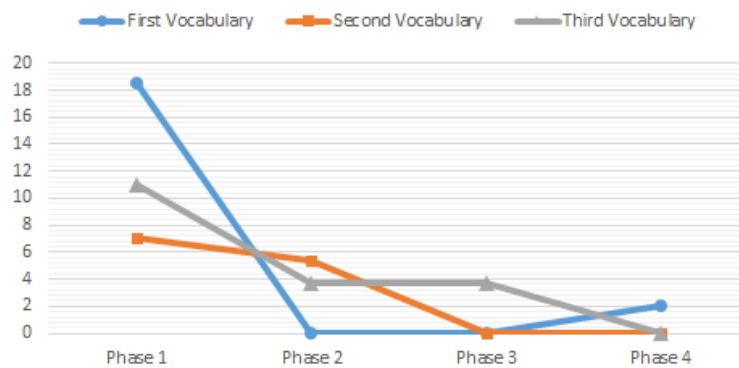


Source: Compiled by author.

The scenarios were displayed in a different order for each user, eliminating the effect of the scenario over the results. It is possible to observe the improvement of the three groups along the levels as their times and number of collisions decrease. With all vocabularies, users go faster at each subsequent level (see Figure 5.15).

In the interpretation test the second vocabulary seemed to have not been learned as fast as expected. However, considering the duration and number of collisions during navigation, it can be seen that the group of the second vocabulary obtained the best results in some levels. The group that used the third vocabulary was the slowest at the third level and also the one that collided more at the third level. However, the third vocabulary had a great improvement at the last level.

Figure 5.15 - Duration of the navigation in each level/scenario
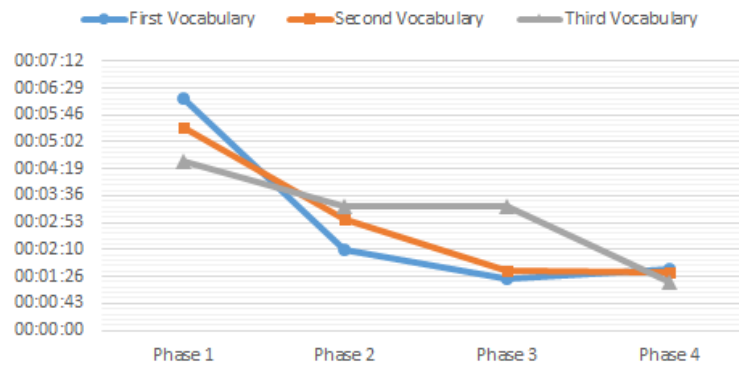


Source: Compiled by author.

## 5.5 Subjective Data Analysis

We proposed three different approaches to build a tactile vocabulary for navigation aid in VE. Our first vocabulary was made by varying hardware parameters as the metaphors to navigation. The other vocabularies were made with a prefixation approach. The prefixation was chosen to create tactons by the concatenation of a smallest set of tactons. The user should remember the three abstract patterns designed as modifiers and the pattern is completed with the vibration of one direction, as the "tap-on-shoulders" idea. The second vocabulary was made by printing one modifier pattern before the iconic representation of the information. And the third vocabulary was made by joining the sign to the prefix in order to make one single pattern (except for the itinerary, that was made as a tactile sequence).

Hirsh and Sherrick (HIRSH IRA J.; SHERRICK JR., 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 language processing: the processing of multiple stimuli at a time; and the processing of sequence of stimuli. Our first vocabulary is the one with more elements to recall. However, the first vocabulary is also the one with tactons made by composition of fewer motors at the same time. The second vocabulary was the one to address the sequence issue. The third vocabulary was the one with tactons made by the vibration of many motors at the same time.

In the second vocabulary four messages were displayed as sequences. Despite their difficulty to correctly respond the interpretation test, the users learned the vocabulary. However, they felt that the patterns in sequence were the most difficult to understand during navigation. Figure 5.16 shows the user's opinion that the messages displayed as sequences were the most difficult to process in the three vocabularies. Sometimes the users did not even perceive the tacton. The attentional blindness (HILLSTROM; SHAPIRO; SPENCE, 2002) may be the factor to explain this result. Many users understood the modifier, but could not perceive the direction. Even with the sequence issue, the performance of the group with the second vocabulary in navigation was slightly better than the first group.

The third vocabulary achieved good results in the interpretation test and in the navigation task. The group that used the third vocabulary was especially slow at the third level. This bad result seem to be more related with the number of tactors activated simul-

Figure 5.16 - Users opinion about patterns that were the most difficult to process during the navigation task
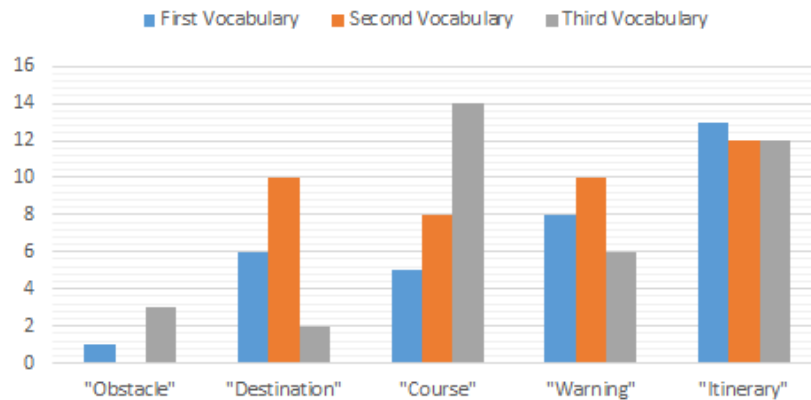


Source: Compiled by author.

taneously. In fact, the first task of the user experiment showed that the worst results were obtained from the perception of several motors at the same time. In the first task the users did not have to understand the meaning of the tacton; they had only to report the number and position of the active tactors. However, many users comprehended well the meaning of the tactons as seen in the second test. So, the processing of multiple stimuli at a time is more difficult, but the way that the information was split into prefixation elements and iconic elements seemed to help the memorization. Such result can be seen during the second task and in the navigation task.

## 5.6 Summary

We have studied three different choices in the design of a tactile language for 3D navigation. Analyzing the users performance we observed how it is influenced by tactile sequences and larger number of stimuli at same time. Even the difference between the performances of the three groups was not significant, the modifier-based vocabularies afforded the best results. The results suggest a great potential from our approach to express complex information without increasing the number of symbols to be learned and remembered. The tactile language designed for navigation in virtual environments could also be used for navigation in physical environments. Therefore, our prefixal approach can be applied to render supplemental information when sight and hearing cannot be used, e.g., for orientation support in dark environments, as mines, or for the visually impaired, first person games for the blind and many others.

# 6 REDESIGN AND APPLICATION TRIAL

As presented in Chapter 5, we tested three different vocabularies with five messages each. Such assessment allowed us to evaluate eleven different families of signals. Those signals were evaluated through an interactive questionnaire and also through a navigation task. With this results in hand, we wanted to create a last tactile vocabulary based on the user's perception and performance on navigation. This last vocabulary was intended to be more usable as its signals were chosen with focus on the user and the task. Therefore, what we called *Final Vocabulary* is a set of tactile icons composed by the best perceived and also more distinguishable patterns of our previous user study.

Along this work we have given some examples of applications that could use the tactile feedback to convey supplemental information. Most of them for sensory complementing, e.g., for orientation support in dark environments. Therefore, we chose to redesigned our tactile vocabulary for aid the navigation in an underground mine which is one of our target applications. We performed user experiments in a virtual representation of a mine and the redesigned vocabulary provided satisfactory results. The experiment was made with some previous participants as with some Mining Engineering students. Even with no previous experience, the users presented a good performance in the task.

In this chapter we present the redesign process of our tactile language and results of a new user experiment.

## 6.1 Tactile Vocabulary Redesign

We redesigned our tactile language observing the four-step method proposed by Chan (2008). As presented in Chapter 2, the Chan's methodology is user-centered and its main advantage is the progressive refining of the tactile icons and the concern about the effects of workload. The icon prototyping is the first step in the Chan's methodology and it was presented in Chapter 5. The five-step methodology of Riddle and Chapman (2012) was used to design the tactile icons. Hereinafter we present the other two steps of the Chan's methodology: the perceptual refining of our set of stimuli and the validation of our icon set based on the results from the navigation task. The last step is related to the user study that will be presented in sections 6.2 e 6.3.

### 6.1.1 Perceptual Analysis

In Chapter 5 we presented a test in which ten selected patterns were displayed through the tactile belt and the participants were asked to inform their given meaning. The same sequence of messages was displayed for all participants, but the vocabulary was different for three distinct groups of participants. From the results of this test we obtained three

confusion matrixes that were used as input for a factorial analysis (see Figure 6.1). The analysis reveals groups of correlated icons concerning its *meaning*. As highlighted in Figure 6.1, the icons used to convey information about Course, Destination and Itinerary were grouped together.

Figure 6.1 - Factorial analysis of the created vocabularies. Factors are related to the interpretation of the tactile signals. The signals used for convey information about Course, Destination and Itinerary were grouped together and are highlighted on the graph
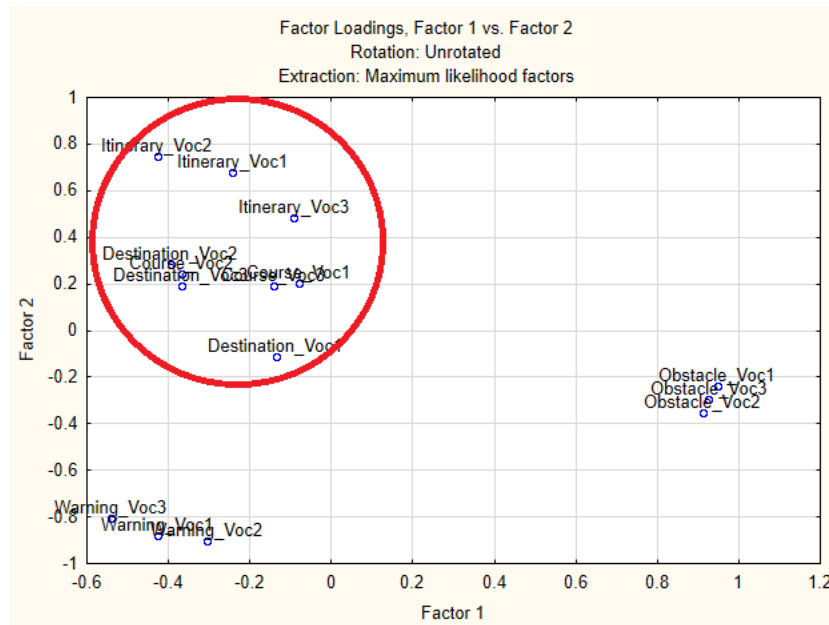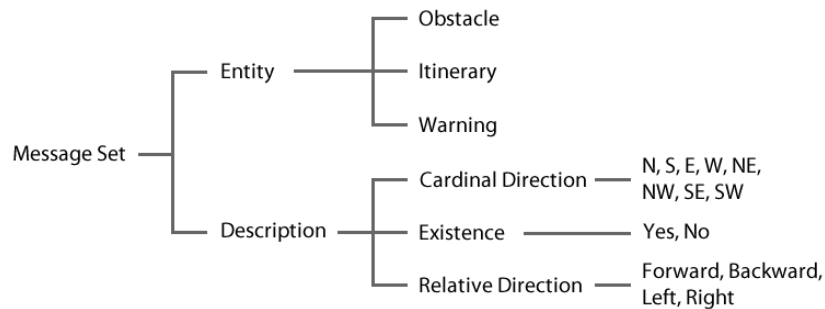


Source: Compiled by author.

We discussed in Section 5.4 that many users had difficulty assimilating the differences between the terms Course, Destination and Itinerary in any of the three vocabularies tested. Those three messages conveyed very different informations, but all of them were used to help the user to plan its route or follow a predefined route to the destination. To simplify the Final Vocabulary we chose to maintain only one of those three messages to aid the users to reach their destination. The Destination pattern allows the navigator to ascertain a position and then plan and follow any route until there. However, the itinerary guides the navigator through a specific route (e.g., the shortest or the safest one), like a GPS navigator. Instead of leaving for the user the task of planning the route, we chose to convey information about *Itinerary*. Thus, the final tactile vocabulary was designed to display only informations about Obstacles, Itinerary and Warning (see Figure 6.2).

### 6.1.2   Analysis of Performance in Navigation

For Chan (2008), when designing haptic icons, it is necessary to look at least four variables: 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. Those were our focus when we redesigned our tactile language. Initially, we have applied metaphors to the design of our patterns in order to facilitate the stimulus association with its meaning. We also removed those messages who caused more confusion due the design of its icons and the similarity of its meanings to ensure the discernibility of the messages in the set. Finally, to complete the choice of the pat-

Figure 6.2 - Message set hierarchy



Source: Compiled by author.

terns that will compose the Final Vocabulary, we considered the user's performance in the navigation task.

Users declared they had felt that the patterns in sequence were the most difficult to understand during the navigation for all three vocabularies (see Figure 5.16). Most of those patterns were well perceived in the perceptual test. However, the tactile icons designed as sequences were avoided in the final vocabulary. We removed the tactile icons that were displayed as sequences and used the remaining tactons to do a new factor analysis.

This time we wanted to guarantee the individual stimulus salience. Therefore, we performed another factorial analysis. This time the factors are related to the *construction of the patterns*. Figure 6.3 shows the result of the analysis. The icons were clustered in three groups, one of them with the icons that convey information about Obstacles. A second group were made by the icons of Course and the remaining icons were grouped in a third set; this one is composed mostly by icons that use the rear motor positioned on the spine. We chose the icons that were positioned more distant from each other on the graph.

Figure 6.3 - Factorial analysis of the remaining icons. Tactile icons displayed as sequences were excluded of the analysis due its performance on navigation task
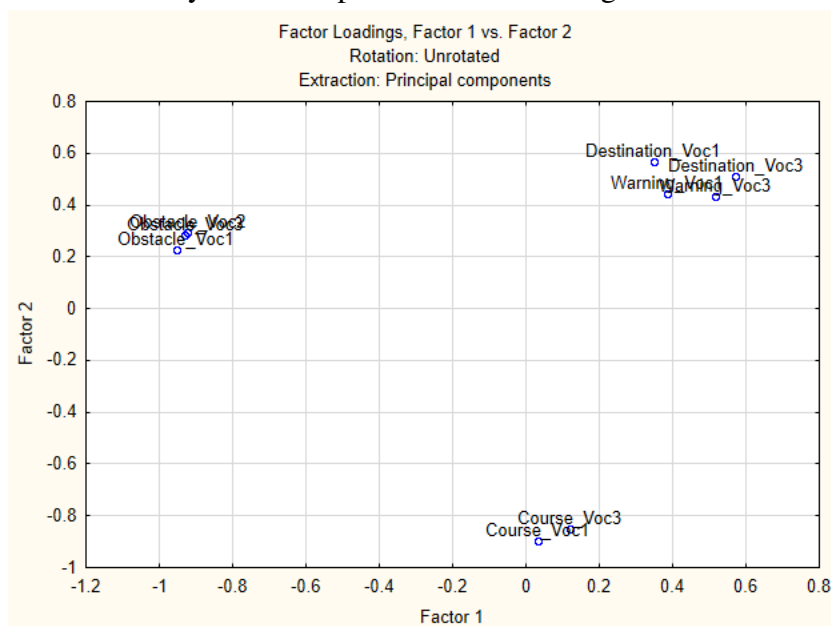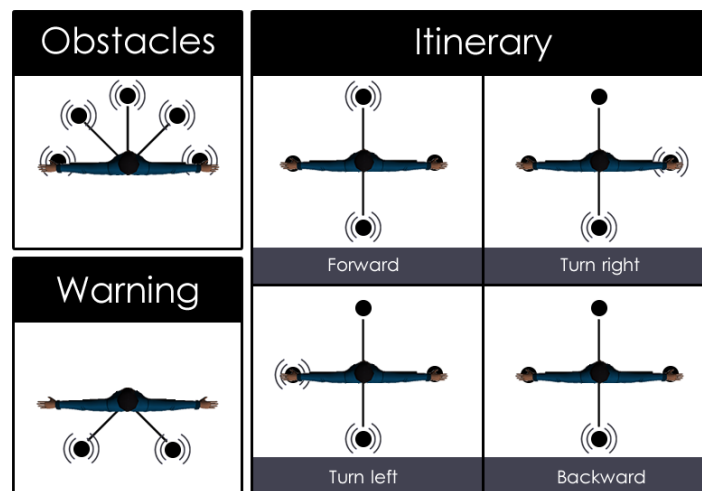


Source: Compiled by author.

### 6.1.3 Final Vocabulary

First, the patterns were chosen according to the results of the interpretation task and the difficulty to process the signal in navigation. Then, we complete the design of the vocabulary matching the icons and the message set according the meaning we wanted to convey. Figure 6.4 shows the Final Vocabulary with the selected patterns. The spine is used as a reference point which helps to correctly identify the position of a vibration around it. The rear motor was used as a prefix for Itinerary messages to guarantee a good perception of its signal. No ambiguity was found in the vocabulary.
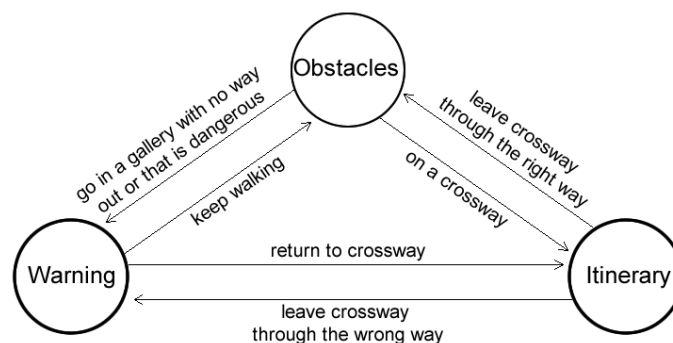
Figure 6.4 - Redesigned vocabulary



Source: Compiled by author.

We demonstrated in Chapter 4 that a person in a completely dark environment could move to an unknown position without colliding just by using the information about Destination and Obstacle. In this tactile vocabulary we kept the information about *Obstacle* but the information about Destination and Course was replaced by *Itinerary*. We display four distinct messages for itinerary indicating that the navigator must go forward, backward, to the left or to the right in order to avoid the most dangerous galleries inside the mine. We also convey information about *Warning* to alert the user that a bad route was taken and it is necessary to return to the predefined route. During the navigation in the mine, the patterns are displayed according to the state-transition diagram shown in Figure 6.5.

Figure 6.5 - The state machine shows how the stimuli are exhibited during the navigation



Source: Compiled by author.

## 6.2 Evaluation

Navigation in underground mines was the application we chose to test the redesigned vocabulary. Underground mines have large areas that are not enlightened and many times the miners count only with the light from their mining helmet. Due the use of explosives, 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.

We hypothesize that the users would get better performances as the redesigned vocabulary was made after a perceptual selection of the tactile icons. This vocabulary also has a smaller message set which can simplify its memorization. We invited some of the users that have volunteered for the previous experiments. Therefore, the evaluation could show the differences between user with previous experience with the tactile display. Some Mine Engineering undergraduate students also were invited to perform the experiment. Hereinafter we describe how the experiment was planned and executed.

### 6.2.1 Experimental Setup

First, we measured the user's torso and then we placed the motors at equidistant positions. After filling a pre-test characterization form, each participant was invited to wear the tactile belt and use the tutorial app. The belt was placed about 3cm above the navel of the participant, at the waist level. The tutorial is a GUI with a step-by-step visual description of the vibrotactile language. It also explains the experiment task and demonstrates how the belt works interactively.

Then, the participant should answer an interactive questionnaire. Eight selected patterns were displayed through the belt and the participants were asked to inform the meaning of the pattern. They should answer if the Tacton represented an obstacle, a warning or an itinerary and then mark its direction. Each tacton was printed during 11 seconds. The same sequence of messages was displayed for all participants. If the user marks the wrong answer the questionnaire shows the right answer (see Figure 6.6). Thus, the user could practice the vocabulary.

Figure 6.6 - Screen for practice the tactile vocabulary
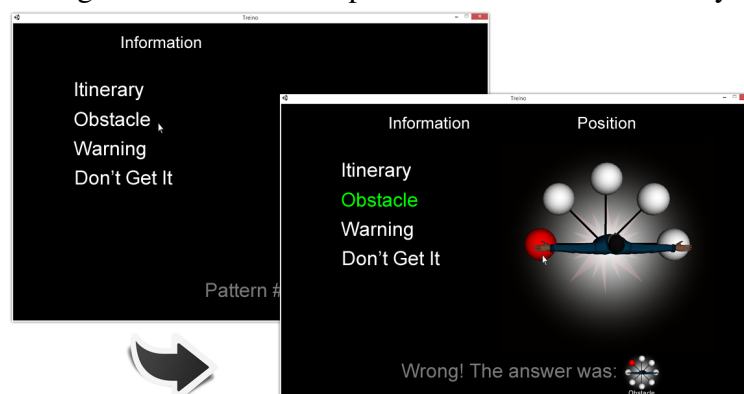


Source: Compiled by author.

Finally, each user navigated through a virtual 3D representation of an underground mine. A practice trial was available, so the user could try the task and get familiarized

with the elements of the scenario and the tactile cues. After the practice trial, the user had to perform three different routes in the mine. In Figure 6.8 we highlighted the three predefined routes in the virtual mine. There were rocks along the path and fumes that aggravated as the user was approaching the rescue chamber (see Figure 6.7). In the second trial the belt did not display the tactile cues. At the end of the navigation task they filled an evaluation form to give their opinions on the tactile vocabulary.

Figure 6.7 - Navigation task: there were rocks along the path and fumes that aggravated as the user was approaching the rescue chamber



Source: Compiled by author.

Figure 6.8 - Predefined routes in the virtual 3D representation of an underground mine. The distance between the beginning and the end of the route is the same for all scenarios
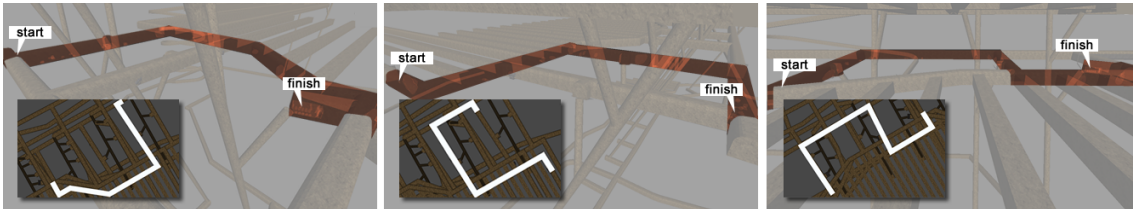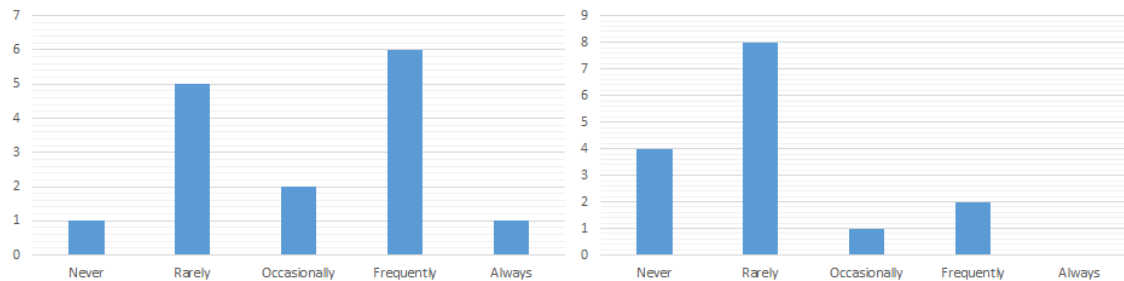


Source: Compiled by author.

## 6.3   Discussion and Results

*Fifteen* users have volunteered to participate in the tests; fourteen were male. The participants have a mean age of 25 years old, covering an age range of 23 - 37 years. Fourteen were students; four of them are Mining Engineering students and ten are Computer Science students. Two users had participated in the test of the hand-based display, seven users had participated in the previous test of the belt and the remaining users had no previous experience with tactile interfaces. Seven users have some degree of myopia or keratoconus.

The volunteers reported in the pre-test questionnaire about their experience with games and their practice with joypads in the past six months. The majority of people have some practice in games and half of the volunteers plays more than occasionally. However, they hardly ever play with joypads (see Figure 6.9). We also asked the users about their experience with 3D games and movies; fourteen users reported they had a satisfactory experience with the 3D technology. This is an important question since we performed the navigation task in a stereo large backprojection of the underground mine.

Figure 6.9 - Participants background experience. Left: Participants experience with 3D games. The responses are based on the past six months before the experiment. Right: Participants experience with joypads. Some users reported to play 3D games frequently, but use keyboard and mouse instead of a joypad



Source: Compiled by author.

### 6.3.1 Vocabulary Practice

The GUI used to practice the vocabulary had the only purpose of training. However, the performance of the users reveals an improvement in the perception and interpretation of the redesigned vocabulary. A few errors were made due a misunderstanding of the perceived position or even due the limited time reserved for this task. The results can be seen in the confusion matrix presented in Table 6.1.

Table 6.1 - 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 |

Compiled by author.

### 6.3.2 Navigation Task

Each user navigated through three predefined routes. The participants took a mean of 6 minutes and 41 seconds to complete the whole task. Three users were removed for the analysis. One of them felt dizzy and were not able to complete the task. Another one lost his way and spend fourteen minutes in the first trial.

Figure 6.10 shows the mean time of each trial. The users took a mean of 2:35min ($\sigma$ = 1:43min) to complete the first trial, 2:06min ($\sigma$ = 0:46min) to complete the second one and 1:57min ($\sigma$ = 0:41min) to complete the third trial. There was a significant reduction in time despite the paths have similar length; one-way ANOVA showed that the difference in time across the trials was significant ($F_{(3.28)}=3.65$, $p<0.036$) as well as the time between the first trial and the last one ($F_{(4.30)}=5.11$, $p<0.033$). However, the difference between the times of trials where the belt displayed the tactile stimuli and the trial where the belt were disabled has no significance ($F_{(4.13)}=0.67$, $p<0.41$); we could improve this analysis if the users had performed other trials without the belt feedback. Also the number of collisions were not so different between the trials (see Figure 6.10).

The previous experience did not seem to affect user performance. The previous knowledge of the Mining Engineering students also do not affect their performance in the task.

Figure 6.10 - User performance in underground navigation. Left: Mean time to complete the navigation task in each trial. Right: Number of collisions in each trial
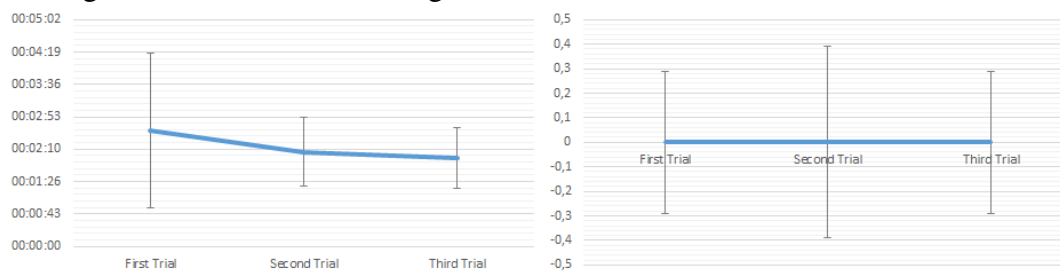


Source: Compiled by author.

Even those who spent more time in the practice trial were not so different in the navigation. Some users improved their performance along the task doing it better in each consecutive trial; other users performed a little worse the second trial were the belt was disabled (see Figure 6.11). In fact, the small population of this experiment restrain us to find significant relations between the variables. Although, the feedback of the users were very important and satisfactory. They show that the redesign improved the usability of the tactile vocabulary indeed.

Figure 6.11 - Individual time to complete the navigation task in each trial. Each line represents an user
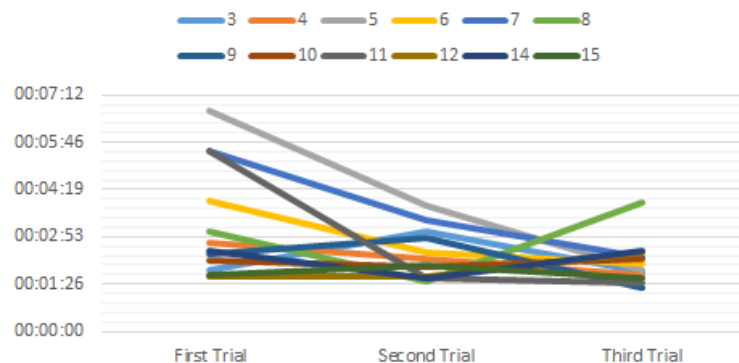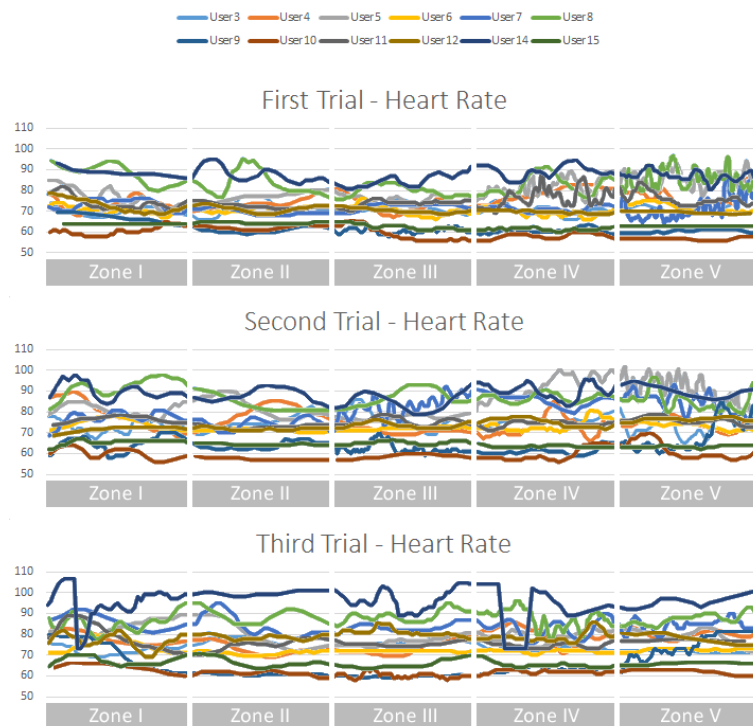


Source: Compiled by author.

During the navigation task we also collected heart rate data from the users. They used a Speedo Heart Rate Monitor and the data was collected with a Polar Heart Rate Monitor Interface ($SEN - 08661$). Figure 6.12 shows three charts with the heart rate measured from each user and for each trial. Each trial of the navigation task was also split in five zones according the intensity of the fumes along the path. Thus, the Zone I concerns a region without any fume while in the Zone V the fume is intense and obstructs the view of the obstacles.

The average HR increases between trials for all users. As the users performed the navigation in a standing position, the variation of their heart rate can be associated to fatigue or anxiety. For some users, the variation of the heart rate was greater in the beginning and for most of them the last zone was where the rhythm of their hearts became more irregular. For all users, the moments when they leave the predefined route and face an obstructed gallery were the most arrhythmic. Figure 6.13 shows an example. The fact that the user presents physical symptoms when gets lost or involved by the fumes can also

Figure 6.12 - Heart rate chart for each trial of the navigation task. Each zone corresponds to the level of fume along the path



Source: Compiled by author.

be related to the immersion in the virtual environment. All users marked high values in a scale about their sense of presence in the virtual underground mine. The hypothesis about the causes of the heart rate variation during the navigation task can be better analyzed in future works.

Figure 6.13 - Orthogonal top view of the underground mine: the white line is a route made by a user; the zones wherein the user navigated through the right path are high-lighted in green and the zones in which the user left the predefined route and faced an obstructed gallery are highlighted in red (Zones III and V). The charts in the figure shows the arrhythmia registered in the red zones. This behavior was also perceived for the other users
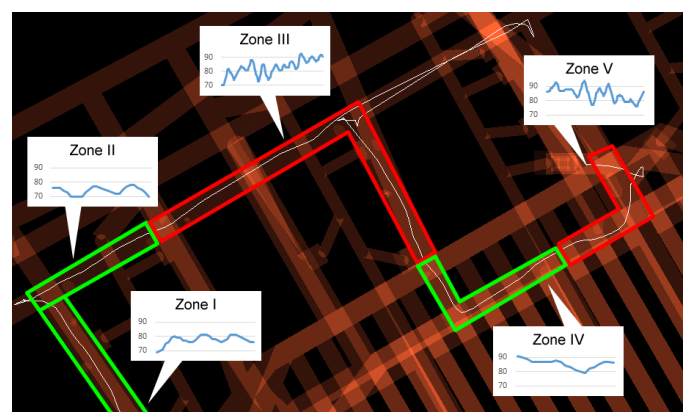


Source: Compiled by author.

In the last form, users who had performed previous experiments with the tactile belt reported they enjoyed this version more. They said that the redesigned vocabulary was easier to learn and to perceive during the navigation. Some negative points were highlighted about the prototype of the belt. Due to its materials and construction, the belt could get a little loose causing the user to miss the vibration of the rear motor sometimes. Through the observation of the experiment and the user comments in the final form, we noticed that our tactile language for navigation has improved usability. What could improve the tactile interaction now is the improvement of the tactile belt.

## 6.4   Summary

In this last iteration we performed a perceptual adjustment of our tactile language and implemented it for the navigation in a virtual underground mine. We have followed the method presented by Chan (2008), but instead of testing the perception of the tactile icons under the influence of arbitrary visual and auditory distractors as he did, we tested its perception during navigation. Its method allowed us to improve significatively the usability of our tactile vocabulary. In a real emergency situation, the life of the mine worker relies on the right perception of the tactile icons delivered by the tactile display. Therefore, the usability of the haptic interface is crucial. After performing an experiment using the redesigned vocabulary for navigation in an underground mine, we noted that the next step to improve the user experience with our tactile interface is to improve the tactile belt.

# 7 CONCLUSION

Prefixation for vibrotactile languages is not a novel approach. Even without using the term "prefix", its possible to find it in the methods for syntax development proposed by Brewster and Brown (2004). It is also used for construction of tactile messages in the Terne's (2008) research about the use and effects of rhythm. Nevertheless, we chose to study the prefixation as a way to increase the expressiveness of a tactile language and we proposed a novel approach for vibrotactile prefixation. This approach was studied in an iterative and incremental process and presented as cycles of design-analysis-redesign of tactile vocabularies for navigation in virtual environments. The result of this study is a compendium that contains a large review of the research on vibrotactile communication and the analysis of different tactile vocabularies and displays for navigation. More than eighty people have participated of the user experiments. We prototyped tactile displays for different body sites covering glabrous skin (hand) and hairy skin (waist). We also addressed the effects of multisensory stimuli and sensory substitution in our experiments through the navigation on completely dark scenarios and enlightened ones. And finally, we have formalized the concept of *Modifier Tactile Pattern* for vibrotactile displays.

The prototyping of haptic devices is the focus of many other works. However, we chose to focus on an experimental-guided study to explore the potential of vibrotactile languages. Our results can contribute to the construction of other haptic interfaces for navigation but there is a lot of work to do on the study about the effects of workload and multisensory stimulation. We expect that our vibrotactile language can be applied with few adjustments to several other applications, such as gaming, robot-teleoperation systems, pedestrian orientation and so on. We have designed and tested a dozen families of tactile icons; those results can shorten the way to the development of a common grammar for tactile navigation. With the ascension of wearable devices with small contact surfaces, such as Google Glasses, the use of prefixes and modifiers can increase the capability of Tacton construction.

As future work, the tactile belt could be improved to be more comfortable and usable. Rosenthal (2011) presents a checklist with design requirements for vibrotactile belts that comprises three dimensions: usability, functionality and performance. Following these metrics can greatly improve the user experience on navigation. Navigation in physical environments can also be tested; the physical environment has elements that cannot be simulated in virtual environments. Our vocabulary can be used for this kind of navigation, but the perception during the locomotion may have several differences from our results. Different ambient conditions and context should be assessed too. For instance, the vibration of the vehicles and tools in an underground mine can difficult the perception of the tactile cues. The application needs to be validated in the real context. Different user profiles also can be assessed; most previous studies focus on a specific profile, as

blind people. A same application can be made for both profiles and then the differences between the user's perception can be highlighted. The construction of frameworks rather than pipelines for tactile interaction design would be a great advance. The designer could be helped by heuristics and the use of tested predefined tactile vocabularies. The results presented in this thesis cooperate for the construction of those frameworks and better methodologies for design of tactile interfaces.

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# APPENDIX A   FORM USED TO TEST PERCEPTION OF THE INITIAL VOCABULARY

Figure A.1 - Form used to evaluate the tactile display and the perception of the tactile cues in the First Vocabulary

Study on Vibrotactile Communication and Its Effectiveness When Applied to Locomotion
Survey #1: Evaluation of display

User name: _____

o   *A set of vibrators will be activated on the tactile display. You should feel them with your hand and mark in this form how many and which vibrators are active.*

| Qts: | Qts: | Qts: | Qts: | Qts: |
|------|------|------|------|------|

| Qts: | Qts: | Qts: | Qts: | Qts: |
|------|------|------|------|------|

| Qts: | Qts: | Qts: | Qts: | Qts: |
|------|------|------|------|------|

Notes: _____
       _____
       _____
       _____
       _____

Source: Compiled by author.

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# APPENDIX B   FORM USED TO TEST INTERPRETATION OF THE INITIAL VOCABULARY

Figure B.1 - Form used to evaluate the interpretation of the tactile icons in the First Vocabulary



Source: Compiled by author.

# APPENDIX C   PROJETANDO VOCABULÁRIOS TÁTEIS PARA INTERAÇÃO HUMANO-COMPUTADOR

## Resumo da Dissertação em Português

O desenvolvimento de componentes de *software* e *hardware* cuja interação é fundamentada nas percepções visual e auditiva é sobremodo comum. Não obstante, outro método de interação que vem se popularizando, principalmente através do uso de aparelhos celulares, é aquele cuja comunicação com o usuário se dá por via tátil. O tato é outro meio pelo qual adquirimos diversas informações sobre o ambiente ao nosso redor e há pesquisas que o apontam como um canal de comunicação tão eficiente quanto a visão e a audição (CONWAY, 2001). O tato pode ser dividido basicamente entre dois outros subsentidos: o cinestésico e o cutâneo. Enquanto que o sentido cinestésico (ou proprioceptivo) procede de receptores musculares e articulares, o estímulo *cutâneo* por outro lado é percebido via mecanorreceptores presentes nas diferentes camadas da pele. Esses receptores permitem a percepção de diferentes tipos de estímulo, como temperatura, pressão, dor e vibração em frequências variadas (LINDEMAN et al., 2006). Nesse âmbito encontram-se as tecnologias de simulação e controle de sensações táteis e as destinadas a comunicação tátil.

No tocante à comunicação tátil, busca-se construir mecanismos que deem suporte à informação de significados complexos, imagens, informações espaciais e alertas, bem como expressões e signos arbitrários via estímulo cutâneo. O maior desafio dessa área foi bem descrito por Sherrick como a busca por um conjunto de padrões que, assim como a escrita e a fala, possam ser claramente discriminados, rapidamente processados e facilmente aprendidos (SHERRICK, 1991). A construção de interfaces que se utilizam da comunicação tátil envolve diversas variáveis como área estimulada, tipo de atuadores usados para produzir o estímulo, relação entre parâmetros de hardware e seu significado em um padrão tátil, duração do estímulo e entre estímulos, entre outras. As diferentes combinações dos fatores supracitados produzem vocabulários táteis com diferentes qualidades afetando seu aprendizado, memorização e interpretação.

Grande parte dos dispositivos que aplicam estímulo cutâneo na interação utilizam-se de padrões icásticos, seguindo uma abordagem conhecida como *"tap-on-shoulders"* (HAO; SONG, 2010). Tal abordagem pode ser exemplificada por uma sensação tátil impressa no lado do corpo do usuário que está voltado para um determinado objeto. O conjunto de padrões táteis nessa abordagem é limitado e pouco expressivo fornecendo uma quantidade pequena de informações ao usuário. Existem pesquisas empenhadas em explorar o potencial de expressividade de diferentes elementos que compõem o estímulo

tátil. Inspirado na estrutura de linguagens naturais, o uso de parâmetros de *hardware* foi explorado como *building blocks* de linguagens táteis e comparados a fonemas por Enriquez (2006). Como projeto de mestrado, nós exploramos os menores elementos dotados de significado de um padrão tátil, seguindo uma definição similar à de morfemas da língua portuguesa. Muitas outras comparações podem ser feitas explorando o efeito de diferentes elementos na percepção, interpretação e aprendizado de padrões táteis, bem como seu efeito para a usabilidade de interfaces hápticas.

Esse trabalho apresenta nosso estudo sobre comunicação tátil e sua aplicação no suporte à navegação em ambientes virtuais. Partindo da ideia de que uma linguagem tátil mais expressiva serviria melhor para dar suporte à realização de uma dada tarefa, logo começamos a esboçar o conceito de Padrão Tátil Modificador estudando a prefixação em sequências vibrotáteis. Demos início a pesquisa experimentando diferentes protótipos de displays táteis, passando por uma versão para a palma da mão até chegar a uma versão em formato de cinto. No entanto, nossa preocupação concentrou-se menos na prototipagem do display e do ambiente virtual do que nas características da linguagem tátil. Nossa linguagem tátil para navegação foi desenvolvida em um processo iterativo de design-análise-redesign. O conceito de proposto de Padrão Tátil Modificador e o desenvolvimento da linguagem tátil serão resumidos a seguir.

## C.1 Proposta de uma Abordagem de Prefixação para Linguagens Táteis

Existem diversas possibilidades de construção de padrões e sequências táteis, cada uma no entanto com suas vantagens e desvantagens em termos de percepção e interpretação. Em displays vibrotáteis, mensagens podem ser construídas por meio da modulação de parâmetros de hardware, como frequência e amplitude, e pelo ajuste do tempo e da ordem de ativação dos motores. Uma outra abordagem de construção é a utilização de métodos de prefixação, como na linguagem Braille. Braille é escrito com seis ou mais pontos em relevo dispostos em duas colunas e três linhas. A combinação desses pontos permite a construção de até 63 (sessenta e três) símbolos, o que não é suficiente para traduzir uma língua escrita. Nesse caso, a capacidade de construção gráfica é incrementada pela concatenação de símbolos. Em Braille, alguns símbolos simples são reservados para que sejam usados como prefixos.

Em Braille, um ou mais prefixos podem ser construídos pela combinação de um mesmo símbolo básico. Logo, é possível reutilizar símbolos para transmitir informações diferentes. Alguns prefixos também possuem o papel de *modificadores*. Como modificador eles afetam o significado de uma sequência inteira ou mesmo de diversas sequências de símbolos. Enquanto o prefixo é preso a uma única palavra e ganhe um significado completo apenas quando encontra-se ligado a um símbolo simples, modificadores por sua vez afetam o significado de diversos símbolos ao mesmo tempo. Nós exploramos tal abordagem na construção do vocabulário tátil para o display da mão. A abordagem de prefixação foi testada e o conceito de *Padrão Tátil Modificador* foi apresentado como um padrão tátil que modifica a interpretação dos elementos que compõem um tacton ou toda uma sequência tátil.

O Padrão Tátil Modificador atua como uma *flag*. Quando ativado o usuário estará recebendo a mensagem de que parâmetros deverão ser entendidos de modo diferente. O Modificador pode ser composto por mais de um padrão e pode ser concebido com a função de alterar o significado do próximo tacton ou de uma sequência inteira. Neste último caso,

a influência do Modificador sobre a sequência dura enquanto o Padrão Modificador estiver ativo ou até que um dado padrão apareça. Logo, como um par de parênteses, um outro padrão pode ser usado para interromper o efeito do Modificador na série. Além de conceitualizar o termo de acordo seu uso em linguagens vibrotáteis, nós também exemplificamos sua construção. Para isso, usamos como exemplo três abordagens comuns de desenvolvimento sintático de tactons apresentadas por Brewster e Brown (2004) e demonstramos como usá-las para a construção de tactons e mensagens táteis com Modificadores.

## C.2 Design e Análise de Vocabulários para Navegação Tátil

### C.2.1 Vocabulário Inicial

A palma da mão foi escolhida devido sua sensibilidade. O display para a mão foi utilizado em testes com usuários e serviu como base para o restante da pesquisa. Esse display foi criado com a finalidade de explorar formas de construção de linguagens táteis e sua expressividade. Para testes com usuários foi escolhida a tarefa de locomoção em ambiente virtual. Produzimos então uma linguagem tátil para comunicar a existência de obstáculos no meio do percurso e a direção do destino.

Usando a Rosa dos ventos como metáfora para orientação, oito motores foram posicionados de acordo os pontos cardeais e colaterais. A vibração desses motores caracteriza a existência e direção de uma dada entidade. Para diferenciar as entidades poderiam ser adotadas abordagens comuns na literatura, como o uso de diferentes frequências ou mesmo de diferentes padrões para cada entidade. No entanto, escolhemos diferenciar as entidades pela utilização de um sinal modificador.

Como nosso conjunto de mensagens continha duas entidades distintas, escolhemos ativar então um sinal modificador para marcar a impressão de uma dessas entidades. Nossa hipótese foi a de que esta abordagem facilitaria a compreensão da linguagem. Um motor central foi utilizado para imprimir o padrão modificador e o display passou a ser constituído por nove motores dispostos em uma matriz 3X3 (ver Figura C.1 (a)). O vocabulário resultante pode ser visto na Figura C.1 (b).

Figure C.1 - (a) Display tátil para palma da mão. Ao lado, (b) exemplos de padrões exibidos pelo display
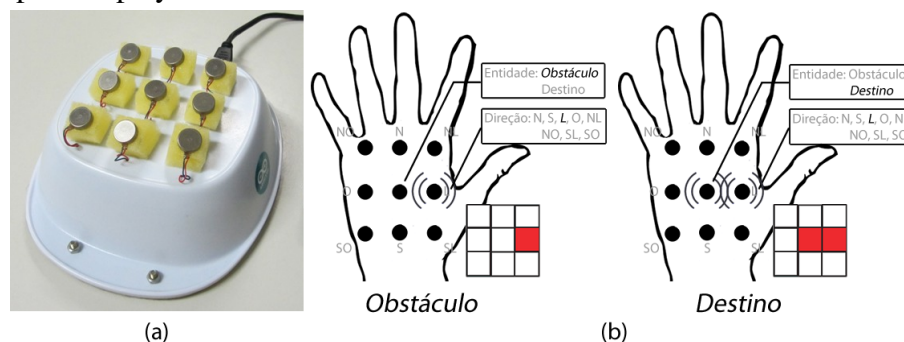


Fonte: Próprio autor.

Os testes realizados com usuários nos forneceram subsídios para esboçar o conceito de Padrão Tátil Modificador. Tal conceito foi aplicado na concepção de novos vocabulários e testado em experimentos com usuários. Sua conceitualização formal tem sido uma importante contribuição da nossa pesquisa.

### C.2.2 Aperfeiçoamento da Linguagem Tátil

Numa segunda etapa, construímos um display em formato de cinto (ver Figura C.2). Assim como o display para a mão, o cinto foi construído dispondo oito motores de acordo os pontos cardeais e colaterais da Rosa dos ventos. A mesma metáfora foi aplicada a sua construção pois o cinto também foi criado para navegação. A escolha do formato como um cinto se deve à referência do tronco na locomoção (ego localização), sendo o torso o local mais apropriado para receber o estímulo tátil dada a tarefa. A quantidade de motores foi escolhida com base na literatura que compara a utilização de displays táteis construídos com diferentes quantidades de atuadores dispostos ao redor do torso.

Figure C.2 - (a) Display tátil em formato de cinto. À direita, (b) indivíduo realizando tarefa de navegação usando o cinto



(a)                                                                    (b)
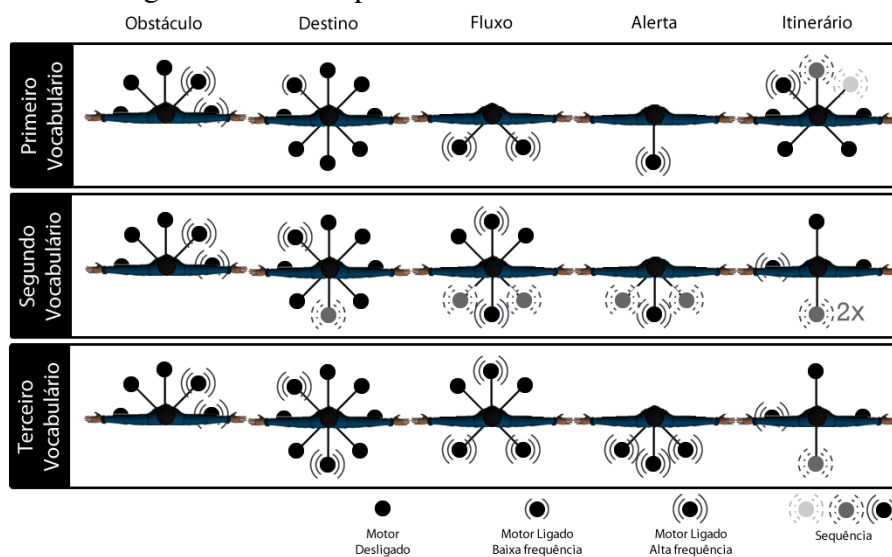
Fonte: Próprio autor.

O cinto também permite que os membros fiquem livres para a realização de outras tarefas, manipulação de objetos e mesmo locomoção. Logo, o cinto pode ser utilizado tanto em ambiente virtual como em ambiente físico. Para teste com usuários em ambiente virtual, foram construídos três vocabulários táteis (ver Figura C.3). Um vocabulário foi concebido a partir de uma abordagem convencional, enquanto que o segundo foi construído seguindo uma estratégia prefixação adotando o uso de padrões modificadores. Um último vocabulário foi construído a fim de identificar questões relacionadas ao uso de Modificadores em sequências táteis e em padrões únicos. Tal comparação nos permitiu identificar questões relacionadas a ambas estratégias e à utilização de ambos os vocabulários na execução da tarefa de navegação.

Desta vez o conjunto de mensagens foi ampliado transmitindo informações sobre *Itinerário*, *Fluxo* e *Alerta*, além de *Obstáculo* e *Destino* como no teste da mão. A construção de ambos os vocabulários seguiram uma mesma metodologia, aplicando metáforas e as características dos parâmetros de construção dos padrões de acordo o conjunto de mensagens definido. Enquanto que na linguagem convencional as entidades foram diferenciadas por posição relativa dos atuadores, frequência de ativação e sequência (forma de onda), nas linguagens baseadas em Modificadores as entidades foram diferenciadas por padrões de prefixação. Ao realizar testes com usuários foram obtidos resultados próximos entre os três grupos de usuários que utilizaram cada um dos vocabulários, mas com os grupos que utilizaram vocabulários prefixados apresentaram um desempenho melhor.

A Figura C.3 mostra como os vocabulários foram construídos. Os sinais para obstáculos foram os mesmos nos três vocabulários e o mesmo padrão para destino no Segundo Vocabulário foi usado como itinerário no Terceiro Vocabulário. Desse modo, onze con-

juntos de estímulo foram testados.

Figure C.3 - Exemplo de tactons em cada vocabulário



Fonte: Próprio autor.

### C.2.3  Redesign do Vocabulário

Na última iteração o vocabulário foi melhorado considerando os resultados dos testes anteriores. Foram feitos ajustes perceptuais considerando tarefas de interpretação dos padrões táteis e do desempenho dos usuários durante a navegação. Este último vocabulário foi testado em uma tarefa de navegação em mina subterrânea, pois esta é uma das aplicações alvo de nossa interface tátil. Novos experimentos com usuários envolveram a participação de pessoas que se voluntariaram anteriormente para o teste do display para mãos e outros que participaram do teste do cinto. Também participaram deste experimento alunos do curso de Engenharia de Minas. A tarefa de navegação foi feita utilizando o cinto tátil e o ambiente virtual foi projetado em um grande monitor 3D (ver Figura C.4(a)).

Figure C.4 - Navegação em mina subterrânea. A Figura (a) mostra um voluntário realizando a tarefa de navegação. (b) mostra a representação da mina virtual
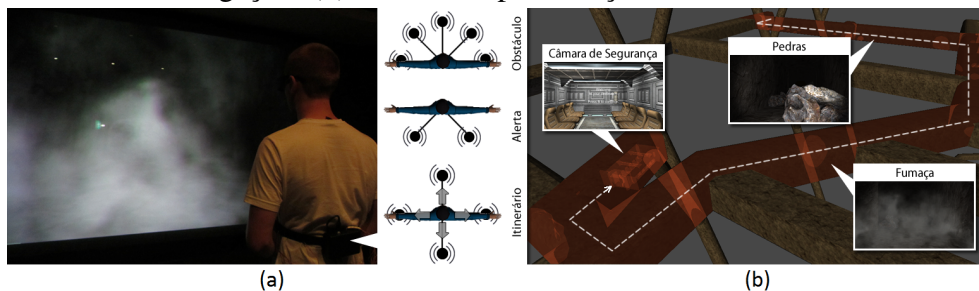


Fonte: Próprio autor.

A tarefa de navegação envolveu uma situação de emergência em que o usuário precisaria trilhar uma trajetória predefinida até uma câmara de segurança dentro da mina. Ao longo do caminho o usuário precisaria evitar colisões com entulhos e caminhos perigosos

(ver Figura C.4(b)); essas informações eram passadas para ele através do cinto. A medida que o usuário avançava em direção à câmara de segurança uma fumaça crescia atrapalhando sua visão do caminho. Os usuários tiveram um desempenho muito melhor neste último experimento. Os resultados mostraram que a percepção dos padrões melhorou. Novas melhorias agora estariam relacionadas ao cinto e não mais ao vocabulário tátil.

## C.3 Conclusão

A abordagem de prefixação foi escolhida como estratégia para melhorar a expressividade de nossos vocabulários táteis. Nós estudamos o uso de prefixos em comunicação tátil e propomos o conceito de Padrão Tátil Modificador para linguagens vibrotáteis. Essa abordagem foi explorada em diversos testes com usuários. O resultado de nossa pesquisa é um compêndio contendo uma larga revisão sobre a área de comunicação vibrotátil e a análise de diferentes vocabulários e displays táteis para navegação. Mais de oitenta pessoas participaram de nossos experimentos. Diferentes protótipos foram criados para renderizar o estímulo tátil em diferentes partes do corpo. Nossos experimentos cobriram fatores relacionados à substituição sensorial e à estimulação multisensorial; voluntários realizaram a tarefa de navegação em ambientes completamente escuros e também em cenários iluminados onde deveriam utilizar visão e tato. E finalmente, formalizamos o conceito de Padrão Tátil Modificador para displays vibrotáteis. Essa conceitualização é uma das principais contribuições deste trabalho.