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EXPLOITATION OF HAPTIC RENDERINGS TO COMMUNICATE RISK LEVELS OF FALLING.

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Abstract

Falls represent a major cause of injury that could lead to death. This observation is even more accentuated in the elderly. Indeed, with aging comes some deterioration (gait disturbances, balance disorders, and sensory motor impairments) that may lead to falls. The research project presented in this thesis is focused on the problem of reducing the risk level of falling. This study proposes a solution for the communication of haptic information to reduce the risk of falling. This solution is part of the design of a haptic communication system in a controlled environment. This new system introduces the notion of haptic perception through the communication of information by touch using the foot, which the literature does not generally mention. For the design of this system, we first studied the use of tactile stimuli to evaluate the possibility of communicating a risk level through a haptic modality. Then, having hypothesized that some factors could influence the communication of stimuli representing the risk levels of falling, we conducted a second study to evaluate the effect of auditory disturbances during the communication of these stimuli. Third, to determine whether the user had the necessary time to act after the perception of the risk level, we analyzed a variation of the simple reaction time when walking on different types of soil. These results encouraged us to do a fourth assessment of reaction time using a new device coupled with a smartphone that can be positioned at different locations on the body. Several experiments have been done to validate each of the steps. With this, we can now communicate a risk level of falling to users through the haptic channel using an active device and easily differentiable stimuli. In addition, we can evaluate auditory factors during such a haptic perception. Finally, we can evaluate the physiological characteristics of the users (response time) while seated and while walking on different types of soil.

Résumé

Les chutes représentent une cause majeure de blessures pouvant entraîner la mort. Cette observation est encore plus accentuée chez les personnes âgées. En effet, avec le vieillissement, certaines détériorations (troubles de la démarche, troubles de l'équilibre, troubles sensorimoteurs) peuvent entraîner des chutes. Le projet de recherche présenté dans cette thèse fait partie du problème de la réduction du risque de chute. En particulier, cette étude propose une solution au problème de la réduction du risque de chute par la perception haptiques. Cette solution intègre la conception d'un système de communication haptique dans un environnement contrôlé. Ce nouveau système introduit la notion de perception haptique à travers la communication de l'information par le toucher avec le pied, que la littérature ne mentionne généralement pas. Pour cela nous avons d'abord étudié l'utilisation de stimuli tactiles pour évaluer la possibilité de communiquer un niveau de risque par la modalité haptique. Puis, ayant émis l'hypothèse que certains facteurs pourraient influencer la communication de ces stimuli, nous avons mené une deuxième étude pour évaluer l'impact des perturbations auditives lors de la perception haptique du niveau de risque. Troisièmement, afin de savoir si l'utilisateur avait le temps nécessaire pour agir après la perception du niveau de risque, nous avons analysé la variation du temps de réaction simple en marchant sur différents types de sols. Les résultats obtenus dans cette dernière étude nous ont motivé à faire une quatrième évaluation du temps de réaction mais en utilisant un nouveau dispositif couplé à un smartphone qui peut être positionné à différents endroits du corps. Plusieurs expériences ont été réalisées pour valider chacune des étapes. Avec toutes ces études, nous pouvons maintenant communiquer aux utilisateurs un niveau de risque à travers le canal haptique en utilisant un dispositif actif et des stimuli facilement différentiables. En outre, nous pouvons évaluer les facteurs externes (auditifs) au cours d'une telle perception haptique. Enfin, nous pouvons évaluer les caractéristiques physiologiques des utilisateurs (temps de réponse) en position assise et en marchant sur différents types de sols.

Dedication

To my children Leslie and Christ-Elvir

To my late father David Tchakouté.

Aknowledgment

This thesis is the culmination of four-and-a-half years of research.

I thank especially Professor Bob-Antoine Ménélas for leading this thesis with accuracy and determination. I also thank him for his patient listening, his kindness, his availability, and his precious advice. So, through this document, I show him my sincere gratitude.

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Chapter 1

Introduction

Walking is one of the principal means of locomotion in human beings. According to the World Health Organization (WHO), an average of about 7,500 steps (each 80 cm in length) are carried out per day for a total of about 2,190 km per year. During the walking process, the human perceptual system is in constant communication with its environment through the sensory motor channels. For the elderly, the walking process can be complex and difficult, as loss of balance can occur.

According to statistics, more than a third of people over 65 fall at least once a year. In this age group, 65% of injuries are due to falls (Stinchcombe et al., 2014). Stinchcombe et al. (2014) reported that the number of self-reported injuries from falls increased by 43% between 2003 and 2009–2010 (Figure 1.1). Canadian data indicate that the number of fall-related deaths among seniors increased by 65% between 2003 and 2008 (Figure 1.2), and the frequency of deaths and death rates associated with age-standardized falls were higher among older seniors.

[1] Source: Enquête sur la santé dans les collectivités canadiennes, fichiers de partage, cycle 2.1 (2003), cycle 3.1 (2005) et 2009–2010 (Stinchcombe et al., 2014).

[2] Source: Statistique Canada, Statistiques de l'état civil, 2003 à 2008 (Stinchcombe et al., 2014).

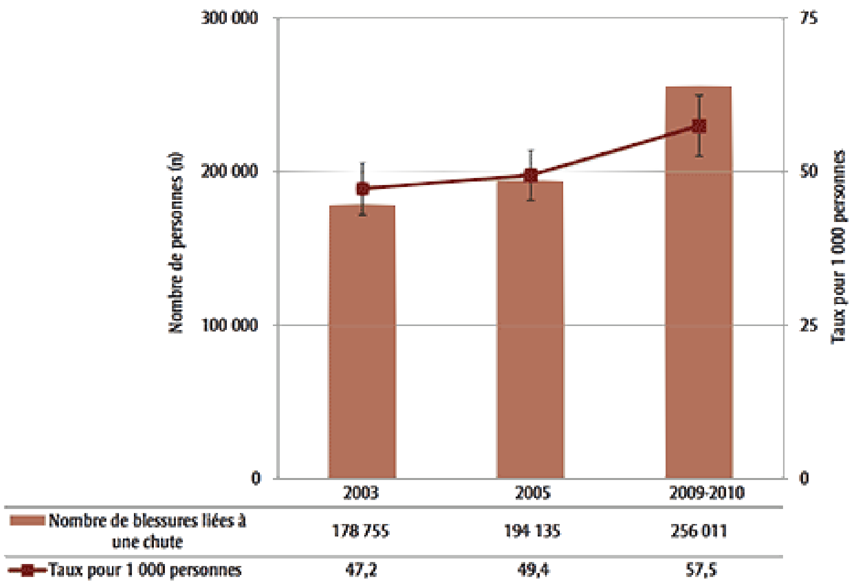


Figure 1.1: Estimated rate and number (per 1,000 population with a 95% confidence interval) of fall-related injuries, adults of more than 65 years, Canada, 2003, 2005, 2009–2010[1]

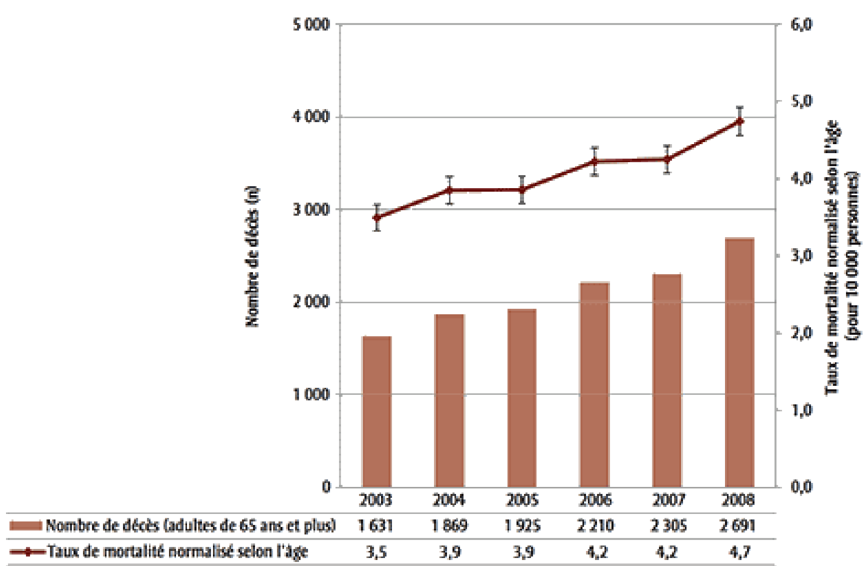


Figure 1.2: Number of deaths due to falls and age-standardized mortality rates (95% confidence interval), adults 65 years and older, Canada, 2003–2008[2]

Falls are an important factor in seniors' loss of independence. Beyond the physical injuries they can cause (fracture of the upper end of the femur), in many cases, the falls leave behind a psychological effect due to the fear of falling again. In some cases, there may be a significant decrease in mobility, which can be caused in general by the flooring surface (paving) and especially by seasonal factors (ice and snow) (Wennberg et al., 2009).

Such findings have contributed to the design and implementation of multiple programs dedicated to the assistance and prevention of so-called accidental falls (Santé, 2005; Filiatrault et al., 2007; Ganz et al., 2007). As pointed out by Filiatrault et al. (2007), to be effective, these programs must target several factors that can lead to falls. Along these lines, many programs have combined the practice of physical exercises with the analysis of balance and of the motor pattern of walking. Others have focused on the control of vision, hearing, and blood pressure. Despite the remarkable results achieved in this field, to the best of our knowledge, no program has yet offered personalized assistance in real time to the user through haptic modality via the foot. However, we believe that recent technological achievements can be exploited to provide personalized assistance to users considered vulnerable in the context of the risk of falling.

Because of such observations, we recently designed an intelligent system to provide ongoing assistance to vulnerable users (older people or those with balance disorders) (Otis and Menelas, 2012). More specifically, we have proposed a device that can prevent falls related to a person's immediate environment, such as slippery ground (sand, snow, ice, and mud), a steep slope, or uneven ground. Controlled by a smartphone, this device consists of a set of sensors and actuators distributed in strategic positions in a shoe. Some sensors are used to characterize the dynamics of walking by measuring the speed and acceleration of the foot or the flexion of the shoe. Many of these sensors focus on measuring lateral and anteroposterior oscillations as well as the distance between two strides, while other sensors provide information about the properties of the environment (humidity, temperature, inclination of the soil, dampness, and rigidity). This device is available, completely transparent to the user, inexpensive, and non-invasive.

Overall, the first component of this project made it possible to use the device to calculate the risk of falls by characterizing gait dynamics, balance, and environmental analysis. After computing the risk level, the second component of this project will evaluate the paradigms of the communication of the risk level computed via the haptic channel when the user is moving or at rest. This second component, which has not been evaluated, will therefore constitute the major objective of this thesis. Our main objective is to carry out this study by proposing the evaluation of the exploitation of haptic renderings to communicate the risk level of falling.

1.1 Context and Problem

With the recent technological developments, we now have a set of tools allowing us to exploit the main human sensorimotor channels (vision, audio, and haptics) in the interaction between humans and machines. Nevertheless, it should be emphasized that the use of visual feedback is largely predominant compared to that of other channels. However, different studies have shown that vision is not always the predominant sense in humans. In fact, in everyday life, the main sensory modalities (vision, haptics, and audio) generally collaborate. This is known as multimodal interaction because humans are rather multimodal. At any given moment, information coming from the different sensory channels are associated to provide a coherent perception of our environment. Studies show that the different sensory channels are particularly effective for specific tasks. Indeed, if it is true that vision is perfectly suited to the comparison of the spatial dispositions of objects, touch is at least as powerful as vision for the discrimination of textures. Moreover, in human-machine interaction, it has been shown that, for various situations, the use of other modalities would be suitable to improve the sensory richness of the interaction.

We think that a modality is directly related to human perception (Menelas, 2014). It has been shown that vibratory messages may, in some cases, be more appropriate than auditory or visual feedback (Marquardt et al., 2009). While walking, a very limited set of haptic messages are exploited. We are now observing an increasing need for haptic interactions in everyday products to improve the user experience. For instance, in the design, the constraints of miniaturization and portability considerably limit computing power and performance. This has an effect on the quality and perception of the transmitted signal, especially in situations where the environment is noisy, as when travelling in an underground train. In this context, the information transmitted is sometimes poorly perceived or almost ignored. With smartphones, for instance, it has been found that the use of vibrotactile feedback (notification and alerts) in consumer products remains limited or binary (yes/no, vibration/no vibration) (Enriquez and MacLean, 2004). There is therefore a problem in human-computer interaction (HCI), namely, the communication of information with daily assistance tools.

The word "haptic," from the Greek (*haptikos*), means "referring to the sense of touch" and comes from the Greek verb *haptesthai*, meaning "to touch" (Frauenfelder, 2015). It is the only bidirectional sensory channel (simultaneous input and output interaction). In addition, one of the most significant aspects of touch is the ability to transmit and improve physical intimacy (a handshake, a hug, etc.). The sense of touch is the fundamental component of haptic communication for interpersonal relationships (Rovers and Van Essen, 2006). The communication of information through this sensory channel is a new science in constant evolution that draws its foundation from robotics and teleoperation. However, this channel offers two main types of feedback: tactile feedback and kinesthetic feedback. With the vibrotactile modality, one can offer a much richer interaction than in the case of a visual interaction. Kangas et al. (2014) combined the gesture of the gaze with the vibrotactile stimulus for the confirmation of interactions. The results showed that vibrotactile feedback may be beneficial in approaches to eye gestures in contrast to visual feedback during eye movement interactions. In our research project, the haptic feedback mentioned will be mainly vibrotactile stimuli unless otherwise noted.

Preliminary work related to this research has investigated the reduction of the risk of falls in the elderly using assistive devices. This is the case with Menelas and Otis (2012), who designed an enhanced shoe to reduce the risk of falls by calculating gait parameters in young and old subjects. The first part of this study consists of identifying different types of soil. In the second part, using an improved second prototype (an enactive sole), 12 participants with Parkinson's disease and nine age-matched controls completed the timed up and go (TUG) test on six types of soil. Overall, the results showed that a vibrotactile stimulus could help reduce the risk of falling. Second, the analysis of the frequency of the vibration made it possible to differentiate the types of soil. Finally, the computed risk of falling made it possible to improve balance. However, some participants did not perceive the vibration that had been communicated. The causes of this limitation included the aging of the subcutaneous sensors responsible for perceptive vibration perception, the advanced stage of the patient's disease, and the quality of the vibrotactile stimulus. Therefore, this limitation leads us to assume that the communication system of vibrotactile stimuli in this study should be improved to ensure reliable communication of the risk of falling. Recently, to reduce the risk of falling on different soil types, Ayena et al. (2017) compared auditory, visual, and vibrotactile signals in people with Parkinson's disease. An instrumented test on TUG evaluated how auditory, visual, and vibrotactile stimuli could affect the risk of falling in old age. A computed risk of falls index was compared to the total duration of the TUG. However, the limitation of this study was not only the reduced number of participants but also the low level of perception of the vibrotactile stimuli sent to the heel.

An analysis of these previous works makes it possible to understand the need for evaluating a haptic communication system to transmit vibrotactile stimuli to the user. To the best of our knowledge, the literature has not reported work on the evaluation of haptic rendering via the foot to communicate a risk level while walking or at rest. The study presented here (this thesis) intends to fill this void.

1.2 Research Questions

Knowing that our problem is articulated around the communication of non-verbal information via the haptic channel using interaction techniques with the foot, the research questions to develop this study are as follows:

- *What might affect haptic communication?*
- *Is it possible to communicate the risk of falling through a haptic modality? If so, how can it be done?*
- *What factors can disrupt the communication of the risk level in moving?*
- *What is the effect of the physiological characteristics of humans in haptic perception?*

These questions are taken up in the conclusion (Chapter 7), which summarizes the results of this research.

1.3 Approaches and Overview

Our study is part of the presentation of a thesis for a PhD in information science and technology at the Department of Computer Science and Mathematics (DIM) at the University of Quebec at Chicoutimi (UQAC). The main objective of this thesis is the evaluation of a system for communicating the risk of falling via the haptic channel while walking. To achieve this goal and answer the research questions identified in Section 1.2, the approach used is to evaluate haptic communication models as well as the perceptual system in humans to analyse the constraints of haptic communication. In addition, we will evaluate the constraints of the system, considering aspects such as the movement and environment of the user.

To achieve these goals, we first focused on a general audience (i.e., young people) to define an adequate model of the haptic communication system. We thus limited the variables to focus on the system itself with healthy people. For this purpose, this thesis is organized according to the following chapters:

Chapter 1–Introduction describes the problem addressed in this thesis and the motivation of the research.

Chapter 2– Related Work discusses existing research in the communication of haptic information while walking.

Chapter 3–Potential of Haptics for Communication assesses the potential of using tactons to communicate a risk level.

Chapter 4–Effects of Auditory Disturbances analyses the effects of auditory disturbances when communicating vibrotactile messages with the foot.

Chapter 5–Reaction Time to Haptic Rendering investigates the variability of response time to four vibrotactile messages while walking on five types of soil.

Chapter 6–Response Time and Reaction Time to Haptic Stimuli analyses the response time and reaction time to a vibrotactile stimuli at rest and while walking on different types of soil.

Chapter 7–Conclusion refers to the research questions identified in the previous section and discusses how they were addressed through the activities conducted for this thesis research.

Chapter 2

Related work

2.1 Introduction

This chapter aims to present the context of the work relating to the communication of the risk of falling by haptic modality. It comprises three parts. The first concerns the perception of tactile information to transmit a level of risk. First, we will present the definitions and methods of tactile communication between individuals. Then, we will be interested in different systems for communicating sensory information as well as in the different ways of conceiving and perceiving them. The second part of this chapter deals with the disturbances that can hinder the perception of tactile information. We will evaluate the constraints related to the effects of our environment during a such communication. The third deals with the evaluation of the physiological characteristics of humans. It aims to explain what limitations are imposed by the human physiology during haptic communication. Finally, we will present the state of play on human reaction times after the perception of haptic stimuli.

2.2 Using Haptics to Communicate

Touch is often considered the first sensory channel in humans. For example, touch gives the fetus its first sensations in contact with its own body and the intrauterine environment (Segond, 2008). The first tactile experiences of a fetus, released from the constraints of gravity, are associated with the somaesthetic (of the whole surface of the body), kinaesthetic (for movements), and vestibular (for orientation) senses with respect to the uterine environment. Before speech, humans already have this primary faculty developed through the tactile channel. Touch is also the last sense in humans because, when humans age, touch is usually the least affected channel.

2.2.1 Importance of touch in the human life

One of the first items of importance concerning touch is social interactions. Crusco and Wetzel (1984); Lynn et al. (1998) conducted a study on the influence of the physical contact of a restaurant waiter with the customers. They pointed out that, when the waiter touched a client on the shoulder or elbow while giving change, this waiter received a larger tip. This result is not specific to culture. Guéguen and Jacob (2005) also observed this influence of physical contact between a server and customers on the tips left in a French bar. Hornik (1992) observed that shoppers were also more conciliatory with a salesperson if they touched the salesperson before submitting a request. Conversely, the lack of human contact can have negative consequences in everyday life. For example, the absence of prolonged touch seems to contribute to the increase of negative states like stress (Field, 2014). Bargh and Shalev (2012) stated, for example, that people who receive less physical contact than others have a tendency in their daily lives to take warmer baths to compensate for the lack of human warmth. On the other hand, people in contact with a cold object report feeling more alone than other people.

The touch in HCI allows more presence to be felt during the interaction. Bailenson and Yee (2007) conducted a study where subjects had to clean the face of a virtual avatar using a haptic device. They observed that these subjects exerted less pressure on the face of the avatar when the latter was female. Chen et al. (2009) studied the feeling of social presence during a textual communication with Skype software. In some cases, this communication was done with haptic feedback via a Geomagic Touch device. In this case, subjects reported an increased sense of presence. Similarly, Sallnäs (2010) demonstrated that the perceived presence is of social origin. The subjects have the impression that the person with whom they communicate is physically close to them.

The haptic modality is therefore of paramount importance in our daily lives and in our social lives. Not only does it allow us to communicate emotions but it also allows us to be more present in HCI. In Chapter 3, we will deal in depth with the communication of another type of information by touch: the risk of falling.

2.2.2 Definitions and concepts

The definitions referenced in this section are from Coutaz and Caelen (1991).

Communication: According to the Larousse dictionary,[1] communication is the act of communicating with someone, of being in touch with others generally by language, or the verbal exchange between a speaker and an interlocutor who is asked for an answer. According to the *Le Petit Robert* dictionary, communication is the passage of messages between a transmitting subject and a receiving subject by means of signs and signals. In general, communication is done through verbal language.

Language: Language is the method of human communication, either spoken or written,

[1] http://www.larousse.fr/dictionnaires/francais/communication/17561

consisting of the use of words in a structured and conventional way.[2]. A language consists of signals corresponding to the physical medium through which the information passes. In the context of this thesis, we will limit ourselves to the non-verbal communication language, for instance, via the tactile modality that relies on learning through touch interaction techniques.

Communication mode: According to *Le Petit Robert* dictionary, a mode is a particular norm under which a fact presents itself or an action is accomplished. In grammar, the mode is a feature denoting the way the speaker presents the process (more commonly known as "action"). From the system viewpoint, a mode represents the system state at a given time. One mode refers to the five sensory channels of the human being–touch, hearing, sight, smell, and taste (reception of information)–and the different means of human expression: gesture and speech (information broadcast). It defines the nature of the information used for communication (visual mode, sound mode, gesture mode, etc.).

Modality: Modality is directly related to the senses. The modality can be defined as a form of exchange that can take place between a user and a digital system (Menelas, 2014).

Multimodality: The term "multimodality" refers to the use of several modalities for carrying out the same task.

Multimodal communication: Communication is said to be "multimodal" if it involves several modes of communication in the exchange of information.

Stimulus: According to the Larousse dictionary, a stimulus is any physical, chemical, or biological element capable of triggering phenomena in the body, in particular, a nervous, muscular, or endocrine phenomena. In the field of experimental psychology, a stimulus is an event likely to determine a detectable excitation as a reaction in humans.

Haptic perception: In the field of cognitive psychology, there are two forms of haptic perception:

[2]Source: `https://en.oxforddictionaries.com/definition/language`

- Cutaneous or passive perception is obtained by stimulation of the skin without movement of the person (Gentaz, 2009). It is obtained by an external stimulation of the skin (e.g., wind blowing on the skin) or by contact (e.g., a hand placed on a piece of cold metal).

- The tactile-kinaesthetic perception, haptic perception (Révész, 1934, 1950), or active perception results from the stimulation of the skin resulting from a person's active movements. In this case, the mechanical deformation of the skin must necessarily add that of the muscles, joints, and tendons resulting from the exploratory movements. This definition was taken up and reintroduced by the psychologist Gibson (1966).

The haptic system: Loomis and Lederman (1986) and Lederman et al. (1987) proposed that the haptic system could be composed of two subsystems: the sensory system and the motor system. According to their interpretation, the motor system serves to increase the performance of the sensory system, optimizing the efficiency of the haptic exploration of objects. In this context, it is possible to conceive of the haptic process as the implementation of high-level haptic functions (cognitive functions) and low-level haptic functions (psychophysical functions) (Tornil, 2006). High-level haptic functions would be used to direct low-level haptic functions.

2.2.3 Methods of communication through the haptic channel

There have been multiple studies regarding the use of haptics for blind or visually impaired people Lévesque (2005). In what follows, we briefly list some of them.

- **The Lorm method**: This is an alphabetic type of communication method invented by Heinrich Landersmann in the nineteenth century (Ellis and Kent, 2016). It is a "coding" of the letters on the palm of the hand: dots or lines are drawn on the fingers and the

[3] fr.wikipedia.org/wiki/Alphabet_de_Lorm

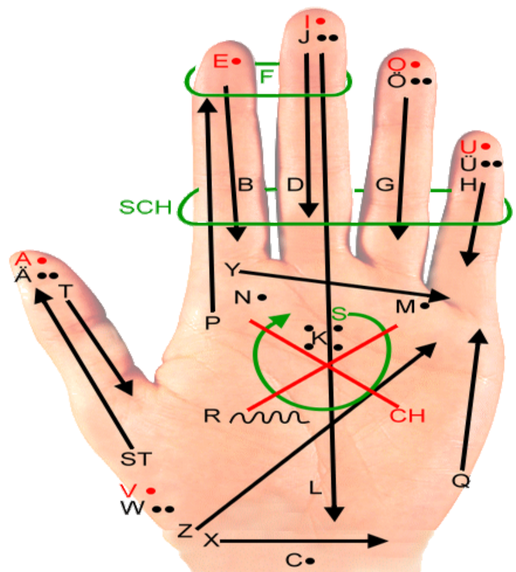


Figure 2.1: Alphabet de LORM [3]

palm of the hand (Fig. 2.1). The letters are positioned on the hand, and one writes on the hand of the disabled person by touching or touching the different locations of the letters to form words.

- **The TADOMA method**: Developed by Sophia Alcorn, the TADOMA method is named after two of its deafblind students: Tad and Oma (Colman, 2015). It captures the speech of the speaker through tactile reading of the lips by placing the thumb on the speaker's lips while the other fingers touch the face and neck (Fig. 2.2).

- **Braille**: The Braille method is a communication method based on a tactile language that can be used by the visually impaired and blind (Jiménez et al., 2009). This method is named after its inventor, Louis Braille.[5]. The principle of Braille is to use an alphabet to communicate (read and write) by means of raised dots via touch.

[4] slideplayer.it/slide/962888/

[5] Louis Braille is the French inventor of the tactile writing system with salient points. Source:fr.wikipedia.org/wiki/Louis_Braille

Figure 2.2: The TADOMA method [4]

- **Vibratese**: This is a method similar to tactile communication of Morse code (Geldard, 1960). It uses five actuators placed on the torso of the user to present three basic elements: letters, numbers, and short words. A read rate of about 38 words per minute can be obtained.

- **The language of tactile signs**: This is a method of communication based on the touch of the hands (Stokoe Jr, 2005). In this method, the deafblind person places his or her hands on the hands of the interlocutor to perceive what is being said by touch (Fig. 2.3). The language of tactile signs requires that the people in the conversation physically touch one another to communicate. A person "speaks" signs in the hand of the "listener" while the listener surrounds them with his or her hands to feel the words that are forming. Because it is a form of intimate communication, instructors can only train one or two people at a time.

[6] `leaderdog.org/clients/programs/deaf-blind-guide-dog-program/tactile-sign-language`

Figure 2.3: The language of tactile signs [6]

Other methods of communication exist, such as the Malossi method (Caporusso et al., 2017), an alphabet-based communication method that is widely used by children and people with cognitive impairments who cannot learn more complex communication methods (e.g., Lorm or Braille alphabets).

We observe that these haptic methods are not only means of communication but also help to supplement other means of communication. For example, they enrich and colour communication by quickly giving information about people, context, mimicry, and even the environment. However, our analysis is that all these methods use the same communication principle: learning a basic language for each method and interaction techniques. Therefore, it would be important to become familiar with the haptic language if we want to ensure we are understood when sending our information.

2.2.4 Transmission of sensory information by touch

Haptic communication is possible through the faculty of humans to perceive their environment. Here, we analyse how the perception process of haptic stimuli takes place. Humans can navigate the environment through the sensory organs (eyes, ears, skin, nose, etc.) that allow one to capture different stimuli (auditory, visual, and tactile stimuli). These stimuli are analyzed and interpreted by the brain. This is perception. Tactile perception in humans is part of the somaesthetic system (set of structures associated with the perception, transport, and final processing of information in the nervous system). The perception of tactile information is carried out at three levels: sensory receptors, transmission (or ascending pathways), and cortical levels (Bluteau, 2010). The sensory receptors will be analyzed in the third section (Section 2.4). To stay within the scope of this thesis, the cortical level will not be analyzed in this related work.

Information transmitted by the cutaneous and proprioceptive receptors is transmitted to the central nervous system by two major ascending pathways: the lemniscal route (or dorsal columns) and the extralemniscal route (anterolateral system). These two paths transmit different information through relays where processing is already done. The extralemniscal route consists of small-diameter axons, which slowly transmit (8 to 40 m/s) a range of information relating to temperature, pain, and coarse tactile information (Bluteau, 2010). In contrast, through large-diameter axons, the lemniscal route rapidly transmits (30 to 110 m/s) information regarding fine tactile sensitivity and proprioceptive sensitivity (Bluteau, 2010). This last path passes ipsilaterally through the medulla oblongata and then crosses the median plane in the middle of the bulb and rises in the brain stem on the opposite side to reach specific nuclei of the thalamus. It finally reaches the primary and secondary somatosensory areas and the posterior parietal areas and motor cortex.

Therefore, haptic communication is possible through the transmission of sensory information by the central nervous system. Indeed, touch allows humans to communicate and interact with their environment. The tactile sensory channel also allows us to experience different sensations, such as pleasure, pain, heat, and cold (Hertenstein et al., 2006). Because of this, we

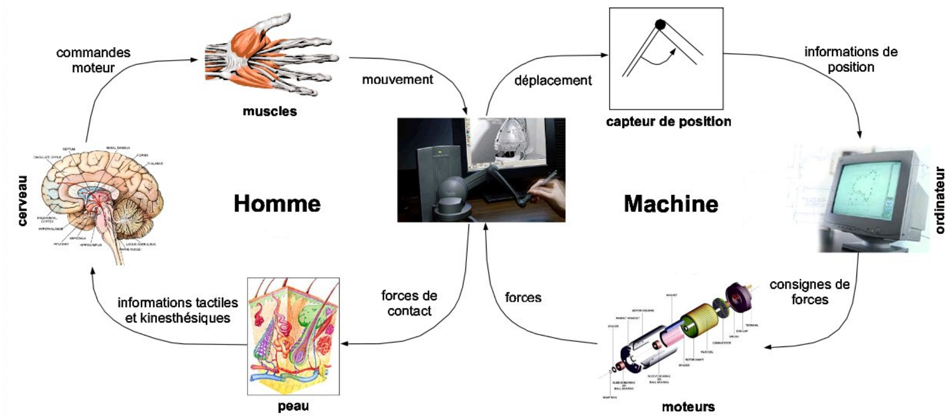


Figure 2.4: The haptic system: haptic interaction between human and machine [7]

will analyse one of the fundamental applications of haptic communication in the next section.

2.2.5 Haptic communication in the blind

In HCI, the communication between the user and the haptic system constitutes in VR the perception–cognition–action loop in which users can perceive the renderings of the environment (real or simulated) through three modes: visual, auditory, and haptic (Figure 2.4). However, blind or visually impaired users cannot move naturally, though they can use other sensory channels or haptic assistance tools to move (Lévesque, 2005).

Zelek et al. (1999) developed an inexpensive device manufactured with plug-and-play, low-power, portable components that transforms deep information (output from stereo cameras) into tactile or auditory information for the visually impaired while navigating. The prototype (Figure 2.5) consists of two stereo cameras, a touch unit (a glove with five piezoelectric buzzers on each finger), and a laptop. Each finger corresponds to a spatial direction (Figure 2.5); for example, the thumb corresponds to the right direction. Using a standard stereovision algorithm, a depth map is created and then divided into five vertical sections, each corresponding to

[7] Source: `http://www.lifl.fr/~casiez/publications/TheseCasiez.pdf`

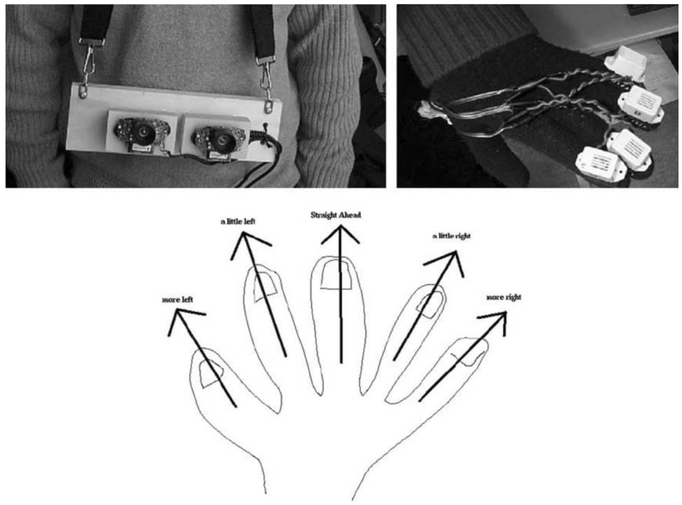


Figure 2.5: Portable haptic assistance tools for blind people. Prototype of the University of Guelph [8]

a vibration element. Johnson and Higgins (2006) created a wearable device that converts visual information into a tactile signal to help visually impaired people avoid obstacles while travelling. The prototype is called the Tactile Vision System (TVS). It uses vibrating motors to inform the user. However, this study is not the most complete in its class. The most complete study on the substitution of vision by touch is the Bach-y-Rita Touch-Video Replacement System (TVSS), which has been in operation since 1963 (Bach-y Rita et al., 2003). They have experimented on the conversion of video images into tactile stimulation in the form of vibrations or direct electrical stimulation. Stimulation has been applied to the abdomen, back, or thigh with tables from 100 to 1,032 points (Bach-y Rita et al., 2003). Cardin et al. (2007) developed a portable system that detects obstacles at shoulder height through a stereoscopic sonar system and returns a vibrotactile feedback to inform the user of the locations. The prototype consists of sonar sensors, a microcontroller, eight vibrators, and a calibration console (PDA).

In summary, the haptic systems presented above uses tactile feedback to communicate with

[8] Source: Dakopoulos and Bourbakis (2010)

the user. This is not an in-depth list of assistive devices for people who are visually impaired or blind. One can refer to the review of Lévesque (2005) and to the study of Dakopoulos and Bourbakis (2010) for a more in-depth presentation.

2.2.6 Signals used to communicate through haptics

In a virtual environment, to simulate haptic sensation, haptic signals are synthesized. This section is focused on the synthesis of haptic signals and the devices used to transmit them. Signal design and device selection are important to ensure information communication through the haptic channel. They both depend on the context of use and the limitations of media and materials.

Hayward and Maclean (2007) reported that there is a direct compensation between signal richness (potential complexity) and signal strength. One of the first rules they stated is the importance of bidirectional communication of a haptic device, especially at the contact points where the stimulus is applied. However, in a haptic system, the stimulus can be considered information generated by a device to be transmitted during communication between two entities (Section 2.2.2). The stimulus therefore plays an important role in haptic communication. We analyse successively different types of stimuli and their designs.

Haptic icons:

Haptic icons are brief programmed forces applied to a user via a haptic interface to transmit the state, function, or content of an object or event, similar to visual or auditory icons (MacLean and Enriquez, 2003). There are two important aspects of a haptic icon: the stimulus and meaning. As such, to create a haptic icon, one must first develop the vibration that the user perceives (stimulus) and then assign the semantics to the stimulus (meaning) (Swerdfeger, 2009). The stimulus of a haptic icon usually mimics natural phenomena (vibration of a hammer).

Tactons:

Tactons, or tactile icons, are structured abstract messages that can be used to communicate non-visually (Brewster and Brown, 2004c). Different actuators can be used to create tactons. In a machine, an actuator is an object that transforms the energy supplied to it into a physical phenomenon that provides a job and modifies the behaviour or state of a system [9]. In the definitions of automatism, actuator belongs to the operative part of an automated system.

The tactons can be used to communicate different types of information:

- Alerts (Brown and Kaaresoja, 2006);
- Indications (Yatani and Truong, 2009);
- Letters (Rantala et al., 2009).

In general, the use of tactons to convey information requires learning. The interpretation of their meaning becomes more difficult as their number increases (Brewster and Brown, 2004c). Hoggan et al. (2009) highlighted the relationships and benefits of tactile icons for optimizing the transmission of vibrotactile information. Indeed, tactons code information by manipulating the parameters of cutaneous perception. The encoding is similar to that of earcons (Brewster, 1998), where each of the sound parameters is modified to encode the information. Similar parameters can be used for tactons (although their relative importance is different).

Haptic icons are different from tactons; the difference between them can be stated as follows. Haptic icons are computer-generated signals that mimic haptic feedback from natural phenomena. The meaning of a haptic icon refers to the associated phenomenon (distal stimulus).

[9] Source: www.larousse.fr/dictionnaires/francais/actionneur/934 Accessed: 2018-05-12.

Tactons are structured, abstract computer-generated haptic signals. The meaning of a tacton refers to the physical properties of the signal (proximal stimulus).

Amplitude modulation: Amplitude modulation used for the design of the tactons is obtained by multiplying the sinusoidal wave of a given frequency by the sine wave of another frequency (Hoggan and Brewster, 2007). The intensity of the stimulation can be used to code values.

The frequency: Frequency can be used to differentiate the tactons. The frequency range $20-1000\ Hz$ is noticeable, but the maximum sensitivity occurs around $250\ Hz$ (Brewster and Brown, 2004c). Studies have shown that using specific frequencies (6 Hz, 70 Hz, and 250 Hz), participants could categorize three distinct perceptual groups of tactons (Hoggan and Brewster, 2007). Perception bandwidth is the frequency with which tactile and kinaesthetic stimuli are detected. We will develop this analysis in depth in Chapter 3.

The waveform: Hoggan and Brewster (2007) showed that the waveform is a good parameter to consider for the design of tactons. Three waveforms–sinusoidal, square (created using the Fourier series), and sawtooth–were created with a resonant frequency of the actuator, varying around 250 Hz. Six participants were able to identify three forms of different waves. In the literature, the waveform is also modified with different variants to differentiate the tactons (Hoggan and Brewster, 2007; Visell et al., 2009; Menelas and Otis, 2012).

Duration and rhythm: It is possible to encode information using pulses of different durations when designing the signal. Gunther (2001) studied a range of subjective responses of pulses of different durations. He found that stimuli lasting less than 0.1 second could be perceived, such as taps, while longer stimuli could be perceived as tactile phrases. In addition, groups of pulses of different durations can be constituted in rhythmic units (Hoggan et al., 2007; Ternes and Maclean, 2008). When multiple events occur on the same area of the skin, differences in the duration of presentation of the stimuli can be used for group events. The rate at which these pulses are read can also be changed.

Various parameters can be used to design differentiable tactons. This can be very useful for designing different signals to be used with the foot. The manipulation of the parameters of the tactons makes it possible to easily create a set of quite different tactons. For example, using existing libraries like that of Immersion Corporation (2012), we obtain a considerable number of tactons very quickly. However, we must know how to differentiate them and propose a set of tactons that will be different from each other. One of the methods used to differentiate between tactons in the literature is multidimensional scaling (MDS), which assists with similarity or dissimilarity analysis in the data (Wickelmaier, 2003). This method of analysis has been used in the past in several works (MacLean and Enriquez, 2003; Swerdfeger, 2009; Ternes and Maclean, 2008; Wang et al., 2016; Wickelmaier, 2003). Considering these promising results, it turns out that MDS analysis is a relevant tool to define a set of easily differentiable tactons. Therefore, this type of analysis will be chosen in this study to obtain a set of easily distinguishable tactons capable of transmitting the risk of falling.

2.2.7 Vibrotactile devices

We can see vibrotactile devices as motors capable of delivering vibrotactile rendering. Today, their practical applications are numerous, ranging from the manipulation of objects in a virtual environment to surgical operations. Nowadays, haptic feedback is also used in consumer applications, especially with mobile phone vibrations to discreetly get the attention of the user when the audio and visual modalities are inappropriate. Nevertheless, using haptics remains limited when compared to visual and auditory rendering. This is probably related to technological limitations, related to the lack of studies on the perception of tactile information. This section discusses this contribution.

One of the main application of haptics in everyday products is in assistive technologies. Meier

[10] `http://cliniqueosteoforme.com/troubles-systeme-vestibulaire/`

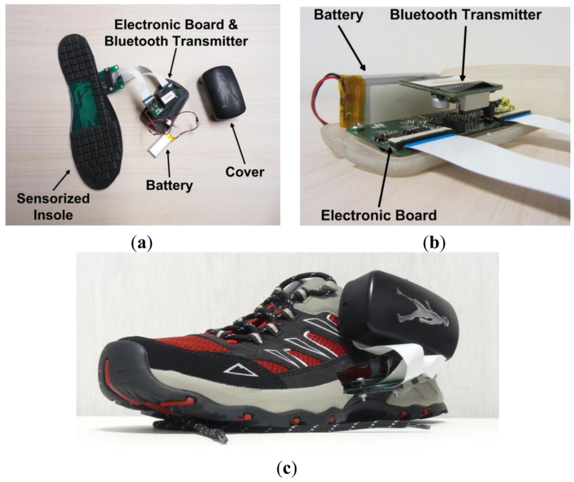


Figure 2.6: Wireless Flexible Sensorized Insole for Gait Analysis [10]

et al. (2015a) introduced an assistive mobile device for navigation that can be attached to users' bodies. In this category, we were able to count handheld devices (Robinson et al., 2010; Rümelin et al., 2011), bracelets (Kammoun et al., 2012; Panëels et al., 2013), shoes (Frey, 2007; Otis et al., 2016; Ayena et al., 2017; Schirmer et al., 2015), belts (Steltenpohl and Bouwer, 2013; Tsukada and Yasumura, 2004), and smartphone applications (Pielot et al., 2010; Bermejo and Hui, 2017). According to Bermejo and Hui (2017), the classification of haptic devices should be made based on the functionality they have on the user's body and the proposed guidelines to ensure richer interactions. For example, the classification of a haptic device should consider the intensity of the feedback, the fidelity factor, comfort, and mobility. In addition, Bermejo and Hui (2017) reported that the addition of portability as a feature of the device may include several constraints, such as form factor, comfort, mobility, and autonomy in terms of energy.

In the category of interactions with the foot, portable devices in the form of wearable shoes encompass several sensors. These technologies often depend on the targeted application. We can distinguish the technologies of detection, data transmission, and wearable data processing

[11] Source: Hegde et al. (2016a)

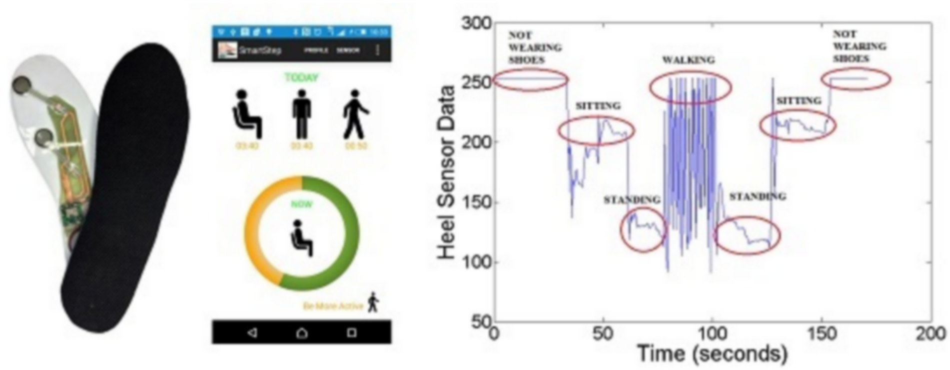


Figure 2.7: SmartStep: an insole-based physical activity and gait monitor [11]

(Hegde et al., 2016a). For example, Figure 2.6 shows an instrumented insole developed for gait monitoring by Hegde et al. (2016a). The normal approach allows a user to remain agile to easily change direction, go up or down stairs, and avoid obstacles. The SmartShoe device developed by Sazonov et al. (2011) is a shoe for posture monitoring and activity recognition in healthy subjects. The most recent version of this device, called SmartStep, has shown promising results on posture and classification of activities (Hegde et al., 2016b). Figure 2.7 shows the SmartStep insole and the associated Android application interface for daily activity monitoring with a smartphone (Hegde et al., 2016a). Using force sensors, an accelerometer, and bending sensors, Otis and Menelas (2012) proposed an augmented device (Figure 2.8) that transmits data via Bluetooth to an Android smartphone for evaluation of the risk of falling (Otis and Menelas, 2012). Twenty-three human subjects were studied, including seven elderly subjects and four subjects with Parkinson's disease. The results suggest that the risk of falling depends on the type of soil.

Similarly, using sensors and an actuator from a smartphone, Schirmer et al. (2015) communicated haptic information for real-time navigation. The user received vibrotactile alerts while walking and turning; the smartphone calculated the path, while the actuators triggered vibrotactile stimuli. Different vibration patterns were used for different paths (front, back, left,

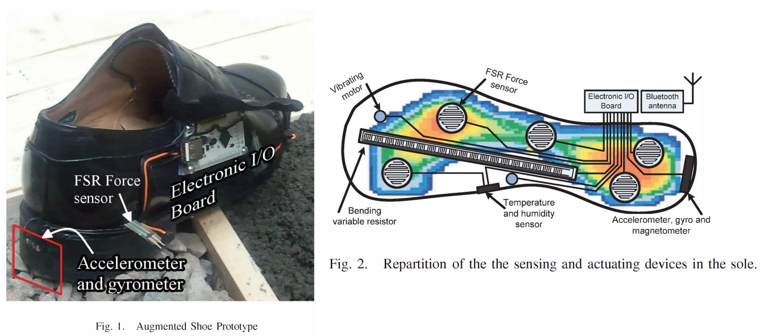


Figure 2.8: Augmented shoe prototype (a). Repartition of the sensing and actuating devices in the sole (b)

and right). Results from 21 subjects studied showed that 99.7% of the time, users correctly identified the path and turns returned by the shoes.

Gagnon et al. (2013b) presented a serious game for learning vibrotactile stimuli presented to the foot. Using a vibrotactile device coupled with a tablet (Figure 2.9), they analysed the maximum number of vibrotactile stimuli that could be memorized when presented to the foot. With training, the preliminary results showed the usability of the serious game for learning a number of vibrotactile stimuli. But the authors posited a limit for the identification of several vibrotactile stimuli. Indeed, the use of a discrimination method such as MDS analysis could have improved the design of vibrotactile stimuli.

Recently, to reduce the risk of falling on different soil types in the elderly and people with

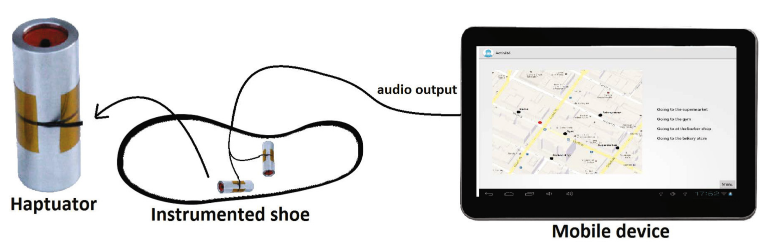


Figure 2.9: Serious games for learning and identification of vibrotactile messages

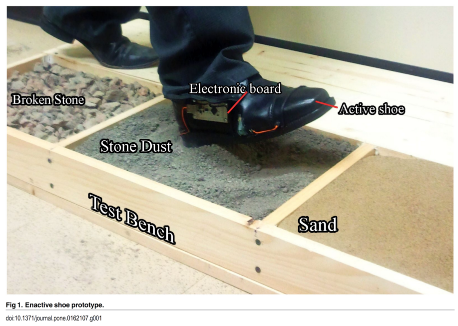


Figure 2.10: First prototype: Insole to reduce the risk of falling

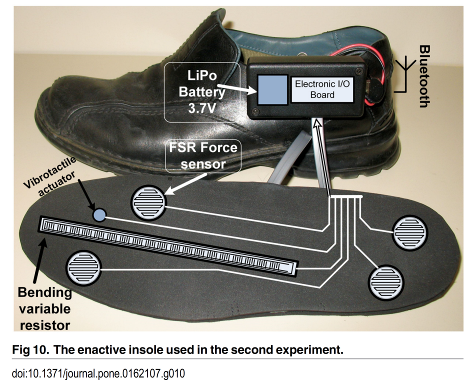


Figure 2.11: Second prototype: Insole to reduce the risk of falling

Parkinson's disease, Otis et al. (2016) used two versions of an insole transmitting vibrotactile returns during identification of the risk of falling. Figures 2.10 and 2.11 present the two versions of the insole used. However, one of the limitations of this study was that some participants did not perceive the vibrotactile signal. Indeed, we think that one solution would be to propose easily differentiable stimuli that would be previously learned by users before being identified.

The observations with these devices are that vibrotactile stimuli are used in a binary approach (Geldard, 1960; Brown and Kaaresoja, 2006; Yatani and Truong, 2009). and their design is not elaborated enough to be perceived properly as in Otis et al. (2016). However, other devices and vibrotactile feedback for daily assistance of users is shown in the work by Hegde et al. (2016a) and Bermejo and Hui (2017).

In summary, an important observation following this analysis allows us to note the importance of the force of the vibration, and the energy consumption regarding the time elapsed between the transmitting of the stimuli and the response (action) of the user. In addition, all these vibrotactile devices mainly use three types of vibrotactile motors: LRAs, ERMs, and haptuators (Yao and Hayward, 2010). However, to achieve the intended purpose of this research, these devices must be analyzed to ensure effective haptic communication. To do this, as part of this thesis, the device will be analyzed according to two specific domains: the time and frequency domains. The understanding of these two domains of the device characteristics could allow us to know their physical characteristics. This would lead to selecting a device that will be adapted for communication of the risk of falling. For this purpose, we could choose the original haptuator (Figure 2.12), which has been used to identify vibrotactile stimuli by Gagnon et al. (2013b); Yao and Hayward (2010). It can be controlled as a loudspeaker of $4-8\Omega$ by most audio amplifiers if the input current and voltage are in the recommended operating conditions.

Figure 2.12: An ideal vibrotactile device: the original haptuator [12]

2.3 Impact of Disturbances on Haptic Perception

Humans constantly interact with their environment, which exposes them to conditions that can be distracting (public places, walking, metro, commercial spaces, etc.). In motion, for example, our attention is mostly occupied by primary tasks, such as walking or visualizing our space while walking. These activities and/or stimuli (visual, walking, and cognitive) can

[12]Source: `http://tactilelabs.com/products/haptics/haptuator/`

influence the perception of tactile information. In this section, we evaluate the distractions of the communication of a risk of falling via the haptic modality.

2.3.1 Visual disturbances

In the field of HCI, the influence of vision on haptics perception is well known. Several researchers have studied the effects of vision on the perception of haptic stimuli. Others have studied multimodal integration (visual and haptic). For example, Welch et al. (1979) noted that vision affects perception of weight. Ernst and Banks (2002) have studied how visual-haptic sensorimotor integration occurs; they found that humans integrate visual and haptic sensory information in a statically optimal way. In what follows, we will limit ourselves to the study of visual disturbances on the perception of haptic information.

Gallace et al. (2007) presented two experiments to investigate whether the change in tactile blindness could also be caused by the presentation of visual stimuli. The participants had to detect a position change between two consecutive tactile displays (activation of two to three actuators on their bodies when visual distractions were also presented). The results show that the phenomenon can be triggered when a change occurs simultaneously in a different sensory modality (here vision). The sensitivity of the participants to detect the occurrence of a change between the two vibrotactile displays decreased when a visual distraction coincided temporally with the beginning of the tactile presentation of the second display. Thus, changes in tactile blindness can be caused by the presentation of visual stimuli.

Chan et al. (2008) described a study exploring the use of haptics for remote collaborators in a single-user shared application. In Step III of their protocol, they conducted a stress test to determine how long it would take participants to learn haptic icons, how quickly they could detect and identify them, and how this ability would be affected by adding to the workload. On average, participants were able to learn the icons using a set of substitution labels in less than three minutes. However, the results suggest that in the absence of other tasks, participants detected and identified the change at 1.8 s and 2.5 s, respectively, but with the addition of visual and auditory distraction tasks, detection times increased significantly to 4.0 s, while identification times increased marginally to 3.0 s.

Lee and Starner (2010) presented two experiments to evaluate wearable tactile displays (WTDs). These displays provided easy-to-perceive alerts for users on the move. Their first experiment was on the sensitivity of the perception of tactile models. It revealed that participants were able to discriminate 24 tactile models with 99% accuracy after 40 minutes of training. The second experiment focused on dual-task performance, exploring users' abilities to perceive three incoming alerts with and without visual distractions. The second experiment revealed that in the presence of a visual distraction, user reactions to incoming tactile alerts become slower for the mobile phone but not for the tactile displays.

Visual distractions were usually exploited to identify whether tactile perception is affected by attention to tasks. For instance, Karuei et al. (2011) explored the potential and limitations of vibrotactile displays in practical wearable applications. They examined whether visual workload, stimulus localization, or performance had an effect on gender and whether users had subjective preferences for one of these conditions. During the visual workload test, the participants were seated first, then walked about 2 m in a single geometric scene showing various visual objects (blocks) in equal amounts. Participants were asked to count the number of times the highlighted block struck the walls in the scene. The results suggested that the visual workload did not seem to affect the vibration detection rate, but it did increase the response time.

In the end, we find that vision is the sensory modality that is much more used in everyday life. It can sometimes be a distracting factor for haptic stimuli, especially textures, and sometimes it can also influence reaction times to haptic stimuli. In our study, the consideration of reaction time and workload must therefore be evaluated as a factor disrupting haptic communication (Pavani et al., 2000).

2.3.2 Auditory disturbances

After seeing the effects of visual disturbances, in this section, we are interested in the influence of auditory stimuli on haptic feedback.

Yau et al. (2009) showed that frequency variation alters the effect of auditory distractions on tactile discrimination tasks, with performance reduced when the frequencies of auditory and tactile stimuli are similar. Reyes-Lecuona and Cañadas-Quesada (2009) analyzed how the duration of auditory stimulus interferes with the haptic perception of rigid surfaces. The results showed that there is an association between short auditory and stiff haptic stimuli, and between long auditory and soft haptic stimuli. Kim et al. (2007) conducted a study of the intermodal relationship of auditory and tactile perceptions. The experiment, which was conducted with 78 stimulus combinations, shows significant results on the effects of the level of sound intensity on tactile perception. Qian et al. (2013) compared the effects of simulated and real auditory distractions on the perception of tactons. The results showed a negative effect of ambient auditory stimuli on the accuracy of tactile recognition, time taken, and cognitive workload. However, the results also indicated that some tactile designs (e.g., those encoded with higher intensities) are more resistant to the effects of auditory distractions.

Chan et al. (2005) discussed the use of vibrotactile feedback to convey basic information with variable intrusion when recipients are absorbed by a visual and/or auditory primary task. They described two experiments designed to perceptually optimize a set of vibrotactile icons and evaluate the user's ability to identify them in the presence of distractions. The results showed that seven icons learned in about three minutes were usually identified in 2.5 s with 95% accuracy in the absence of distractions. With distractive visual and auditory tasks, the time required to detect a haptic icon change increased from 1.9 s to an average of 4.3 s.

From this analysis, we see the negative effects of auditory events on tactile perception. However, this evaluation allows us to seriously consider the assessment of auditory disturbances when communicating the level of the risk of falling. This study will be developed in Chapter 4.

2.3.3 Cognitive disturbances

The visual channel is the main mode of information in many applications in HCI. Although this modality is suitable in many situations, there are scenarios in which the visual channel may be overloaded by the amount of data presented. For example, answering a phone call while walking down stairs can put us in a multitasking situation with an overloaded cognitive workload. In this context, the transmission of information via the haptic modality can be ignored. However, several studies support the use of haptic feedback as a means of communication (Levitin et al., 2000; MacLean, 2008b; Chan et al., 2005) because it can increase human performance, unlike visual feedback (Boy, 2017). However, one question arises: What is the influence of the cognitive load modulated by the attention on the haptic communication? After explaining cognitive load, we will review some works covering this area.

Attention [13] is a complex cognitive function that is paramount in human behaviour. It allows one to focus on one main task while ignoring the other aspects, but it also involves cognitive efficiency, whether in perceiving, memorizing, or solving problems. However, daily, humans are often required to perform several tasks simultaneously, such as when we hold a conversation while driving. Our attention can thus be shared between the main task and the secondary tasks. In this case, we must concentrate on managing the many pieces of information because of the

[13] Source:http://www.happyneuron.fr/cerveau-et-entrainement/attention

workload, and this requires more cognitive resources. A double task situation may require more resources, and this will cause a drop in the performance in the main task.

In human–machine interaction, to show the utility in the haptic interaction, Novak et al. (2011) conducted a study to analyse the psychophysiological responses of a haptic task with three different difficulty levels and two different physical load levels. Four physiological responses were recorded: heart rate, skin conductance, respiratory rate, and skin temperature. The subjects were at rest in front of a screen manipulating the HapticMaster (haptic device) with their dominant arms. The results showed that the mean respiratory rate, variability of the respiratory rate, and skin temperature had significant differences between the levels of difficulty independent of the physical load and can be used to estimate the cognitive load in a haptic interaction. Oakley and Park (2008) evaluated the tacton recognition performance organized into a two-dimensional set. The tactons were presented on a wearable device worn on the wrist while users performed three different distraction tasks. Two tasks involved completing work on a computer, while the last was mobile and required the participants to walk around. Tasks were chosen to represent common activities and explore different aspects of distraction. One of the objectives of this work was to establish whether the performance of tactile recognition varied between different distraction tasks, or whether the parameters of the stimulus were affected differently. Distraction (double or multitasking) can mask the perception of vibrotactile signals. The major finding observed in this study is the importance of the influence of cognitive disturbances because input of data with a mouse into the computer is considered a secondary task to be performed by the participants. However, Oakley and Park (2008) are not alone in conducting studies on the subject. Tang et al. (2005) conducted a study to explore how haptic feedbacks could be used as another means of transmitting information when the visual system is saturated. They evaluated three haptic models for conveying ordinal data to participants performing a large visual tracking task. The evaluation demonstrates that the information provided by these models is perceptually available even when users are visually busy. The results show that participants could accurately perceive and process the ordinal data provided via the haptic channel while managing a cognitive workload. This study may be considered in the rest of our work as the beginning of a solution to validate the design of haptic signals that can be transmitted when participants have a significant cognitive workload.

Finally, the major observation that we can drawn here is that it is possible that the cognitive distractions among the users have not been analyzed much in the literature. However, they are parameters to be considered in the perception of tactile information via the haptic modality. However, according to the evaluation of the previous works, we note that a cognitive load can influence the capacity of perception of the haptic renderings.

2.3.4 Motor disturbance: Walking

Walking is a natural mode of locomotion. In humans, walking is one of the main means of transport and part of the tasks or activities naturally carried out to move. Walking involves the sensors on the soles of the feet that allow a human to provide postural adjustments to balance while moving. In this case, the foot participates in a direct and sustained way to our movements. In neuropsychology, studies on the perception of plantar touch are interested in the control of posture and balance. However, the question that arises here is how walking can be a disturbing factor in communicating a risk of falling via the haptic modality ?

The following studies may provide an early answer to this question. Kavounoudias revealed that tactile afferents from the lower limb area participate in a fine and organized manner in the regulation of the erect posture (Kavounoudias et al., 2001). Because cutaneous mechanoreceptors are sensitive to stretching of the skin or superficial tactile scans, they can take part in direction, velocity, body movement, or friction being exerted on the surface of the feet. This friction can cause perceptual conflicts, especially if the soil has a different texture (Otis et al., 2016). As a result, the transmission of information by the haptic modality in this condition could be ignored. In addition, older subjects have less ability than youths to divide their attention between two or more tasks.

Oakley and Park (2008) indicated that distraction should be considered when designing vibrotactile signals. They described an experiment in which the task of distraction was to walk (up and down a corridor) and each participant had to leave his or her non-dominant hand (with the wearable device attached to the wrist) inactive for the duration of the study. This task involved little or no mental distraction; the participants were able to perform the task almost independently and were able to observe a focus on the PDA. The results indicate a significant decrease in haptic feedback perception performance during walking.

In summary, in everyday life, humans perform various types of walking (i.e., walking on an airplane floor or up/down stairs). Observations from previous studies point out the influence of the motor disturbance. However, this thesis should consider walking as a major distraction task while communicating stimuli to alert users.

2.4 Different Elements Involved in Haptic Perception

To be able to explain or situate the various elements that may be involved in the haptic perception process, we make an analogy with a general case in everyday life: the passport application process. Imagine there is a person wishing to obtain a passport. This person must apply first to the right department in charge of delivering passports. If the person does not contact the service, he or she will have to be reoriented, which will take extra time and increase the overall time of the process. In addition, it will also be necessary for the person to complete the correct forms; otherwise, additional time will be added. Then, the passport application itself will also take a while to reach the right person, who must process the application until it is obtained. If the request is validated by the appropriate service, the passport will be delivered (Figure 2.13). This process took a total time that is a function of the time required by each element involved in the process and the orientation of the person.

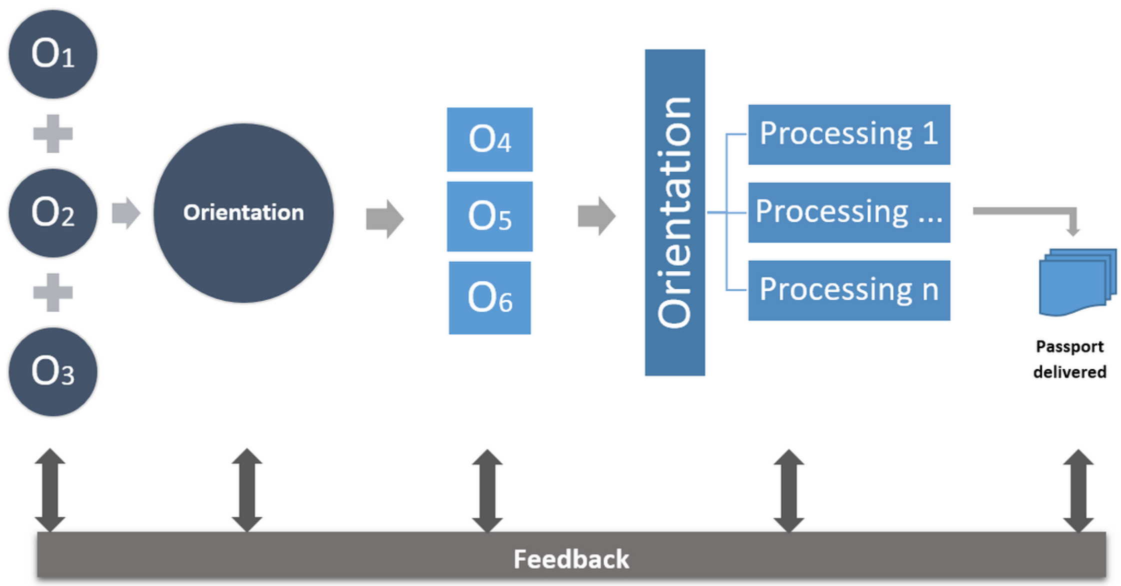


Figure 2.13: Passeport application processing

By analogy, the passport application process (Figure 2.13) can be likened to the process of perceiving a haptic signal with an overall perception time. As in the case of the passport application, a first constraint in this process will be the identification of the point of contact with the signal (i.e., the skin receptors responsible for haptic perception). If the signal is not applied to the correct skin receptor, it is likely that the signal will not be received. The second constraint will be the identification of how to perceive these signals, and the third will be to identify the overall time that the process took to judge its effectiveness. The identification of its elements is the basis of the evaluation of the haptic communication process. For this, in the first part of this section, we will analyse the different skin receptors involved in haptic communication, then the right way to perceive them and discriminate the signals (psychophysical laws) and finally the global component of the process, namely, the reaction time.

2.4.1 Skin receptors

Here, we summarize skin tactile mechanoreceptors that intervene directly in haptic perception. The perception of tactile information implies the solicitation of the human physiological receptors, which are in the skin (2.14). Depending on the type of stimuli, somatosensory receptors[14]can be classified as follows (Tornil, 2006; Sauleau, 2009):

- Thermoreceptors: related to the sensations of hot and cold;
- Nociceptors: related to the sensation of pain;
- Mechanoreceptors: related to tactile discrimination.

Depending on the anatomical position, we have exteroceptors and interoceptors (viscerorecep-tors and proprioceptors) (Sauleau, 2009).

Cutaneous tactile mechanoreceptors are receptors that inform the central nervous system of sensations of touch, vibration, and cutaneous tension (Table 2.1. They are sensitive to the mechanical deformations of the skin induced by contact with objects (Sauleau, 2009; Tornil, 2006). They are at the origin of the exteroceptive sensitivity of epicritic touch (discriminative) and allow the exploration and analysis of the external environment. There are four main mechanoreceptors: two in the epidermis and two in the dermis. In the literature, we can also speak of a fifth: the pilose endings (very sensitive detection of a slight contact) (Sauleau, 2009).

[14]Somatosensory receptors are specialized peripheral organs where the transduction and coding of the quality, intensity, duration, and location of the stimulus take place.

[15]`lejournal.cnrs.fr/articles/quand-le-toucher-decline`

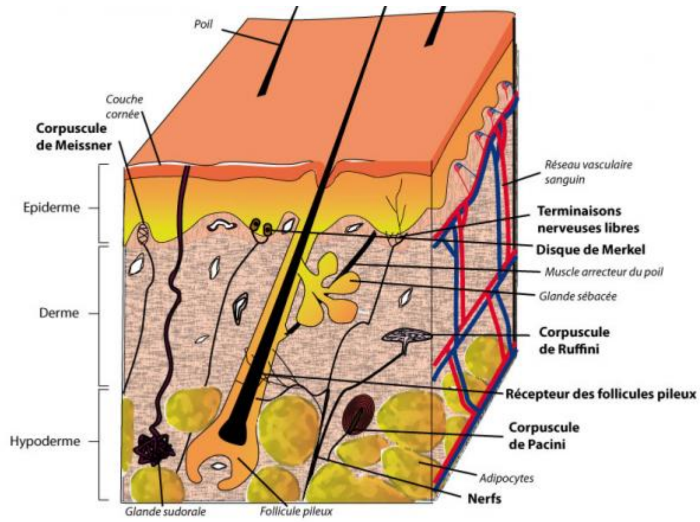


Figure 2.14: The sensory nervous system of the skin[15]

Tableau 2.1: Main touch receivers[16]

Receiver type	Adaptation rate	Frequency of stimuli	Receiving area	Function
Merkel nerve ending	Slow adaptive (AL I)	0.3–100 Hz	Small, well defined	Localized pressure
Ruffini corpuscles	Slow adaptive (AL II)	15–400 Hz	Large, indefinite	Pressure, stretching of the skin
Meissner corpuscles	Fast adaptive (AR II)	10–100 Hz	Small, well defined	Tact, speed
Pacini's corpuscles	Fast adaptive (FA I)	40–800 Hz	Large, indefinite	Vibration, acceleration

Mechanoreceptors are usually classified according to their rate of adaptation, whether fast adaptation (FA) or slow adaptation (SA), and their type of receptor: type I (small) or type II (large) (Tornil, 2006; Sauleau, 2009). Pacini corpuscles (FA II), located at the palm, finger, and foot, respond better to high-frequency vibrations ($40-800$ Hz), unlike Meissner corpuscles (FA I), which are sensitive to vibrations at low frequencies with a field surface between 1 and 100 mm^2 (Dargahi and Najarian, 2004). As for Merkel nerve endings (SA I), they respond to normal skin indentations, while Ruffini's corpuscles (SA II, $10-500$ Hz) respond to the lateral stretching of the skin (Loomis and Lederman, 1986). Pacini's corpuscles and Ruffini's corpuscles detect the large dimensions of the objects, while the other two detect the fine edges (Dargahi and Najarian, 2004).

[16]Source: (Tornil, 2006)

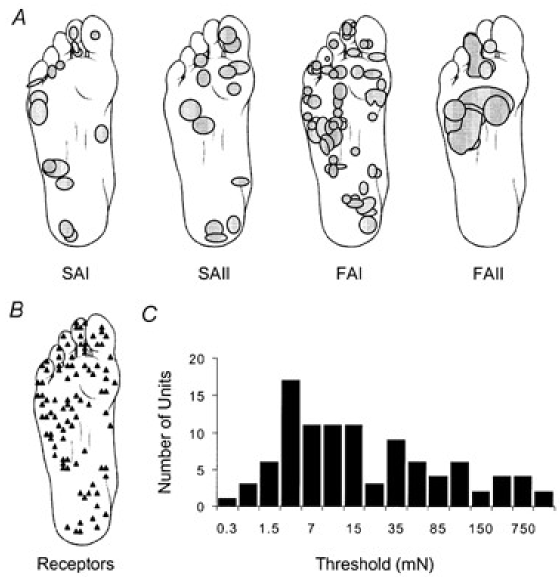


Figure 2.15: Distribution of mechanoreceptors of the sole of the foot [17]

All these types of mechanoreceptors are present in different skin layers of the palm and the sole of the foot. Indeed, the plantar surface has a rich sensory innervation. It is defined by a well-distributed organization of cutaneous mechanoreceptors under different layers of the skin. The diagram below (Figure 2.15) illustrates the distribution of these different types of receptors in the sole of the foot, namely Pacini corpuscles (FA II), Meissner corpuscles (FA I), Ruffini corpuscles (SA II), and Merkel nerve endings (SA I) (Figure 2.15).

Blanchet (2009) presented some work that measured the sensitivity of the plantar tactile receptors using a vibrometer (sensitivity to vibrations of 30 and 256 Hz), a caliper (discriminatory sensitivity between two points), and monofilaments (threshold of pressure detection). The results of this work reveal the following:

- The five points of the plantar arch detect pressures between 0.0677 and 0.6958 Pa and the eight points of the peri-malleolar area score between 0.4082 and 0.6958 Pa.

[17] Source:(Velázquez and Pissaloux, 2008)

- The minimum discriminable length between two points in the arch is between 10.45 and 11 mm;
- For the vibration, all the subjects achieved the same score at 30 and 256 Hz; therefore, the vibrometer used in this experiment was not discriminatory enough for young healthy adults due to the high sensitivity of the arch to pressure;
- SA I and FA II (Meissner and Pacini corpuscles) respond to compression and the SAII type (Ruffini corpuscles) respond to stretching the skin (Fitts, 1954).

The results of this work further justify the choice of tactile receptors (plantar, in particular) as the first constraint or first contact interface for the communication process. In the end, mechanoreceptors are important in the process of communicating haptic information. We have noticed that they have several functions and can intervene in equilibrium and that they make it possible to discriminate vibrations at specific frequencies. This first element involved in the haptic communication process should be analyzed for the positioning of the device on the user's foot. This motivates the choice made in Chapters 5 and 6.

2.4.2 Laws related to haptic perception

Since we have analyzed the sensors of the foot, now we will point out how haptic stimuli are perceived: laws related to haptic perception. In the history of psychology, the study of active touch dates to the eighteenth century with the work of the physiologist Ernst Heinrich Weber [18](1795–1878) (Weber, 2008). These studies focused on the measurement of tactile sensitivity on different parts of the body. Some researchers have extended this work. All these works are found in the field of psychophysics in the form of laws.

[18] `fr.wikipedia.org/wiki/Ernst_Heinrich_Weber`

Weber-Fechner's law: In psychophysics, the law of Weber-Fechner or Bouguer-Weber describes the relationship maintained by sensation with the physical magnitude of a stimulus. According to this law, perceived sensation meets the equation 2.1:

$$S = k \times \log(I), \tag{2.1}$$

where S is the perceived sensation, I the intensity of the stimulation, k a constant, and *log* is the logarithmic function in mathematics.

Based on the work of Weber, Gustav Fechner explained his law according to which "the sensation varies as the logarithm of the excitement." Following the notion of a differential threshold, the experimental validation of this low was made possible. Indeed, according to this law, Weber's fraction is supposed to be constant. It answers the equation 2.2:

$$\frac{\Delta I}{I} = K, \tag{2.2}$$

where ΔI is the differential threshold (SD), that is, the smallest difference in perceived stimulus; I is the intensity of the standard stimulus; and k is the characteristic constant of the sensory modality in question. The value $\frac{\Delta I}{I}$ is also called the *relative differential threshold* or *Bouguer-Weber report*.

Stevens' law: Stevens' power law (Stevens, 1957) seeks to describe the relationship between the physical magnitude of a stimulus and the intensity of perception. It is considered as a variant of the Weber-Fechner law. According to Stevens' law, perceived sensation meets the equation 2.3:

$$S = K \times I^a, \tag{2.3}$$

where S is the perceived sensation, I is the intensity of the stimulation, K is a constant, and *a* is said to be Stevens' exponent, which depends on the type of stimulation. Stevens' law has largely contributed to psychophysical studies by analyzing a wide variety of different stimulations (sound, light, touch, etc.). According to Stevens (1957), the magnitudes of the sensations can be measured on a scale of ratios constructed by direct methods in which the answers of the subjects are expressed by numbers (Bernyer, 1962). These scales reveal that, on quantitative or prosthetic continuums, such as loudness, heaviness, length, velocity, duration, etc., equal ratios of stimuli produce equal subjective relations (Bernyer, 1962). From this basic principle, it follows that the "psychophysical law," linking sensation and stimulus, is an exponential function.

Other laws of psychophysics exist (Tornil, 2006). For example, Accot's law (Accot and Zhai, 1997) specifies the time when the task relates specifically to the follow-up of a trajectory. The law of power and the minimal jerk law (Flash and Hogan, 1985) tend to model the trajectories of gestures. In this thesis, we are interested in laws related to haptics that allow us to know the thresholds of tactile perception. A limitation in the perception of haptic stimuli is the rate of information perceptible while communicating. This rate can be measured by a perception threshold. In psychophysics, there are two thresholds of perception: the threshold of absolute perception and the threshold of relative perception. The absolute threshold concerning sensitivity is the smallest stimulus energy necessary to produce a sensation, whereas the relative threshold concerns the resolution of sensation, which is the variation of the energy required to have a minimal difference of perception. The differential threshold is the minimum difference of stimulus from which an individual manages to differentiate two stimuli (Jones, 2000). We also use the expression *just noticeable difference* (*JND*) (Tan et al., 1994). Thresholds of physiological perception of a tacton in humans can be quantified by mathematical laws (Section 2.4.2). Weber-Fechner's law is based on this relative threshold. For example, if the intensity of the stimulation is 10 and the minimum variation is felt at 12, then $JND = 2$ units of this level of stimulation.

2.4.3 Response time to haptic stimuli

In this section, we want to analyse the last element of the haptic perception that makes it possible to measure the efficiency of the haptic communication system: the response time. The response time or reaction time corresponds to the latency time between the presentation of a stimulus (auditory, visual, haptic, etc.) and the response to this stimulus. This answer may be an action (movement, slowing down, stopping the walk, etc.). Reaction time informs us about the time taken by the information to be perceived. It consists of the nerve impulses perceived by the brain: perception of the message, integration, and elaboration of an answer. However, a reaction should not be confused with a reflex. A reaction is indeed a voluntary act, while a reflex is a totally involuntary muscle response. Reaction time can vary according to several factors (Kosinski, 2008). This response is short in infancy until the late twenties, then increases slowly between 50 and 60 years and lengthens more quickly after 70 years (Welford, 1988; Jevas and Yan, 2001; Luchies et al., 2002; Rose et al., 2002). Luchies et al. (2002) also reported that the age effect was more pronounced for the response time of complex tasks. For a user in good condition, this time is usually at least one second. The reaction time also becomes more variable with age (Hultsch et al., 2002). This influence of aging on reaction time has also been reported by (Lajoie and Gallagher, 2004). However, reaction time can also be influenced by uncomfortable walking conditions (fog, rain, or night) and by physical conditions (fatigue, illness, or taking medicine, alcohol, or drugs) (Kosinski, 2008). [19]

In this section, we observe that reaction time is an important physiological characteristic in humans. It can have a negative effect on the perception of stimuli when it is long. Moreover, reaction times may affect the perception of haptic stimuli while walking, depending on the task

[19] `fr.wikipedia.org/wiki/Temps_de_réponse_(psychologie)`

the participant performs. The measurement of the reaction time could provide an important clue for the haptic system's design. Indeed, calculating the overall response time to a stimulus could inform us about the speed of the user's action. In the following section, we will analyse the reaction time of humans in an uncontrolled environment. This study will be developed in Chapters 5 and 6.

2.5 Conclusion of the Related Work

In this chapter, we describe the problem of our work. It concerns the use of haptic messages to alert a user about the risk of an accidental fall. For this, we reviewed three main aspects of the literature:

- the use of haptics to communicate information,
- the influence of disturbances on haptic perception, and
- the identification of different elements involved in haptic perception.

These points are important aspects in the field of HCI, especially at the level of the haptic communication system (hardware and software) using the foot to interact. Precisely, these points informed us about the vibrotactile stimuli able to inform a user about the risk level of falling. Alternatively, these points identify techniques for communication of this risk and the different constraints (external environment and physiological characteristics) that could influence the transmission of information. However, the means and techniques of interaction and communication implemented in HCI are limited because they do not consider the type of information, quality of information, or the time to communicate this risk level. As the analysis of the studies in this chapter shows, a substantial effort remains to cover the level of devices used to communicate and how to communicate the level of risk. Another major finding is that the devices and communication signals used to inform users in a context of mobility are still unsatisfactory in the face of the magnitude of the problem of the risk of falling. Although significant progress has been made in this area, it appears that no study has yet provided an assistance tool for communicating risk levels to those considered vulnerable in their daily activities using foot interaction as a point of contact. Therefore, considering all the above and to the best of our knowledge from previous work, no research work has investigated the effect of the environment (soil types and disturbances) during the communication of a risk of falling with the foot. No study has developed easily differentiable stimuli for communicating this type of information when walking on different types of soil. Our approaches will be to propose a haptic communication system capable of considering all these aspects when communicating the level of risk to reduce falls among the elderly.

We propose an analysis of the types of haptic stimuli that we will classify as the level of risk; this analysis concerns design, identification, and communication of risk levels (Chapter 3). From this initial work, we will be able to provide easily differentiable stimuli to communicate levels of fall risk. After being able to communicate this information, the continuation of our methodology will concern the analysis of the disturbances that interfere during the transmission of the information. Many distractions can influence haptic communication (Section 2.3); therefore, our second evaluation will concern the analysis of the effects of auditory disturbances when identifying risk levels while walking on different types of soil (Chapter 4). The rest of our methodology concerns the evaluation of physiological characteristics, including the reaction time to stimuli when walking on different types of soil (Chapters 5 and 6).

Chapter 3

The Potential of Haptics For Communication

3.1 Abstract

The use of the haptic channel in multimodal interfaces holds several advantages for communication, one of them being that it allows decreasing the load of the visual and auditory channels. Tactons are abstract messages that can be used to communicate non-visually. In this paper we describe a study in which we tested if a set of four tactons can be used to convey a risk level (four states) through an enactive shoe. To this end, two experiments have been run. In the first experiment with 14 participants, we used a multidimensional scale analysis to identify the six most different tactons from an initial set of 30 tactons. In the second experiment (with 38 participants), we evaluated participants' ability to recognize four preselected tactons among these six. For each trial, participants had to perform 12 identifications (three times for each tacton) until they reached a score greater than 95%. The number of trials required and the completion time are analyzed. We found that the repetition significantly improves the

recognition rate of tactons but does not speed up the completion time.

3.2 Introduction

Previous studies have established that the haptic channel offers great opportunities to communicate information in a context in which the visual and/or auditory channels are overloaded Ménélas et al. (2010); Menelas et al. (2014). These works have mostly evaluated the hand's ability to discriminate and identify haptic messages. Also, conveying simple binary information was previously explored in some applications, such as driver assistance Eichelberger and McCartt (2016). However, communication of a risk level using tactons under the sole of the foot is a new strategy. Moreover, here we are concerned with an alphabet having two bits of information (four possibilities).

Other studies have exploited the sense of touch to communicate more than one bit of information. For instance, researchers have studied different communication strategies such as vibrataese Geldard (1957), haptic icons MacLean and Enriquez (2003), tactile melodies van Erp and Spapé (2003), tactons Brown et al. (2006), and tactor arrays Cholewiak and Collins (2003); Cooke et al. (2010). In doing so, some metrics, such as task completion time (CT) in seconds Hoggan et al. (2007), detection rate (%) Karuei et al. (2011), discrimination Luk et al. (2006), and performance (%) Tan et al. (2003) have been widely used. Until now, however, few studies have investigated the communication of information using haptic feedbacks through the sole of the foot as reported in (Menelas and Otis, 2012). Here, we investigate the exploitation of a haptic channel to convey haptic stimuli through the sole of the foot using an enactive shoe (Figure 3.1).

This enactive shoe aims at preventing accidental falls related to gait disorders or to conditions of the physical environment Otis and Menelas (2012); Otis and Ménélas (2014). Thanks to

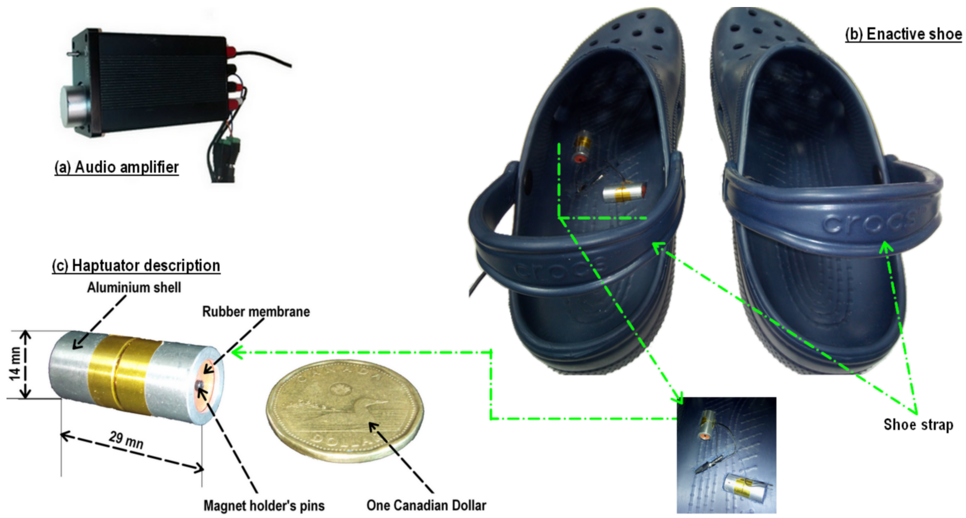


Figure 3.1: Enactive shoe system overview: (a) Audio amplifier to managed output signal. (b) enactive shoe: A rear strap enabling the shoe to be firmly strapped on the foot. (c) Haptuators mounted in the left foot: is an ungrounded moving magnet voice-coil type linear actuator with a magnet that moves axially when the current flows through the coil Yao and Hayward (2010).

an inertial measurement unit and force sensors, it allows the detection of the phases of the gait Yu et al. (2010), the posture of the user Barkallah et al. (2015), and physical properties of the environment Otis and Ménélas (2014). Also, a biofeedback cue is exploited to improve balance by means of vibrotactile actuators Ayena et al. (2016a). The designed shoe (Figure 3.1) includes embedded software that allows the evaluation of crucial information such as a risk level (low, medium, high, and very high). These four risk levels can be seen as the data of a two-bit alphabet. Herein, we study whether a set of four vibrotactile messages can be used to communicate a risk level (four states) throughout an enactive shoe.

While a considerable amount of research suggests that tactons could be useful in communication between humans and machines Paneels and Roberts (2010), only a few mainstream devices take advantage of the possibilities offered by the haptic modality for such a task. In fact, most of the current use of haptic feedbacks in everyday products can be seen as simple binary warnings (yes/no) Enriquez and MacLean (2004), walking directions, and/or obstacle avoidance Velãzquez et al. (2009a). In our case, it seems to be appropriate to use the haptic channel, since the visual and auditory channels are already overloaded while walking Chan et al. (2005). Our study is investigating the potential of the foot plantar for the presentation of haptic messages. Doing so, the device will cover the two most important features meaning being able to analyze the gait Gagnon et al. (2013a); Otis et al. (2016) and to communicate with the user. In addition, the haptic modality appears to be a viable alternative, since touch represents one of the most ancestral human senses Nussbaum and Rorty (1992) and a profound communication channel for humans Lévesque (2005).

To the best of our knowledge, there is no research on the recognition of most distinguishable stimuli and the performance of conveying information (risk level) to the sole of the foot through an enactive shoe. At this stage of the research, we are in a preliminary step where we want to be sure that participants are able to learn the vibrotactile messages presented under the foot. Therefore, it is important to eliminate every parameters that could impact such a result; this is why participants are seated in a peaceful environment. Afterwards we will run experiments to mimic more realistic scenarios. To conduct such a study, we focus on two points: first, the design of six easily discernible tactons through an MDS analysis; second, the effect of iteration on the identification of tactons presented under the sole of the foot.

3.3 Related Work

The literature related to the rendering of haptic messages falls into two groups: haptic icons and tactons Menelas and Otis (2012). Haptic icons are computer-generated signals that mimic haptic feedbacks from natural phenomena MacLean and Enriquez (2003). The meaning of a haptic icon refers to the associated phenomenon (distal stimulus). Tactons are structured, abstract computer-generated haptic signals Brewster and Brown (2004a). The meaning of a tacton refers to the physical properties of the signal (proximal stimulus). In the next four subsections, we study the use of haptic icons and tactons. We follow this with an analysis of vibrotactile stimuli across the body in a mobile context, and, finally, we discuss the identification of vibrotactile stimuli.

3.3.1 Uses of Haptic Icons

Haptic icons can be used to convey information by manipulating various parameters. With low-level engineering, we can obtain various effects of haptic icons by manipulating signal parameters like amplitude, frequency, and waveform MacLean and Enriquez (2003); MacLean (2008a).

Enriquez et al. Enriquez et al. (2006) combined various haptic signals (a simple waveform at a constant frequency and amplitude) serially or in parallel to form haptic words. They found that users could recall an arbitrary association between a haptic stimulus and its assigned arbitrary meaning for a period up to 45 minutes. In order to perform some basic tasks (such as list selection, scrolling, location-finding, direction signaling, and alerting), Luk et al. Luk et al. (2006) enhanced the role of haptics in mobile interaction by designing haptic icons with different parameters (direction, waveform, duration, and amplitude). Their results suggest that the waveform is the most interesting parameter for mobile user interfaces interaction. Ternes et al. Ternes and Maclean (2008) used rhythm in association with frequency and amplitude to produce 84 haptic icons. Recently, Schneider and MacLean Schneider and MacLean (2016) presented the Macaron, a web tool to help in the design of various vibrotactile stimuli. They used time-varying frequency and amplitude for Macaron's initial implementation. The next subsection reviews the uses of tactons.

3.3.2 Uses of Tactons

Tactons have been widely used: on the one hand, to communicate different types of information for instance alerts Brown and Kaaresoja (2006), directions Yatani and Truong (2009), and single-character information Rantala et al. (2009); on the other hand, to provide several signals by manipulating the interactive actuators' parameters. For instance, Pietrzak et al. Pietrzak et al. (2009) found that they could increase the amount of information presented to the participants by increasing the number of independent parameters in tactons.

Noticeable results observed in the past include those of Hoggan and Brewster Hoggan and Brewster (2007), who showed that the use of waveforms (sine, square, or triangle wave) as a texture parameter in tactons' design offers a better discrimination rate than frequency or amplitude modulation. In contrast, we observed that frequencies, amplitudes, and different durations enable better vibrotactile responses, which means a better identification rate Brewster and Brown (2004a). Brown et al. Brown et al. (2006) investigated recognition rates for tactons that encode a third dimension of information using spatial location. They found that tacton recognition rate can be increased from 48% to 81% by reducing the number of values of a single parameter. Thereafter, Qian et al. Qian et al. (2009) designed a set of tactons by manipulating the pulse duration and the interval of vibrotactile signals. Fifteen participants were able to identify and order the relevance of seven pairs of tactons. This approach seems to be appropriate for paired comparison but not for identification.

From this brief review, it appears that both haptic icons and tactons can be used to convey information. In this study, we want to communicate with the user in uncontrolled environments, therefore tactons appear to be more appropriate. Indeed, unlike haptic icons, tactons will not be perceived by users as vibrations related to natural phenomena (e.g., walking). The next subsection reviews the use of vibrotactile stimuli across the body in a mobile context.

3.3.3 Uses of Vibrotactile Stimuli Across The Body In a Mobile Context

Recently, Karuei et al. Karuei et al. (2011) used vibrotactile stimuli across the body in varied conditions to explore the potential and limitations of vibrotactile displays in practical wearable applications. Through two experiments, they compared detection rate and response time to stimuli on 13 body locations in different conditions. In particular, they analyzed the top surface of the foot. They concluded that the wrists and the spine are generally best for detecting vibrations and are the most preferred body location. Unfortunately, they did not study the position that interests our study, the sole of the foot. Our study investigates the potential of the sole of the foot. It is expected that this will improve the usability of the device. We expect users to have better perception through the sole of the foot compared to other body locations, since the haptic interface on the sole will not hinder the person while walking. In our case, actuators (Haptuators Hwang and Choi (2012); TactileLabs (2012)) are inserted into the enactive shoe.

3.3.4 Identification of Vibrotactile Stimuli Presented Under the Foot

Most works have focused on the hand's ability to identify haptic messages; very few have addressed an application with the feet. One of the few works on this topic studied the usability of an instrumented tile Fortin et al. (2014) and insole to render vibrotactile signals via physical properties of the soil such as ice, cracks, and sand Visell et al. (2009). More recently, Meier et al. evaluated vibrotactile feedbacks in different areas of the body, including the sole of the foot and the toes, for an application in navigation Meier et al. (2015b). Their study suggested that the foot provides the most promising results for the recognition of vibration patterns while walking. Also, it suggests that the use of vibrotactile feedbacks on the foot (side/sole/top) reduces stress and the need for visual attention.

Other studies have focused on the rendering of tactile stimuli via an instrumented shoe. For instance, by using an array of 16 dots of actuators, Velazquez et al. Velãzquez et al. (2009a) showed that some geometric shapes could be discriminated in order to guide a blind person while walking.

According to what precedes, tactons have been widely used to convey information by manipulating their parameters. The foot (side/sole/top) is used as the body location to which to convey information, but few studies have been done on the sole of the foot Meier et al. (2015b). Moreover, very few studies have used a learning process to evaluate the transmission of information to the sole of the foot. From these general studies, we conclude that the use of differentiable tactons presented to the sole of the foot with an enactive shoe seems to be an appropriate approach to convey information.

To design easily differentiable tactons, our first experiment described in this paper includes the design of a set of the most dissimilar possible vibrotactile stimuli. The next section describes the step involving the use of an MDS analysis for this task. Evaluations with participants were approved by the local Ethical Committee of University of Quebec at Chicoutimi (certificate number 602.360.01).

3.4 Experiment 1: Use of a Multidimensional Scaling Analysis to Define a Set of Easily Differentiable Tactons

This experiment aimed at designing and selecting the most easily differentiable tactons among a set of 30 tactons classified into five families (Table 3.1). To design the tactons, we first relied on the literature (Chan et al., 2005; MacLean and Enriquez, 2003; Cooke et al., 2010) to collect a large set of tactons, based on which we designed a set of 30 tactons. Then, we used the MDS analysis to select the most easily differentiable tactons.

3.4.1 Preliminaries on MDS

Multidimensional scaling (MDS) helps to analyze similarities or dissimilarities in data. Considering a set of n objects, to determine the similarities (or dissimilarities) in these objects, the MDS algorithm analyzes the $n \times n$ similarity (or dissimilarity) matrix of the same objects. Each matrix entry (i,j) represents the similarity rating for each pair of objects (O_i ˆ O_j). Thus, the algorithm provides the relative position of the objects in a selected number of dimensions (parameters). However, for non-metric similarities (such as the perception rating), a stress criterion is used to set the right number of dimensions. Diagrams such as the screen plot and the Shepard diagram are also used to help decision-making. For further details on MDS, one can refer to Wickelmaier (2003).

MDS analysis has been used several times for the study of haptic perception. For instance, MacLean et al. MacLean and Enriquez (2003) have used a clustered MDS analysis for perception mapping to determine the weight of some haptic icon parameters. The same technique was exploited by Chan et al. Chan et al. (2005) to evaluate the identification accuracy of selected haptic icons. More recently, MDS has helped characterize and quantify the effects of employing different haptic exploratory procedures on perceptual similarity spaces Cooke et al. (2010).

3.4.2 Positioning and Orientation of Haptuators

Mechanoreceptors on the sole of the foot are usually classified based on their rate of adaptivity and receptive field Velázquez and Pissaloux (2008). There are four types of mechanoreceptors in the sole of the foot: slow-adapting type I (SAI), slow-adapting type II (SAII), fast-adapting type I (FAI), and fast-adapting type II (FAII) Velázquez and Pissaloux (2008). Only two afferents, one FAI and one FAII, have their receptor terminals on the hairy skin of the calf

Tableau 3.1: The complete set of 30 Tactons (presented in six families) before they are differentiated by participants

Families equation	Tactons pair frequencies (f_a(Hz), f_b(Hz))*
Family A	(30,-); (50,-); (70,-); (90,-); (110,-); (130,-)
Family B	(3,61); (3,121);(6,60); (6,121);(12,60);(12,120)
Family D	(2,121); (10,61); (10,121); (30,61); (30,121)
Family E1	(30,-); (60,-); (120,-);
Family E2	(30,-); (60,-);(120,-);

** if f_a or f_b = 0 it is remplaced by '-'*

Kennedy and Inglis (2002). Therefore, it seems that stimulation of FAI mechanoreceptors is more suitable for transmitting information to the foot Velázquez and Pissaloux (2008). However, Defne Kaya (2014) has identified some interesting features: The FAIs are the Meissner corpuscles, which best respond to light touch, and the FAIIs are the Pacinian corpuscles, which are best for vibrations. The position of the Haptuators has been selected in order to utilize FAI and FAII to obtain the best perception while transmitting our signal. In order to convey the same vibration to FAIs and FAIIs, the transmitted signal is the same on both Haptuators.

3.4.3 Participants

The experiment was conducted with 14 participants (11 males and 3 females) aged 22 to 32. Eleven were undergraduates, and three were graduates. According to our pre-experimental questionnaire, four participants were familiar with haptics.

3.4.4 Experiment Setup

This experiment used an enactive shoe with two Haptuators as shown in Figure 3.1. This technology has been used to enhance realism in virtual environments and to identify virtual ground in Nordahl et al. (2012); Serafin et al. (2010). The vibrating device was directly in contact with the sole of the foot of the participant. Participants sat in a peaceful environment while wearing the enactive shoes on both feet. For this experiment, as a preliminary step, only the left shoe is embedded with Haptuators.

The sound card of an Android device was utilized to produce the signal. These signals were then amplified (by an audio amplifier shown in Figure 3.1 a) and sent to both Haptuators in (Figure 3.1 c) embedded into a shoe (Figure 3.1 b). Earphones were also used in order to send a non-distracting noise to participants. We did this to eliminate both the potential disturbances of the experimental environment and the sound generated by the Haptuators.

3.4.5 Selected Tactons

As suggested by MacLean et al. MacLean and Enriquez (2003), different waveforms and frequencies were explored to create the initial set of tactons. Sawtooth waveforms were first discarded due to a low perceived sensation and a high similarity with the sine waves. High signal frequencies were also perceived as too similar to sine waves, as suggested in Gagnon et al. (2013c). However, signal amplitude modulations (square and sine wave convolutions) provide interesting stimuli. Thus, inspired by those first observations and by our previous work Menelas and Otis (2012), five waveform families were created with six frequency configurations each (from 30 Hz to 120 Hz), giving a set of thirty tactons. Those families (Table 3.1) are described as follows:

- Family # A are pure sinusoids waves. It provides a smooth and continuous sensation;

- Family # B waveforms are low-frequency sinusoids waves modulated by a higher frequency sinusoids.

- Family # C waveforms are similar to those in family # B, with closer sinusoids frequencies. It provides a rough vibration sensation.

- Family # D waveforms are sinusoids modulated by a square wave;

- Family # E waveforms are sinusoids modulated by a quadratic function. It provides an increasing or decreasing tactile sensation.

From this first set, a preliminary paired comparison was conducted, rating each pair as identical or different. This step allowed stimuli that were too similar to be merged. From this evaluation, the initial set was reduced to 18 stimuli. Table 3.2 shows the families' equations (A; B; C; D; E_1; E_2) and a summary of the selected stimuli. The first column shows the general signal equation of the waveform, while the second gives the number of stimuli as well as their corresponding parameters.

3.4.6 Experimental Protocol

The goal of this evaluation is to provide a dissimilarity matrix, which will be analyzed by a multidimensional scaling analysis. The experimental protocol followed two steps: a familiarization phase and a test phase.

Familiarization phase: In the first step, participants were free to familiarize themselves with the tactons. A familiarization step was used because most of the participants were not familiar with haptics. For this, the 18 tactons were sequentially and randomly presented to users. A demonstration with all the steps was shown to participants. Samples of rated pairs of tactons were also presented to participants because we wanted to explain the entire procedure to participants before they started. After a maximum of five minutes, the participant was invited to begin the experiment.

Test phase: This phase consisted of comparing each pair of the 18 preselected tactons, leading to 153 ($n \times \frac{(n-1)}{2}$) pair comparisons. Each tacton was played during one second, separated by another second. The participant was allowed to repeat the pairing up to two times for any reason (distraction or uncertainty). For each pair of tactons, participants had to rate their dissimilarity from one to five. This range allowed a compromise between ease of comparison and the number of possible ratings. No particular criterion was given; nevertheless,

Tableau 3.2: Summary of the selected *Tactons*

Family equation	**Tacton frequencies (f_a(Hz), f_b(Hz))**
A = $\sin(2\pi f_a t)$	1: $\sin(140\pi t)$; 2: $\sin(180\pi t)$;
B = $\sin(\pi f_a t)$ $\times \sin(2\pi f_b t)$	3: $\sin(3\pi t) \times \sin(122\pi t)$; 4: $\sin(3\pi t) \times \sin(242\pi t)$; 5: $\sin(6\pi t) \times \sin(122\pi t)$; 6: $\sin(6\pi t) \times \sin(242\pi t)$; 7: $\sin(12\pi t) \times \sin(122\pi t)$;
C = $\sin(2\pi f_a t) \times$ $\sin(2\pi f_b t)$	8: $\sin(62\pi t) \times \sin(102\pi t)$; 9: $\sin(62\pi t) \times \sin(142\pi t)$; 10: $\sin(102\pi t) \times \sin(142\pi t)$; 11: $\sin(50\pi t) \times \sin(142\pi t)$;
D = $\sin(2\pi f_a t)$ $\times$ square(50%; f_b)	12: $\sin(4\pi t) \times$ square(50%; 61); 13: $\sin(4\pi t) \times$ square(50%; 121); 14: $\sin(20\pi t) \times$ square(50%; 61); 15: $\sin(60\pi t) \times$ square(50%; 61); 16: $\sin(4\pi t) \times$ square(50%; 121);
$E_1 = t^2 \times$ $\sin(2\pi f_a t)$	17: $t^2 \sin(120\pi t)$;
$E_2 = (-t^2 + 0.5)$ $\times \sin(2\pi f_a t)$	18: $(-t^2 + 0.5) \sin(120\pi t)$

f_a, f_b are frequencies given in Hz

Tableau 3.3: Guideline For Paired Tactons Rating

Value	Meaning	Guideline
1	Identical	No difference between variations
2	Similar	Vibrations barely different
3	Lightly different	Vibrations have common similarities
4	Different	Vibrations easily differentiable
5	Strongly different	Clear difference between vibrations

the guidelines shown in Table 3.3 were set out to help the participant. Every five minutes, a pause was prompted to prevent user fatigue.

3.4.7 Results and Discussion

We obtained a perceptual map by doing a non-metric multidimensional scaling. The analysis used a regrouped dissimilarity matrix of several participants, from which the perceptual space was created. This matrix was obtained from direct pair comparison of the tactons. In this experiment, we were focused only on the distance between stimuli, with the hypothesis that the most different tactons would be mapped as the farthest apart. To highlight the fact that dimension may represent classification parameters, the Manhattan distance has been preferred over the Euclidean distance, giving a lower importance to tactons on the same axis. MDS analysis was done using the MATLAB MDscale function. Data collected from this test include the dissimilarity matrix, the time of the test's completion, and the number of repetitions required for each pair of tactons. Following subsections show the MDS analysis and some statistics as well as a discussion of the proposed set of tactons.

The data collected during this evaluation were used to plot an average perceptual map of the

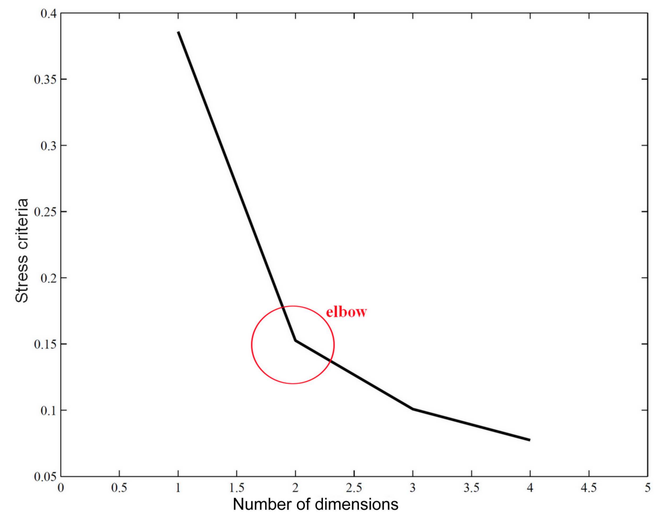


Figure 3.2: Scree diagram: Elbow marked to the second dimension with the stress below 0.15.

18 studied tactons. The MDS analysis was performed on the average matrix of the 14 non-similarity matrices. This matrix was obtained by taking the average results of each participant for each of the pairs being compared. To define the ideal number of dimensions to be used in this analysis, the study of the stress criterion was done using a scree diagram (Figure 3.2). This picture shows a marked elbow at the second dimension with stress below 0.15. Thus, according to the guide proposed by Wickelmaier Wickelmaier (2003), a two-dimensional analysis seems to be a good compromise, given the data in the matrix used. The Shepard diagram (Figure 3.4) demonstrates a good correspondence between disparities and distances, which validates our choice. The perceptual map obtained by the MDS analysis is illustrated in Figure 3.3, where each dot represents one of the 18 tactons as numbered in Table 3.2.

Moreover, the Shepard diagram (Figure 3.4) validates this choice, showing a good correlation between disparities and distances. Upon glancing at Figure 3.3, one observes that tactons A-2, B-5, B-7 and E_2-18 are apart and distant from the others. Moreover, some of them seem to have really tight correlations, such as the pairs (C-9; C-10) and (C-8; E_1-17). Those last

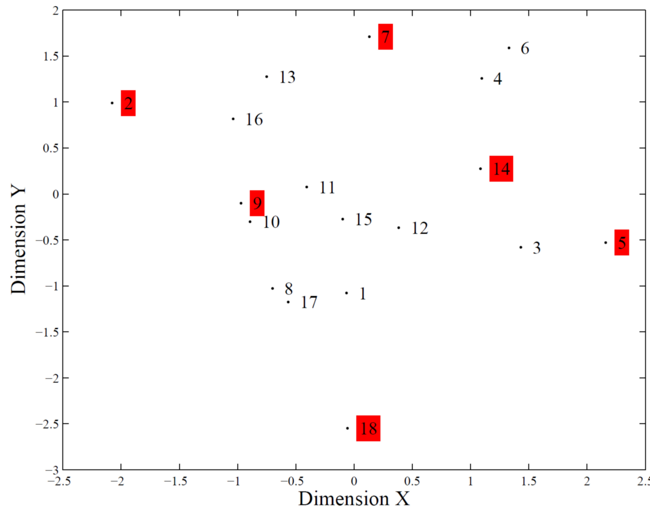


Figure 3.3: Measured perceptual map of *Tactons*: MDS of average data of the eighteen *Tactons* from Table 1

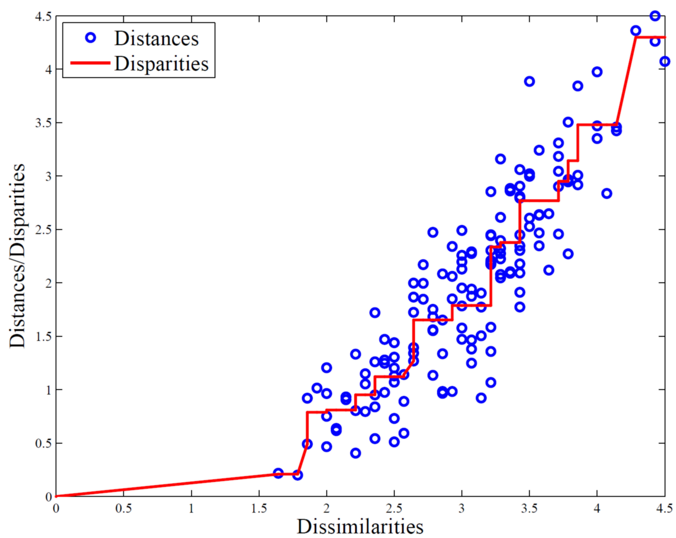


Figure 3.4: Shepard diagram showing relation between disparities and distances

observations highlight, on the one hand, a highly differentiable set of tactons (set {A-2; B-5; B-7; E_2-18}); on the other hand, they show that some tacton pairs can be easily misinterpreted and that they should not be used to convey information. We also notice that when frequencies are higher, more tactons are high on the provided perceptual map. However, these rules do not apply to all evaluated tactons.

Like Brewster et al. Brewster and Brown (2004a), our experiment highlights waveforms (families) and frequencies as the dominant parameters of our perceptual map. We used an algorithm to extract the farthest tactons from our perceptual map (Figure 3.3) in order to select a set of tactons that could be easily recognized. The algorithm first created all possible sets of tactons. Then, we computed the shortest Manhattan distance between each of the set members. Having done so, we were able to choose the sets with the largest and smallest distances. Out of these, a set of six tactons was highlighted by the algorithm (see Figure 3.3), four of which correspond to the previous visual analysis of the mapping.

On the basis of this experiment, we can state that, for most participants, the six tactons extracted from the mean dissimilarity matrix were perceived as the six most different tactons. Therefore, these six are suggested to be used as vibrotactile signals.

It remains to be assessed whether these (easily differentiable) tactons can be used to communicate information to the sole of the foot. This question is explored in the next section, wherein an experiment is proposed to validate the choice of four tactons among those six to convey a risk of falling.

3.5 Experiment 2: Use of the six Selected Tactons to Communicate a Risk Level

This section reports an experiment that evaluates the impact of a learning process on the participants' recognition capabilities for the set of stimuli discriminated by means of the MDS analysis.

The aim of the study is to learn whether repetition improves the recognition of information

Tableau 3.4: Steps of the experiment #2

Different steps of the experiment	
1. Selection phase	User selects four of the six Tactons identified previously
2. Association phase	Each selected tacton is associated to risk level : Tacton ->Risk level
3. Test phase	Four tactons are randomly presented. The user has to identify appropriate risk level

transmitted to the foot. Do participants easily recognize this information? We have previously done a study on a serious game allowing participants to learn how to associate tactons with falling MacLean (2000). In the experiment described in the previous section, we selected the most differentiable six tactons using MDS. In this experiment, we want to learn whether repetition helps improve the recognition rate. If yes, what is the recognition rate, and how many iterations are needed to reach a recognition rate greater than 95%?

3.5.1 Participants

A total of 38 participants (30 males and 8 females, unlike in the first experiment) aged between 20 and 40, were invited to participate. Among them were four postgraduates and ten graduates; the rest were undergraduates. Five subjects had previous experiences with haptic messages—all of them reported having used haptic vibrations in everyday life with smartphones.

3.5.2 Experiment Plan

We used the same materials as described in Section (3.4). Participants were invited to sit in a chair throughout the experimentation. An explanation followed by a demonstration was given to participants. Participants were also encouraged to ask questions if needed. Once this phase was completed, they were encouraged to wear the enactive shoe, and then the test began. The experiment was divided into three phases (selection of the tacton, association with a risk level, and recognition of tactons) described as follows:

1. **Selection of four Tactons among six (selection phase):** This selection is concerned with users' selection (Table 3.4 – (1)). The participants had to select the four most differentiable tactons (according to their own feelings) among the six suggested in Figure 3.3. Since Garzonis et al. Garzonis et al. (2009a) noticed that tactons' selection play an important role in recognition, each selection was recorded during the test phase for the next steps.

2. **Association of the four selected tactons to a risk level (association phase):** This association consisted in matching the four selected tactons to four potential risk levels (Table 3.4 – (2)). The association process was controlled to avoid duplication of participant' choices. These associations were recorded for the next step.

3. **Differentiation of the tactons (test phase):** Each tacton was randomly presented three times for recognition (Table 3.4 – (3)). For these 12 (three rounds $\times$ four risk levels) trials, we recorded the percentage of correct recognitions (the score). Since it was crucial for the participants to perfectly interpret the stimuli, we used a repetition to see if a recognition of 100% could be achieved. If the score was less than a threshold of 95%, the participant restarted the process (reiterated) until reaching this threshold. The number of iterations and the CT (Completion Time) were stored. The score was

displayed on the screen after each trial, and the participants got information about their performance. To avoid errors due to fatigue, participants could take a break of five minutes after the trial if they did not succeed.

3.5.3 Results

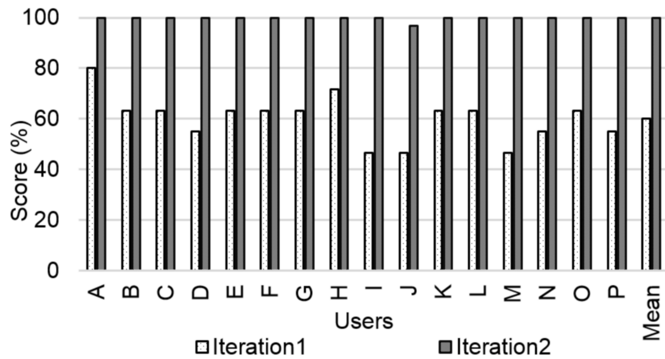


Figure 3.5: G_2 Score per recognition (two iterations)

For analytical purposes, we organized the presentation of our data according to the number of iterations it took to reach a score greater than 95% in five groups (G_1, G_2, G_3, G_4, and G_5). Figures 3.5 and 3.7 report respectively the score and the CT of participants of G_2 (two iterations). Also, Figures 3.6 and 3.8 report respectively the score and the CT of G_3 (three

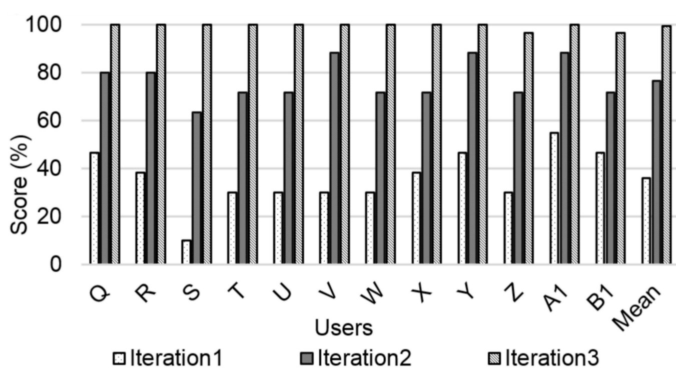


Figure 3.6: G_3 Score per recognition (three iterations)

Tableau 3.5: Score Mean and Completion Time Mean

IT \ G - N	G_1 - 5		G_2 - 16		G_3 - 12		G_4 - 4		G_5 - 1	
	S	T	S	T	S	T	S	T	S	T
1	99.30	50.30	60.50	60.80	35.90	36.90	16.40	39.80	30.00	17.10
2			99.80	61.80	76.50	67.40	44.60	54.50	46.70	20.70
3					99.40	61.70	63.33	46.90	63.30	30.33
4							98.30	41.40	80.00	25.65
5									96.80	22.07
SD	69.51	34.86	49.74	34.82	43.59	30.22	38.51	20.78	34.72	10.11
R^2					$y_3 = 31.75x + 7.1$		$y_4 = 26.44x - 10.45$		$y_5 = 16.69x + 13.29$	
					0.9748		0.9874		1	

IT= iteration, S = Score (Unit: Second), T = Completion time (Unit: Percentage),
N = Number of participant, *G = Group, SD = Standard Deviation, R^2= Coefficient of Determination*

iterations). Table 3.5 presents the mean score and CT of successful participants split into five distinct groups:

1. Group G_1 includes participants who succeeded with the first iteration (N = 5),
2. Group G_2 includes participants who succeeded with the second iteration (N = 16),
3. Group G_3 includes participants who succeeded with the third iteration (N = 12),
4. Group G_4 includes participants who succeeded with the fourth iteration (N = 4) and
5. Group G_5 includes participants who succeeded with the fifth iteration (N = 1).

All participants were able to identify more than 95% within five iterations, with an average of 2.47 ($\bar{x} = 2.47$) and a standard deviation of 0.98 ($\sigma = 0.98$). In the two extremes (Table 3.5), we have participants from G_1 and those from G_5. G_1 contains five participants of the 38 (i.e., 13%) whereas G_5 contains just one (2%). All participants in G_1 took more time than the other groups during the familiarization phase (7 minutes average for each participant of G_1).

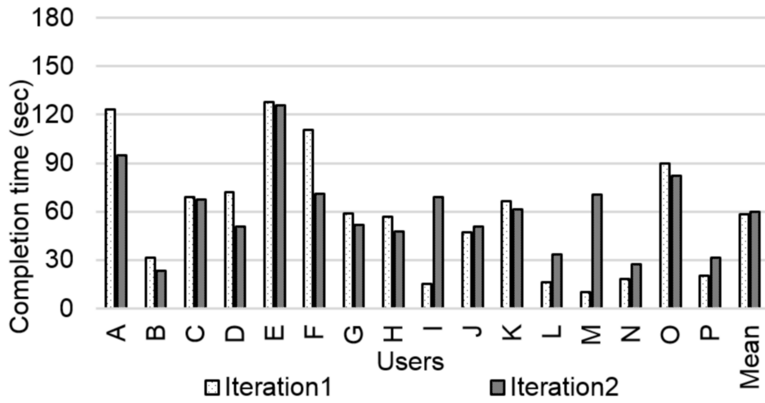


Figure 3.7: G_2 Completion time per recognition (two iterations)

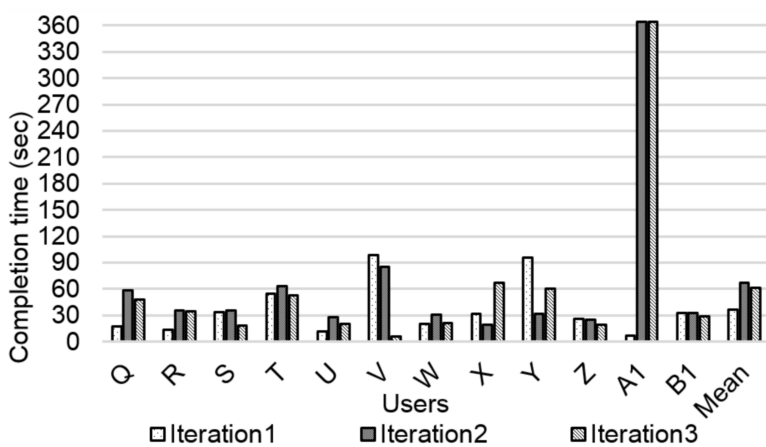


Figure 3.8: G_3 Completion time per recognition (three iterations)

According to Figures. 3.5 to 3.8 and Table 3.5, we can observe that G_2 obtained an average score of 60.5% (σ= 16.83) at the first iteration and 99.8% (σ = 23.97) at the second one. Participants in G_3 obtained at the first, second, and third iterations, respectively, average scores of 35.9% (σ =14.19), 76.52% (σ = 22.40), and 99.44% (σ = 27.33). G_4's results show that 4/38 (10%) of the sample took four iterations to successfully learn the tactons. The coefficient of determination (R^2) and equation of linear regression for G_3, G_4, and G_5's scores shows the strength of the relationship between scores and iteration (Table 3.5).

The next section describes a statistical analysis of these results.

3.6 Statistical Analysis

We had the following hypotheses:

1. **$\mathbf{H}_1$ hypothesis for score**

    - H_{01}: The null hypothesis (H_{01}): *iteration has no impact on the score*.
    - H_{a1}: The second hypothesis (alternative hypothesis H_{a1}): *at least one mean is not equal: iteration has an impact on the score*.

2. **$\mathbf{H}_2$ hypothesis for CT**

    - H_{02}: The null hypothesis (H_{02}): *iteration has no impact on completion time (CT)*.
    - H_{a2}: The second hypothesis (the alternative hypothesis H_{a2}): *iteration has an impact on CT*.

We assumed that, for the null hypotheses H_{01} and H_{02}, all means would be equal, and for the alternative hypotheses (H_{a1} and H_{a2}), at least one mean would be different from all the others. Our significance level is $\alpha = 0.05$. The independent variable was iteration (the number of trials to succeed), and our dependent variables were scores and CT. We had more than two groups (independent or not), and the dependent variables were quantitative. As the results were classified by group, we present the analysis that tested hypotheses for G_2, G_3, and G_4. Firstly, we used Minitab 17 to perform a T-test for G_2's results (two iterations), and secondly, a one-way analysis ANOVA1 for G_3 and G_4's results (three and four iterations), because we only have one independent variable.

3.6.1 T-Test Analysis

T-test of scores observed for participants in G_2: For participants in the group G_2, we observed at the first iteration an average of M_1 = 60.5% and a standard deviation of σ_1 = 16.8. At the second iteration, the average was M_2 = 99.7%, whereas the standard deviation was σ_2= 23.97. Our data's distribution was sufficiently normal for the purpose of conducting a T-test. Additionally, the assumption of homogeneity of variance was tested and satisfied via the F-test ($F_{(30)} = 174.96$, $p = 8.6 \times 10^{-13}$). The independent samples T-test was associated with a statistically significant effect $t_{(30)} = -17.39$, and p <0.05. Thus, the difference between S_1[1] and S_2 is significant. We can therefore say that iteration influenced scores.

T-test of CT observed for participants in G_2: For participants in the group G_2, we observed at the first iteration an average of M_1 = 59.88% and a standard deviation of σ_1 = 26.75. At the second iteration, the average was M_2 = 58.28 %, whereas the standard deviation was σ_2= 39.14. Using a significance alpha level of 0.05, the Anderson-Darling normality test for T_1[2] (A-Squared = 0.33, p-value = 0.47) and T_2 (A-Squared = 0.44, p-value = 0.25) indicates that the CT does not follow a normal distribution. However, the assumption of homogeneity of variance was tested and satisfied via the F-test ($F_{(30)}$ = 0.13, $p = 0.894$). Since the p-value is greater than the α level, there is no evidence for a significant difference in CT at the first iteration versus at the second iteration. Therefore, we fail to reject the null hypothesis H_{02}.

[1] *S_1, S_2, S_3, S_4, and S_5 are respectively the mean scores at iteration 1, 2, 3, 4, and 5.*
[2] *T_1, T_2, T_3, T_4, and T_5 are respectively the mean completion times in seconds at iteration 1, 2, 3, 4 and 5.*

3.6.2 One-way Analysis of Variance (ANOVA1) for G_3 and G_4

ANOVA1 of scores observed for participants in G_3: The p-value of ANOVA1 for G_3 score is lower than α ($F_{critical}$ = 3.28, F(2, 35) = 174.96; $p = 8.6 \times 10^{-13}$) with the effect size (ES) of 0.913. This result suggests that one or more means are significantly different. Using post-hoc Tukey's pairwise comparisons, it can be seen that there is a significant difference between (S_2 and S_1), (S_3 and S_1), and (S_3 and S_2). Thus, there is evidence that the S_1, S_2, and S_3 for G_3 are different. So, for G_3, we can reject the null hypothesis and confirm the alternative hypothesis.

ANOVA1 of scores observed for participants in G_4: The p-value of ANOVA1 for G_4 scores is also lower than α ($F_{critical}$ = 3.49, F(3, 15) = 15.76; $p = 1.8 \times 10^{-5}$), with an effect size (ES) of 0.6085. This result suggests that one or more mean scores are significant different. However, using post-hoc Tukey's pairwise comparisons, a significant difference can be seen between (S_3 and S_1), (S_4 and S_1), and (S_4 and S_2), but no difference between (S_2 and S_1), (S_3 and S_2), or (S_4 and S_3). Thus, there is evidence that the S_1 and S_4 for G_4 are different. We can therefore conclude that there is a statistically significant difference between the mean scores for G_4 (S_1 and S_4). So, for G_4, we can reject the null hypothesis and confirm the alternative hypothesis.

ANOVA1 of CT observed for participants of G_3 and G_4: We performed an ANOVA1 for G_3 and G_4. The results are reported in Table 3.6, which shows that all p-values are insignificant at the 0.05 level. Progression of CT is not like the progression of the score. Then for the CT there was no significant result for any of these groups. To sum up, we fail to reject the null hypothesis H_{02} for CT of G_3 and G_4.

Tableau 3.6: ANOVA1 Results for Completion Time (CT)

G_2	F(1,30)= .01	$F_{Critical}$ = 4.17	p-value = .893
G_3	F(2,33)=.48	$F_{Critical}$ = 3.28	p-value = .62
G_4	F(3,12)=.21	$F_{Critical}$ = 3.49	p-value= .88

3.7 Discussion

MDS analysis: MDS analysis allowed us to produce a set of effective tactons grouped into a family of six (A1, B1, C1, D1, E_1, and E_2), as shown in Table 3.2. The results from MDS analysis allow us to support the idea that various tactons should be proposed. This is in line with the analysis made in Garzonis et al. (2009a). Therefore, it seems that if a participant chooses tactons according to his own preferences and abilities to recognize them, the association should be easier to learn.

Impact of iterative learning on score: According to Figures. 3.5 to 3.8 and Table 3.5, the results (Section 3.5.3) show that the scores increased after each iteration. Scores tended to grow with a steep gradient after each iteration (Table 3.5) for G_1, G_2, G_3, G_4, and G_5. This is due to the fact that participants tended to improve themselves by trying to focus and get the right tacton associations. We understand that participants need to learn before becoming effective. Indeed, it has been shown that haptics is not quite adapted to identification but more to differentiation MacLean (2000). These results also show that practice may be very helpful for getting an excellent recognition rate in order to convey a risk level. For example, G_5's performance (2% of the participants had difficulties in succeeding) suggests that participants had to improve themselves in order to succeed. In particular, five iterations were sufficient to reach the goal. But only three iterations were statistically significant (G_2, G_3, and G_4). This suggests that performance increases with iteration. Therefore, according to the significant result of differences among the scores (S_1, S_2, and S_3) for G_3, we can conclude that the score has a significant effect after three iterations.

Impact of iterative learning on CT: We observe that for G_2, the CT just increases by one second between the first and the second iteration. However, G_3 achieves an increasing CT at the second iteration, then decreases on the third one. The same scenario is also observed for G_4. Lastly, G_5 achieves the same scenario as G_4 but with five iterations. We can assert that CT does not increase with iteration. Indeed, statistical analysis revealed that for G_3 and G_4 there was no significant results letting us assume that iteration has an impact on CT.

Communication of information: We were able to evaluate the effectiveness of communicating information (risk level) with six tactons using an enactive shoe. From the observed results, it appears that a significant average of three iterations is needed to learn to recognize at a rate of at least 95% tactons presented under the sole of the foot. After three iterations, participants were able to perceive risk level information with about 95% accuracy. It is therefore admitted that a learning phase, familiarization, and a mean of $\bar{x}= 2.47$ ($\simeq 3$ iterations) are needed to communicate a risk level consisting of a two-bit alphabet to the sole of the foot with an enactive shoe.

3.8 Limitations

Tactons selected by a perceptual map (MDS analysis) do not consider the context of use (knowing that participants completed the test while they were sitting). Therefore, we need a new assessment to design tactons that take into account the context of daily activities (for instance, with disturbance).

Moreover, participants voluntarily chose four tactons among six. This selection was made according to individual preferences. We do not analyze the selected tactons, nor their results.

However, considering these two possibilities in a future research could give information about people's tacton preferences and validate the effectiveness of these tactons' usability in everyday life.

Participants were sitting during the experiments. They will have to stand if we want to transmit information in a mobile context.

Our study does not report results on different foot positions, as done by Karuei et al. Karuei et al. (2011), nor on the disposition of Haptuators on the enactive shoe to increase the information transfer (IT) rate, as done by Tan et al. Tan et al. (2010). It will be important to evaluate the IT rate under the sole of the foot with six tactons discriminated with MDS analysis and to evaluate the actuators' location inside the insole to optimize perception. This will define some guidelines to design an enactive interface for the sole of the foot.

Further studies should analyze the results of the familiarization phase in order to find relevant results in practice. This would lead to produce a guideline on tacton preferences for the sole of the foot and enable their comparison with the studies of Velazquez et al. Velázquez and Pissaloux (2008); Velãzquez et al. (2009a). Also, a walking situation is influenced by the environment with some amounts of disturbance. For instance, an increase in the cadence (walking velocity) could influence the recognition performance negatively Meier et al. (2015b).

3.9 Conclusion and future works

This paper addressed the exploitation of tactons to communicate information in a two-bit alphabet (low, medium, high, and very high) via vibrotactile actuators embedded inside an enactive shoe. This haptic information is rendered to the sole of the left foot. From a set of 30 tactons, we conducted our first experiment to obtain a non-similarity matrix, which was necessary to construct a perceptual map. We extracted from this matrix six tactons (by means of an MDS analysis) that were the most likely to be easily differentiable. In order to evaluate how repetition affects the learning of these tactons, we conducted a second experiment using four tactons among the six to communicate a risk level to the sole of the foot. We found that repetition significantly improved the recognition rate of tactons but did not speed up the completion time (CT). These results suggest that a serious game might help people associate a tacton to a risk of falling. In fact, as the repetition does not help improve the CT, the fun aspect of the game should be valuable to help people facing such a time-consuming task. Given the limitations of this paper, in the near future, we plan to evaluate the impact of external perturbations in a controlled environment as well as the impact of the learning after a short (a few days) and a long (a few weeks) period.

Chapter 4

Impact of Auditory Distractions on Haptic Messages Presented Under the Foot

4.1 Abstract

When compared to vision and audition, communication capabilities of the haptic channel remain underexploited. In this paper, we investigate the impact of auditory distractions on the learning of haptic messages presented under the foot plantar. From a set of six haptic messages that have been designed in order to be easily differentiable one from another, participants have to select four. With and without the presence of auditory distractions, we evaluate the completion time and the number of iteration required to reach an identification rate greater than 95%. For both measures, we observed that having auditory distractions was detrimental to the performances of users.

4.2 Introduction

In human-machine interaction, to take advantage of full capabilities of human sensory-motor capacities main modalities (vision, haptics, and audition) are generally exploited. That defines a multimodal interaction. Like many researchers, we think that a modality is directly related to human senses (Fikkert et al., 2007). We define the modality as the form of exchange that can be established between a user and a digital system (Menelas, 2014). In contrast to the unimodal condition where only one form of communication is possible, in a multimodal rendering several forms of communication are available. When compared to the unimodal condition, the design of a multimodal rendering one has to take into account interactions that may exist between different channels. For Friedes, multimodality appears as an aggregate of several unimodal renderings, where each one has its own characteristics (Freides, 1974). Each channel must thus be assigned to the rendering of a particular type of information (Nesbitt et al., 2003). Bowman et al. Bowman et al. (2004) adopt a more general view by defining multimodality as the combination of several modalities that aims to provide a richer interaction. They recognize six types of multimodal associations: complementarity, redundancy, equivalence, specialization, competition, and transfer. Recently, beyond the interactions between the different modalities, Menelas showed that the task to perform played a preponderant role in a multimodal interaction (Menelas, 2014). He proposed a taxonomy based on the tasks that the user wants to achieve. All these studies focused on situations achieved in a controlled-environment (immersive room, work station etc.). Therefore, one question arises: what happens if one has to exploit a multimodal rendering in an uncontrolled environment like on the street or in public transport? In other terms, would the association of some rendering be detrimental to performances of users? We are interested in this situation, as our project concerns the use of the haptic feedback to communicate information to a user using an enactive shoe. This enactive shoe has been designed in order to prevent accidental falls

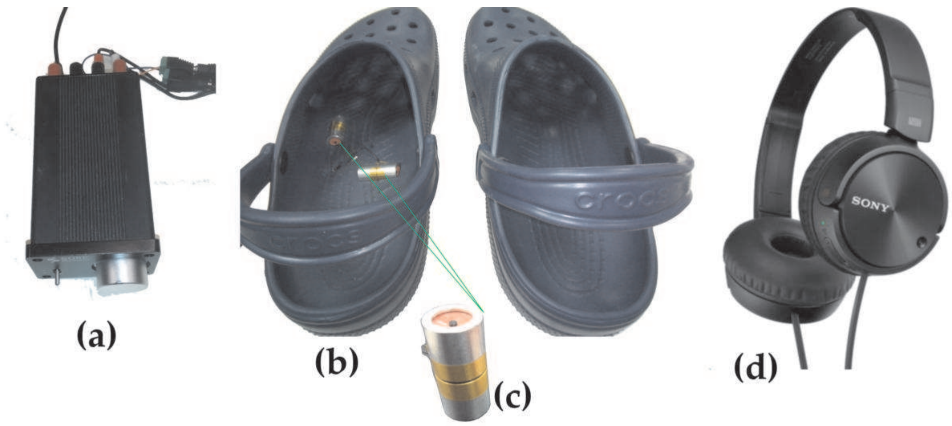


Figure 4.1: Enactive shoe system overview: (a) Audio amplifier to manage output signal. (b) enactive shoe: A rear strap enabling the shoe to be firmly strapped on the foot. (c) Haptuators mounted in the left foot. (d) Earphones to render auditory distractors.

(Figure 4.1) (Otis and Menelas, 2012; Otis et al., 2016; Ayena et al., 2016b). This device has a set of sensors used to characterize the dynamics of walking, the gait and physical properties of the environment (Otis et al., 2016; Ayena et al., 2016b). Besides, it regroups several actuators (notably a haptuator Yao and Hayward (2010)) aiming to transmit haptic signals to the user (see Figure 4.1). These signals will be used to alert the user to dangerous situations or to correct anomalies of his gait. In this sense, these signals appear as an aid aiming to assist the user (Otis and Menelas, 2012; Otis et al., 2016; Menelas and Otis, 2012). We are interested in transmitting these messages by the mean of haptic messages because this channel may allow to communicate with the person without preventing him from being fully aware of his external environment; as it could have been with visual or audible communications. Knowing that users will wear the shoe during walking (uncontrolled environment), the objective is to be able to transmit haptic messages that remain interpretable in spite of the distractions of the environment. While walking in a street, such distractions may be the walk in itself, visual or auditory stimuli. As a preliminary work, we investigate here how auditory distractions may impact the learning of haptic messages presented to the foot plantar via an enactive shoe. We have selected to study the impact of auditory distractions for two main reasons. Recently, Meier et al. Meier et al. (2015c) evaluated the suitability of vibrotactile feedbacks, in different areas of the body including sole of the foot and toe, as a mean of guidance. Their study suggests that, firstly, the foot provides the most promising results for the identification of vibration patterns while walking. Secondly, the use of vibrotactile feedbacks on the foot (side/sole/top) allows to reduce the stress and the need for visual attention. Other research has investigated the rendering of tactile stimuli via instrumented shoe.

The main contribution of this paper is to study the impact of auditory distraction on the identification of a *tacton* presented under the foot plantar.

4.3 Related Work

The study of haptics as an information mediation channel has focused on the hand (Brewster and Brown, 2004b; Chan et al., 2005). In this study, we are interested in evaluating the perception capabilities of the foot in the presence of distractive sounds. Following sections briefly, review the identification of haptic messages presented under the foot plantar and the impact of auditory distractions on the perception of haptic messages.

4.3.1 Identification of Haptic Messages Presented Under the Foot

When compared to other areas of the body, the use of foot for haptic perception remains limited. One of the first works on this topic studied the usability of an instrumented tile to mimic physical properties of soils such as ice, crack and sand (Visell et al., 2009). Later, Turchet et al. Turchet et al. (2013) observed that haptic feedbacks presented to the feet may enhance the realism of walking or simulate it. In the same way, Nordahl et al. Nordahl et al.

(2010) have studied the combination of haptic and sound feedbacks in order to simulate the sensation of walking on virtual surfaces. The haptic information was presented at the foot of the user through an instrumented shoe. The studies carried out indicated that subjects were capable to recognize most of the stimuli in the audition only condition, and some of the material properties such as hardness in the haptics only condition. Recently, Meier et al. Meier et al. (2015c) evaluated the suitability of vibrotactile feedbacks, in different areas of the body including sole of the foot and toe, as a means of guidance. Their study suggests that the foot provides the most promising results for the identification of vibration patterns while walking. Also, it indicates that the use of vibrotactile feedbacks on the foot (side/sole/top) allows to reduce the stress and the need for visual attention. Other studies have investigated the rendering of tactile stimuli via instrumented shoe. For instance, by using an array of sixteen dots of actuators, Velãzquez et al. (2009b) have shown that some geometric shapes could be discriminated in order to guide a blind person while walking.

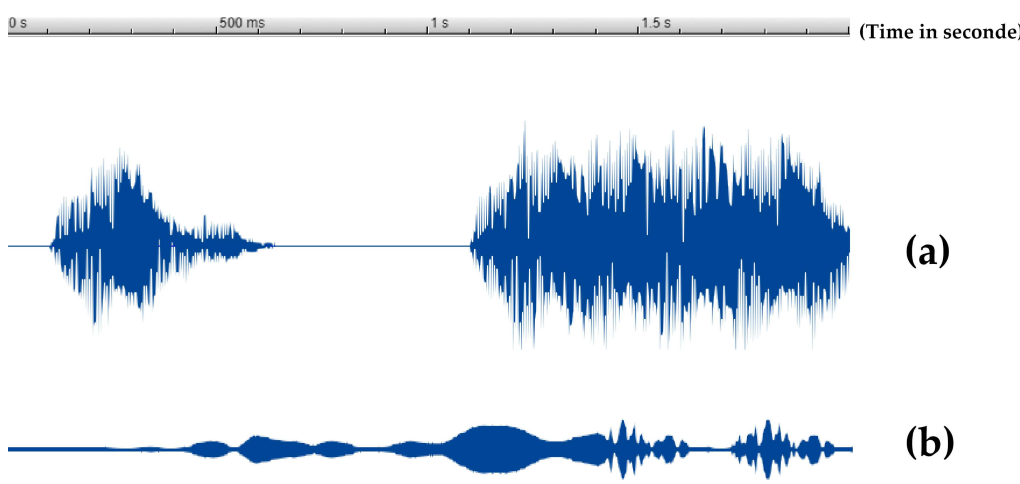


Figure 4.2: Auditory distractions send on participant's ear during the test. (a) Audio wave frequency of a car horn. (b) Audio wave frequency of approaching ambulance siren. Wave frequencies have been obtained using ®WavePad Sound Editor software.

4.3.2 Effect of Auditory Distractions on the Perception of Haptic Messages

There has been little work into how auditory distractions influence the haptic perception of a person on various work tasks. Chan et al. noted that the learning and identification capabilities of vibrotactile messages decreased significantly with the addition of visual and audible disturbing elements (Chan et al., 2005). Later, Tikka and Laitinien noticed that when interacting with mobile devices, auditory stimuli do biased the perceived intensity of haptic feedbacks (Tikka and Laitinen, 2006). In the same way, Qian et al. specified that the type of background sounds had a significant effect on identification accuracy, identification time, and probably on the cognitive workload as well (Qian et al., 2013). These results confirmed those presented in Oakley and Park (2008) where Oakley and Park showed that walking could significantly affect the ability to identify haptic messages. However, this work did not analyzed the level of external distraction that was tolerated nor the influence of age or training on the ability to identify haptic messages.

To the best of our knowledge, no research has yet investigated the impact of audible distractions on the perception of haptic messages presented via the foot. This work addresses this aspect. The next section describes the performed experiment. We ended with results and discussion. The evaluation with participants was approved by the local Ethical Committee of the University of Quebec at Chicoutimi (certificate number 602-462-01).

4.4 Exploited Signals and Apparatus

Two types of signals are exploited in this study: Haptic messages and auditory distractions. The haptic channel is used as a communication medium whereas audio signals are exploited as distractors.

4.4.1 Selected Tactons

Given that the cutaneous sense, a rich and a powerful communication medium, remains underexploited when interacting with computers Menelas et al. (2014), we want to exploit haptic messages to communicate with the user throughout the foot. For this, we are interested in using mechanoreceptors situated under the foot plantar. They are responsible for sensing and transmitting physical deformations, caused by external forces, to the nervous system (Velãzquez et al., 2009b). To ensure the ability to transmit tactile information to the user, the haptic messages used in this study are *tactons*. Brewster and Brown Brewster and Brown (2004b) defined *tactons*, or tactile icons, as structured, abstract messages that can be used to communicate messages non-visually. Here we use a set a six *tactons* represented in Table 4.1. They are coming from a previous study Menelas and Otis (2012) and they are designed to be easily differentiable. They will be used to convey the information of a two-bit alphabet. From this set of six *tactons* (T_1, T_2, T_3, T_4, T_5, and T_6), participants have to choose four preferred considered to be the most different. We allow participants to express their preferences among a set of six *tactons*, based on the work reported in (Garzonis et al., 2009b). These authors have observed that there is a strong positive correlation between preference and successful identification of auditory notifications. The six proposed *tactons* are shown in Table 4.1.

4.4.2 Selected Auditory Distractions

We used two auditory distractions (see Figure 4.2). They are external noise commonly heard in everyday life. The first metaphor mimics the sound of a car horn and the second is an approaching ambulance siren. The duration of each stimulus is two seconds, with an intensity of 60 dB SPL. To avoid abrupt noise onsets, noise distractions intensity increased gradually. The auditory distractions are presented continuously during the test in the associated condition.

Tableau 4.1: Proposed Tactons

Name	Equation
T_1	$\sin(180\pi t)$
T_2	$\sin(6\pi t)\sin(122\pi t)$
T_3	$\sin(12\pi t)\sin(122\pi t)$
T_4	$\sin(62\pi t)\text{square}(50\%;71)$
T_5	$(-t^2+0{:}5)\,\sin(120\pi t)$
T_6	$t^2\sin(120\pi t)$
	$t = [0 : 1/9600 : 1]$ sec.

4.4.3 Apparatus

To render the *tactons*, we use an enactive shoe with two Haptuators as shown in Figure 4.1. Haptuators are vibrating devices directly in contact with the foot plantar of the participant. The Haptuator is discreet and fits well in the designed enactive shoe. The sound card of an Android smartphone is exploited to transmit the *Tactons*. These signals are then amplified (by an audio amplifier showed in Figure 4.1 - a) and sent to both Haptuators in (Figure 4.1 - c) embedded into a shoe (Figure 4.1 - b).

We use a Sony Noise Canceling Headphone, Black - MDRZX110NC (Figure 4.1 - d) in order to render a distracting auditory and canceling external noise to participants.

4.4.4 Positioning the Haptuator Under the Foot

We perceive and distinguish various tactile feeling on the skin by touching. We know that people can easily discriminate a very fine signal of a surface thanks to the tactile feeling. For instance, it is reported that our finger can distinguish a micron order difference of surface roughness of sandpapers (Asamura et al., 1998). This differentiation is possible thanks to the mechanoreceptors located under the skin. Indeed, Pasquero reported that mechanoreceptors are characterized by the size of their receptive field and their adaptation rate to a stimulus (Pasquero, 2006). Types I allows to discriminate small and well-defined borders while types II intervene for large and poorly-defined borders. Also, Velazquez and Pissaloux reported that mechanoreceptors of the foot plantar are usually classified based on their rate of adaptivity and receptive field (Velázquez and Pissaloux, 2008). Generally, there are four types of mechanoreceptors in the foot plantar: slow adapting type I (SAI), slow adapting type II (SAII), fast adapting type I (FAI) and fast adapting type II (FAII) (Velázquez and Pissaloux, 2008). Only two afferents, one FAI and one FAII, have the receptor terminal on the hairy skin of the calf (Kennedy and Inglis, 2002). Then, it seems that stimulation of FAI mechanoreceptors is more suitable for transmitting information to the foot (Velázquez and Pissaloux, 2008). However, Kaya has identified some interesting features: The FAIs are the Meissner corpuscles that best respond to light touch, and the FAIIs are the Pacinian corpuscles which are best for vibrations (Kaya, 2014). The position of the haptuators has been selected in order to be in contact with FAI and FAII. Hence, a better perception of the signal is expected. In order to convey the same vibration with a quick perception, the transmitted signal will be identical on both haptuators and will be located on FAIs and FAIIs.

4.5 Experiment

The experiment aims at measuring the impact of auditory distractions on the learning of *tactons* presented to the foot. Participants have to learn to identify four *tactons* presented on the foot plantar. To reflect a real-life situation, we assess how everyday sounds do impact performances of their task.

Two experimental conditions are specified: with audio distraction (AD) and with no distraction

(ND). Namely, in the ND condition, only the *tacton* is rendered via the enactive shoe. In the AD condition, during the rendering of the *tactons* under the foot plantar, auditory distractions described previously are also rendered through the headphone. For both conditions, we evaluate the performances of participants to identify four *tactons* specifically the completion time and the number of iterations required to reach an identification rate greater than 95%.

4.5.1 Participants

A total of 38 participants (21 males and 17 females) aged between 20 and 40, took part in the experiment. In this set of participants, one counts four postgraduates and ten graduates. The others are undergraduates. Based on our pre-experimental questionnaire, five participants had previous experiences with haptic messages. The later reported having used haptic messages in everyday life with smartphones. More importantly, all participants reported normal levels of auditory and tactile perception. Figure 4.3 shows a participant experimenting the system.

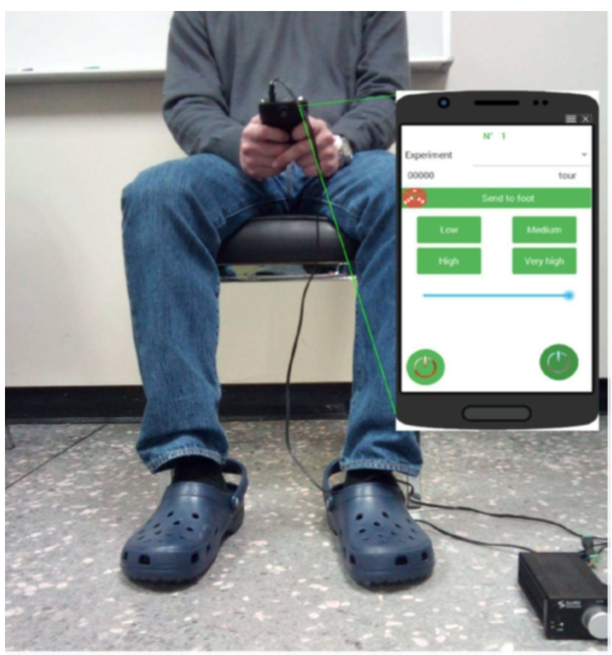


Figure 4.3: Experiment setup while no distraction condition. A seated participant performing the test with the device mounted on the left foot.

Participants are randomly divided into two groups (G_1 and G_2) of 19. To minimize learning effect, participants of G_1 completed the test in the ND condition (No Distraction) then in AD condition (with Audio Distraction). Participants of the second group G_2 performed the test in the opposite order.

4.5.2 Experimental Plan

Materials described previously are employed for this experiment. At the beginning of the test, participants are invited to sit. The details of the experiment are presented. They are also encouraged to ask questions if needed. After all, they are asked to sign the associated consent form. Subsequently, participants have to wear the described enactive shoe. At this stage, each participant is invited to choose four *tactons* among the six described at subsection 4.4.1. To do this, the participant uses a software running on an Android device. It allows to render *tactons* by touching buttons on the screen of the mobile device. Afterwords, the evaluation begins.

The evaluation consists of several trials where the participant seeks to correctly identify the *tactons* rendered via the enactive shoe. For each participant, the total number of trials required will be the number of rounds that this participant needs to achieve an identification score greater than 95 %. For each trial, the participant is asked to randomly identify each *tacton* three times. Hence, a total of twelve identifications have to be made. For each trial, we record the identification score, the number of iterations, and the completion time taken to complete theses twelve identifications (Duration). The percentage of correct identification is defined by the ratio between the number of correct identification and 12.

Tableau 4.2: Results summarized and presented for both conditions

ND condition			AD condition		
Participants	Iterations	Durations	Participants	Iterations	Durations
5	1	32.394	3	1	101.47
17	2	45.79	20	2	81.63
12	3	30.75	4	3	86.99
4	4	44.43	4	4	78.89
4	5	20.82	1	5	78.35
			1	6	75.22
			1	7	85.76
			1	8	64.16
			1	9	58.36
			1	12	102.88

4.6 Results and Discussion

4.6.1 Results

All participants successfully completed the test with an average time of 30 minutes. Regarding the number of iterations required to achieve an identification rate greater than 95%, in ND condition the average iteration is 2.47. It rises to 3.32 when auditory distractions are presented. In the same way, the average duration to complete all identifications rise from 38 sec in ND condition to 82.36 sec in AD condition. Results are reported at Table 4.2.

For both factors, we observed that having auditory distractions negatively affects the identification of *tactons*. In the ND condition, five participants completed the test at their first iteration. A maximum of five iterations have been required by one participant. Among the participants, we observed that the shortest duration was 51 sec. whereas the highest was 149 sec. On the other hand, in the AD condition, three participants completed the test at their first iteration. A maximum of twelve iterations has been required by one participant. For comparison, one notes that in the AD condition, six participants completed the test in six or more iterations. No participant required so many iterations in the ND condition. In terms of duration, in the AD condition, among the participants, we observed that the shortest duration was 54 sec whereas the highest was 271 sec.

In general, we see that participants required more iterations (12 iterations) in condition AD than in the condition ND (5 iterations). Looking at participants' performances (iteration and duration), Figure 4.4 shows that the duration of the AD condition is generally the biggest. This can be confirmed by the fact that participants took more iteration to succeed (Figure 4.5).

Tableau 4.3: Two-sample T-test results for H_1 and H_2 hypothesis

Summarized data	AD*		ND*	
	Iterations	Durations	Iterations	Durations
Sample size	38	38	38	38
Mean	3.32	82.36	2.47	38
SD	2.48	20.76	0.951	19,94
SE Mean	0.4	1.9	0.16	5.7

* AD= Auditory distraction condition; ND= No Auditory distraction condition.

In terms of number of iterations, in the ND condition, (Figure 4.4 and Figure 4.5 - b), we see that five participants completed the test at their first iteration. 17 participants had to go to a second iteration. 12 participants completed the experiment after three iterations while four made it after four iterations. Only one participant succeeded with five iterations. All

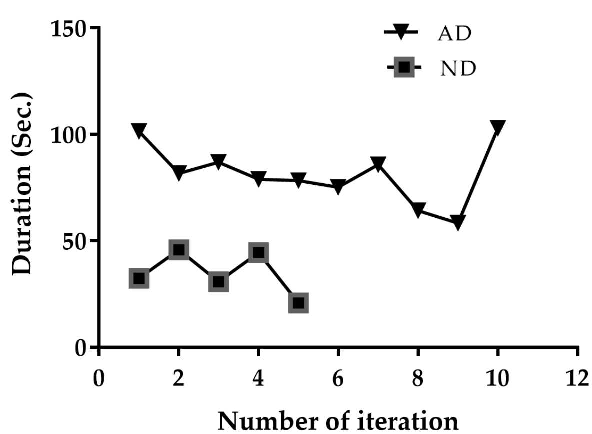


Figure 4.4: Summarized results of durations (AD vs ND) and iterations (AD vs ND)

corresponding durations are reported in Table 4.3.

In terms of iteration, in the AD condition (Figure 4.4 and Figure 4.5 - a), we see that three participants completed the test at their first iteration. 20 participants had to go to a second iterations. But four participants had to go to the third and the fourth iteration. Finally, only one participant succeeded with five, six, seven, eight, nine and twelve iterations. All corresponding durations are reported in Table 4.3.

4.6.2 Statistical Analysis

We are looking for the effect of each independent variable in each condition of the experiment. We have one assumption: Do distractions have any effect on the identification of *tactons*?

In this analysis, we want to study the effect of auditory distractions on the identification of

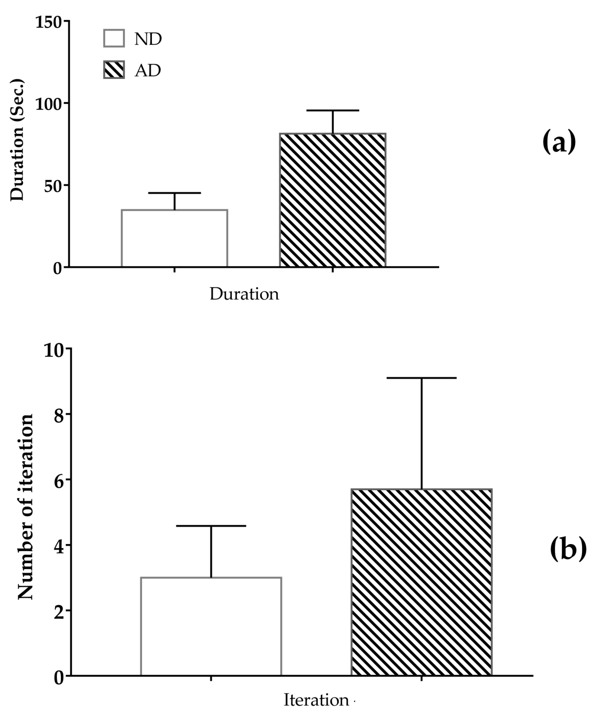


Figure 4.5: Performance of participant on both conditions [Auditory Distraction (AD) vs No auditory Distraction (ND)] : (a) Number of iterations by participants; (b) Duration by participants

the *tactons*. Identification of *tactons* can be achieved in one or many iterations with different completion times. Our independent variables are therefore iteration and completion time (duration). The results of the T-test presented here will validate the following hypothesis tests:

1. H_1 hypothesis for effect of the auditory distraction on the number of iterations
   (a) H_{01} The null hypothesis: The auditory distraction has no effect on the iteration.
   (b) H_{a1} The alternative hypothesis: The auditory distraction has an effect on iteration.
2. H_2 hypothesis for effect of auditory distraction on the completion time
   (a) H_{02} The null hypothesis: the auditory distractions has no effect on the completion time.
   (b) H_{a2} The alternative hypothesis: The auditory distraction has an effect on completion time (duration).

Our approach is as follows. We assumed that for the null hypotheses (H_{01} and H_{02}), all means are equal and for the alternative hypothesis (H_{a1}, and H_{a2}) at least one mean is different from another. Our significance alpha level is 0.05. The dependent variable is "distraction" and our independent variables are "iterations" and "durations" to recognize stimuli. To evaluate hypothesis H_1 and H_2 two T-test are conducted for the two conditions (with audio distraction and without distraction). The sample observation is N=38.

T-test of the Number of Iterations on Two Conditions (ND and AD)

A paired-samples T-test was conducted to compare the number of iterations to succeed the test in two conditions (with audio distraction (AD) and no distraction (ND)). Results of this analysis are reported in Table 4.3. There was a significant difference in the number of iterations t(37)=2.359, p = 0.023. Indeed, the mean of the differences between factor is 0.842 located into the 95% confidence interval (0.119, 1.565). The boxplot displaying the mean of iteration's variation on both conditions is presented in Figure 4.6. These results suggest that the audio distraction does have an effect on the number of iterations. Specifically, observed results suggest that when humans are exposed to auditory distractors, the number of iterations to learn stimuli increases. Since the p-value is greater than our alpha level (α=0.05), then we can say that we failed to reject the null hypothesis H_{01} and validate the H_{a1}.

T-test of the Duration on Two Conditions (ND and AD)

A paired-samples T-test was conducted to compare the completion time (duration) to succeed the test in two conditions (audio distraction (AD) and no distraction (ND)). Results of this analysis are reported in Table 4.3. There was a significant difference in the duration t(37)=11.099, p = 2.48×10^{-13}. Indeed, the mean of the differences between factor is 43.866 located into the 95% confident interval (35.857, 51.874). The boxplot displaying the full range where the duration varies is presented in Figure 4.7. These results suggest that the audio distraction does have an effect on the duration taken by participants to recognize vibrotactile messages. Since the p-value is greater than our alpha level (α=0.05), then we can say that we failed to reject

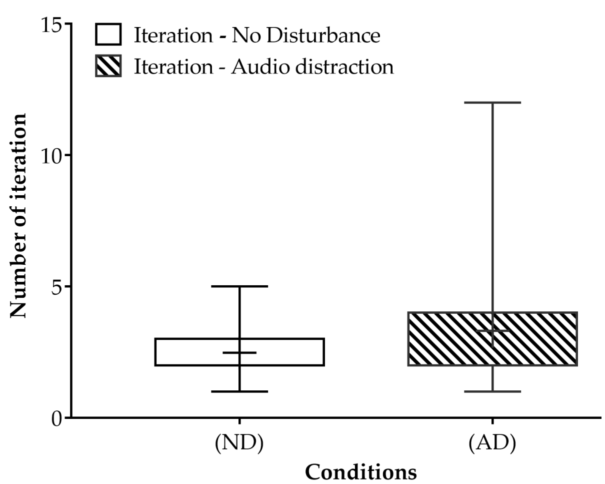


Figure 4.6: Boxplot of iteration (AD vs ND)

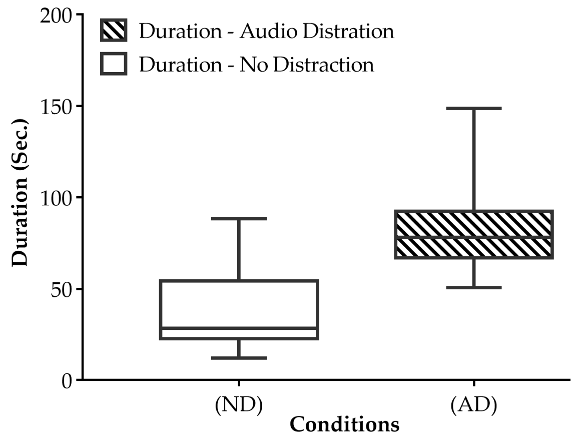


Figure 4.7: Boxplot of duration (AD vs ND)

the null hypothesis H_{02} and validate the H_{a2}.

The validation of this hypothesis thus becomes a major fact for the transmission of information using the haptic channel to the foot with auditory distraction. However, in our study, we simulated auditory distraction, but it would be interesting to confirm these results in a non-controlled external environment.

4.6.3 Discussion

In this research, we have evaluated two main hypothesis. The first one was referring to the possibility of auditory distraction to influence the number of iteration. According to results exposed in the previous subsection, it is clear that the audio distractions does have a significant effect on the number of iteration.

These results are in line with the study of Qian et al. suggesting that background sound has a significant effect on the identification time (Qian et al., 2011). Considering that the position and the types of device exploited in these studies are different this suggests that observed results may be extended to other body parts. Of courses, more studies are required to validate such observations. Mainly, considering that haptic interactions are likely to be used in wearable devices, the impact of external auditory perturbations has to study in detail.

On the basis of these results, it therefore appears that to complete this study: two aspects have to be investigated. They are: the impact of walking and the influence of aging on haptics perceptions. These aspects will be investigated in a future work.

4.7 Conclusion

This paper was aimed at measuring the impact of auditory distractions on the learning of haptic messages presented to the foot. 38 participants took part in the experiment while being at sited in a quiet position wearing the enactive shoe. They have to learn to identify four *tactons*, among a set of six, presented under the foot plantar. To reflect a real-life situation, we assess how everyday sounds do impact the performances of their identification task. For this, for two conditions: with and without auditory distractions, we evaluated how much iteration and time are required to reach a recognition rate greater than 95%? Results showed that both iteration and completion time are negatively affected by the presence of auditory distractions.

In a near future, while sending a haptic message on the foot, one extension of this study, on one hand, will be to evaluate the impact of external disturbing factors occurring in everyday life like walking task, cognitive task (counting and counting down). On another hand, we plan to identify haptic messages while walking on different types of soil in a noisy environment with youth versus elderlies participants.

Chapter 5

Simple Reaction Time to Vibrotactile Stimuli

5.1 Abstract

This study investigates the Reaction Time (RT) to vibrotactile messages presented under the foot plantar on different types of soil. We determine whether the reaction time varies while walking on different types of soil (mobile situation). A total of six young participants (n=6) aged between 21 and 28 took part firstly in this study where they had to walk on five types of soil (concrete, carpet, foam, gravel, and sand). The methodology includes 360 repeated measures. The findings have consistently revealed a decrease of the reaction time to vibrotactile messages when walking on the three deformable soils (foam, gravel, and sand).

5.2 Introduction

With aging, many features that intervene in the postural control decline (Hay et al., 1996; Teasdale et al., 1991), it results that, the incidence of falls is more than 30 percent per year for people over 65 years old (Ganz et al., 2007). In this group of the population, falls can cause physical injuries including fractures, reduce functionality, admission to a nursing home and sometimes death (Ménélas and Otis, 2015).

RT plays a very important role in our lives as its practical implications may be of great consequences. Hyman mentioned that RT is a linear function of stimulus information expressed in bits for the special case in which response and transmitted information are each equal to stimulus information (Hyman, 1953). Bricker noticed that the amount of information an organism must process or transmit is the crucial determinant of RT (Bricker, 1955). The RT is a direct consequence of the time taken to transmit the stimulus measured by the skin mechanoreceptors along the nerve to the brain and the response given to the neuromuscular system until the first action of the muscles involved in postural control. Psychologists have named three basic kinds of reaction time experiments: Simple Reaction Time (SRT), Recognition Reaction Time (RRT) and Choice Reaction Time (CRT) (Bricker, 1955; Kosinski, 2008). In a RRT situation, there are some stimuli that should be responded to, others that should get no response but there is still only one correct answer (Kosinski, 2008). In CRT experiment, there are multiple stimuli, and each stimulus requires a different answer (Kosinski, 2008). Based on reaction time's definitions provided by (Kosinski, 2008), we will position our evaluation within the framework of a reaction time (RT) because when there are only one stimulus and one response (feeling or not) within a walking process . Our methodology is concerned with reaction time (RT) while walking in various types of soil.

Prior to our study, there is no significant traceable thread in the literature about evaluation of the RT to a vibrotactile message presented under the foot while walking on five different types of soil. We want to analyse the time needed to perceive a message sent to the sole of the foot during walking. We hypothesized that, RT, is greater when we have more difficulty to walk on a type of soil. In other words, RT depends on the types of soil. To this, we want investigate the impact of RT to vibrotactile messages presented on the foot when walking on five types of soil.

This study is organized as follows: in the second section, we present related works, then follows the third and fourth section where we present our methodology with a full description of the experiment. The obtained results are presented in the fifth section and discussion follows in the sixth section. Finally, we present conclusion and further research in the seventh section.

5.3 Realated work

In this section, we will analyze studies related to RT in order to convey vibrotactile messages under the foot plantar on different types of soil.

5.3.1 Reaction Time in Medical Applications

RT has been extensively investigated for many years in medical applications for instance to influence the balance ability (Kosinski, 2008). Also, Reaction time (RT) is one of the most important parameters used in psychology to evaluate human tasks (Kosinski, 2008). Various studies have measured the fastest response time to the human touch at about 155 milliseconds (Robinson, 1934; Welford, 1980b). Braverman et al. showed that a RT test is an accurate predictor of early attention complaints and memory impairments (Braverman et al., 2010). Moreover, Gorus et al. showed that participants with cognitive deterioration demonstrated more slowing RT than healthy elderly(Gorus et al., 2008). Recently, Jain et al. studied a comparison of visual RT (VRTs) and auditory RT (ARTs) on the basis of gender and physical activity levels of participants (Jain et al., 2015). Participants were asked to concentrate on the fixation cross and press the “space bar” key, as soon as possible once target stimulus appears on the screen. They found a significant difference between RT of male and female students. In addition, significant results were found for the ARTs, which were faster than the VRTs. It is known that the RT has a direct impact on the risk of falling (Barr et al., 2014). For instance, Lajoie et al. investigated with two groups (fallers and non-fallers) the possibility to get a basic variable to predict the risk of falling (Lajoie et al., 2002). Results showed that RT is an interesting predictor of falling in the elderly, due to the sensory and motor components associated. Given that in everyday life, many falls occur on different types of soil (Ayena et al., 2015),(Otis et al., 2016) or when walking on a stairway (Jackson and Cohen, 1995), the communication of a vibrotactile signal could be influenced by the RT of the person as well as the types of soil on which they are walking. The literature highlights usability of SRT on medical applications (balance impairment, auditory, and visual task) but not the evaluation of a simple RT to vibrotactile messages on the foot. As far as the RT from different stimuli is concerned, the literature is mature but, the above studies did not consider the specific case that we are investigating here.

5.3.2 Foot Reaction Time

under the foot on different types of soil has resulted in some interesting initiatives for investigating foot RT experiment and methodologies. Montés-Micó et al. investigated the difference between the eye-hand and eye-foot visual RT among young soccer players versus non-soccer players (Montés-Micó et al., 2000). Eye-hand and eye-foot visual RTs were determined by means of a computer-controlled stimuli device. Results showed firstly that there are statistically significant differences between eye-hand and eye-foot RTs between players and non-players of soccer. Secondly, the results demonstrated a fast SRT time with soccer players. Recently, Mali et al. conducted a study to compare Visual Reaction Time (VRT) and Auditory Reaction Time (ART) of hand and foot in young adults before and after physical training (Mali et al., 2013). VRT and ART were determined with the help of an electronic instrument “Response Analyzer”. Results show that both VRT and ART were significantly decreased in all four limbs after physical training of six months. Pfister et al. compared Reaction Response Time (RRT) between hand and foot with a controlled devices for medical application (Pfister et al., 2014). To evaluate RT they assumed that, for physiological, anatomical and ergonomic reasons, the time required to release a switch with the hand is shorter than the time required to release a switch with the foot. They tested both the dominant and non-dominant hands and feet by performing the “Kick-Test” for each participant. Results demonstrate a significant faster RT with the dominant extremity and Simple Reaction Time (SRT) test demonstrates significant faster RT of the hands compared to the feet. All these studies focused on foot RT, but not on the case, which interests us here, namely, conveying a risk level of falling under the foot plantar while walking on different types of soil.

5.3.3 Reaction Time in Communication of Information

It is known that many factors do affect RT (Kosinski, 2008). RT has been widely used to convey information, to test how rapidly stimuli information can be processed and a response to it can be activated (Luce, 1986). Some studies have used SRT when work requires performance in a dual task to assess the risk of falling. This paradigm is called a probe RT. This is the case of Ming et al., they studied physical and cognitive factors associated with falls by the elderly by evaluating the probe reaction time (P-RT) (Hu et al., 2009). They used a wearable trial tool, easy to use and useful for the evaluation of the risk of falling and they discuss the relationship when walking between simple RT, probe RT and participant’s risk of falling. Results showed that probe RT is useful for the evaluation of the risk of falling and when the attention demands while walking increase. Niemi and Näätänen stated that a typical SRT includes many factors that can be varied on several parameters: the warning signal (WS), the foreperiod (FP), the reaction stimulus (RS), the response (R), and the intertrial interval (ITI) (Niemi and Näätänen, 1981). For instance, Drazin evaluated the relationship between RT and foreperiod (Drazin, 1961). Also, Peon and Prattichizzo (Peon and Prattichizzo, 2013) studied RT during conveying information by comparing different sensory modalities (vibratory, auditory and visual). Results showed that the haptic canal (strong modality) can provide faster RT than the auditory one.

These studies investigated the risk of falling by evaluating SRT with various tools for communicating information by the visual, audio and haptic canals. However, these studies have focused attention on RT in various conditions, with factors like hand, finger, and foot. Obviously, they did not assess the impact of the type of soil, nor the evaluation of RT while walking (for mobile application). The haptic canal can be used for RT experiment, but in this study, we will use an RT experiment to convey vibrotactile messages under the foot aimed at alerting the user (De sa and Carrico, 2011). Our approach differs in the sense that we are planning to exploit the haptic modality to convey information under the foot plantar on different types of soil. This paper is intended to evaluate the RT when transmitting a vibrotactile message under the sole of the foot on different types of soil.

To sum up, they are various applications of RT.. Several researchers have investigated the RT but about the impact of RT vibrotactile messages on various type of soil the literature still young. The vibrotactile message in everyday life could be used to inform the participant of important information about a physical situation (in balance or not) or an external environment (an alert). Moreover, in an uncontrolled environment, people walk on different types of soil without paying attention to the impact of that type of soil on their balance. Their attention is often occupied by a secondary task after walking. Then, it is therefore important to investigate the impact of types of soil affecting RT when conveying vibrotactile messages while walking.

5.4 Evaluation Setup Of The RT to Vibrotactile Message

The aim of this experiment is to evaluate the RT to a vibrotactile message presented under the foot plantar while walking on different types of soil.

5.4.1 Participants

Six young students from the University of Quebec at Chicoutimi participated in the study. They were recruited by means of a general invitation to participate in a study related to the reduction of the risk of fall. All the youths attended the session voluntarily. The participants were aged from 21 to 28 (two female and four male). All were novices to haptic technologies. For health issues, all participants were instructed to wear socks and we cleaned all components after each session. Before the experiment, they were totally naive about all aspects of the test and were given general instructions concerning the task. All participants follow up an interview including a questionnaire and none of them reported any problem with foot sensitivity. All volunteers involved in this study were informed about the experimental protocol and gave written consent before participating. The experience and consent form had been previously approved by the local ethics committee (certificate number 602.434.01).

5.4.2 Apparatus

For this experiment, we use an enactive insole developed in the laboratory (Figure 5.1 c). It consists of an insole device equiped with two Mark II Haptuators. The haptuator is a high-bandwidth, iron-less, recoil-based electromagnetic vibrotactile actuator (Ellis et al., 2011). It

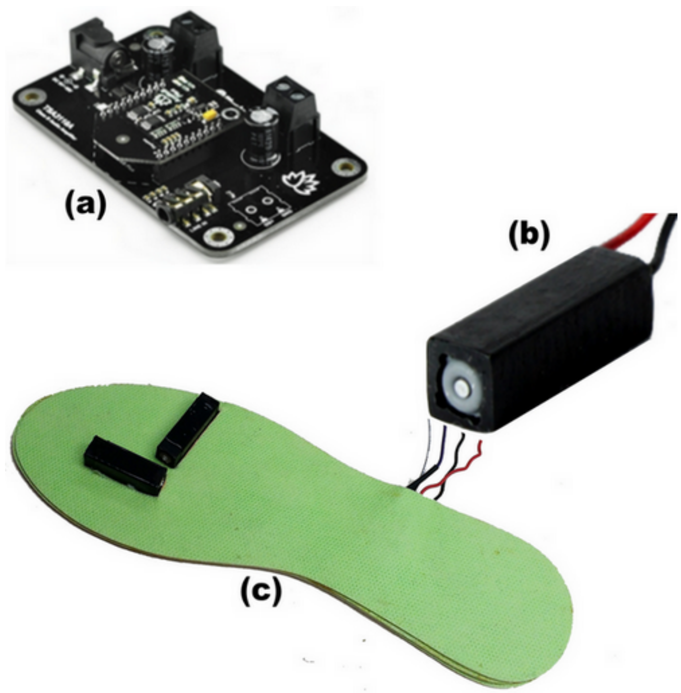


Figure 5.1: Enactive insole: (a) signal amplifier; (b) Mark II haptuator; (c) insole.

is driven as a common loudspeaker. (Figure 5.1). The smartphone is fixed at the ankle (Figure 5.2). Measurements are performed between 60 to 362 Hz since the optimal response of the vibration receptors (Pacinian corpusles) is reported to be at frequencies between 10 – 500 Hz (De sa and Carrico, 2011).

Figure 5.2: Positioning of the enactive insole on the foot: (a) signal amplifier is fixed on the ankle; (b) Enactive insole is wear into the shoe.

For the experiment, users have to walk on several types of soil representing the natural flooring surface materials that we commonly find in the daily life: concrete, foam, carpet, sand, and gravel (Figure 5.3 3). We have designed a longitudinal and wooden partitioning device to accommodate selected sole types (Length =5m, Width =1m Height =0.05m). We filled each partition with real materials.

5.4.3 Exploited Vibrotactile Messages

A set of four vibrotactile messages is proposed in the experiment. They are based on the same rhythm signal and duration of one second. They are designed according to various studies of psychophysical perception reported in (Visell et al., 2009; Menelas and Otis, 2012). The waveform of each vibrotactile message is described by equation (Table 5.1). W_1 defines a pure sinusoidal wave (121 Hz). W_2 is an amplitude modulation of W_1 by 60 Hz of pulsing vibration. W_3 is a modulation of W_1 by a 3 Hz sinusoid of rapid impulse vibration. W_4 is a 53 Hz sinusoid modulated by a 31 Hz of rough vibration sensation. W_5 is a Gaussian function where a, is the amplitude of the signal, e is the Euler number, b is the position of the center of the peak, and c adjust the bandwidth of the function. W_6 is a sinusoid modulated by a quadratic function providing an increasing or decreasing tactile sensation.

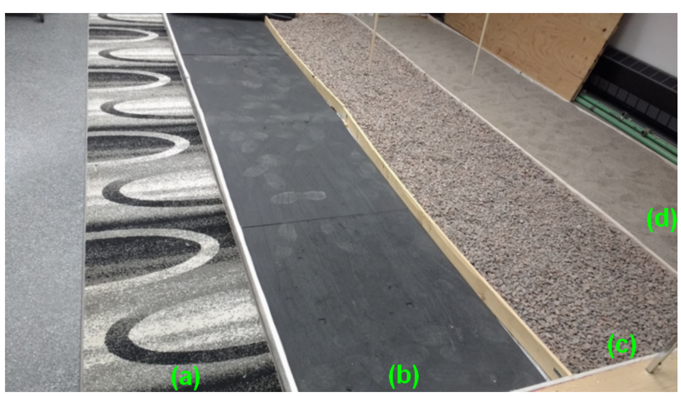


Figure 5.3: Types of soil. Left to right: (a) Concrete, (b) Carpet, (c) Foam, (d) Gravel, (e) Sand.

Tableau 5.1: List of equation of tactons

Equation	Number
W_1 = a sin(2π121t) W_2 = a sin(2π60t) sin(2π121t)	(1) (2)
W_3 = a sin(2π3t) sin(2π121t)	(3)
W_4 = a sin(2π31t) sin(2π53t)	(4)
$W_5 = ae^{\frac{(x-b)^2}{2c^2}}$	(5)
W_6 = (-t2 + 0:5) sin(2π60t)	(6)
with t = (0: 1=9600: 1) sec.	

5.4.4 Evaluation Procedure

At the beginning of the experiment participants are seated, wearing an ear protection and the enactive insole on the left foot. They are then invited to select four among the six vibrotactile messages. Thereafter the evaluation starts.

Participants have to walk on the 5 types of soil (Figure 5.3). Three trials are needed on each soil. For each trial selected messages are randomly conveyed under the foot plantar. Doing so, 360 repeated measures (6 participants $\times$ 5 types of soil $\times$ 3 trials $\times$ 4 messages) are performed.

Whenever the participant perceives a message he/she is instructed to lift the foot as quickly as possible. We have adopted this method to ensure that the gesture performed with the foot corresponds to the member who is solicited and to obtain an optimal reaction time. Indeed, we could have just asked the person to press a button with the hand. But here we want to ensure a faster reaction time following the distance of the nerve impulse caused by the vibration on lower limb excited. The RT is computed by calculating the acceleration of the foot movement. The accelerometer attached to the foot is used to determine the real time of the stimulus perception through the speed of movement of the foot. The acceleration (m/s2) was recovered on the three axis x, y, z and was compared with an acceleration threshold value. If the value of the acceleration on one axis were equal to the threshold, the identification time (t_2) would be saved and we would compute the RT with the initial time of the stimulus conveyed (t_1): $RT_i = t_{i2} - t_{i1}$ where i represents one vibrotactile message on a type of soil. If the vibrotactile message is not perceived after the maximum time of 5 seconds, then the signal is sent back.

The overall time is 45 minutes with a break of 5 minutes between the two steps.

A semi-directed interview with Likert-based question was conducted. In our post-experimental interview, we asked participants the following question: What do you think might be the level of risk for each soil according to your RT to this soil? This question was intended for user's experience about the comprehension, and explanation of RT data analysis on different types of soil.

5.5 Results And Discussion

All participants went through the experiment successfully.

Tableau 5.2: Mean RT in milliseconds by participants in each type of soil.

Participants	Concrete	Carpet	Foam	Gravel	Sand
A	312.5	330	330	365	347.5
B	252.5	320	397.5	527.5	587.5
C	492.5	472.5	492.5	365	907.5
D	420	445	530	777.5	710
E	490	487.5	460	545	665
F	372.5	405	460	470	450
Means	**390**	**410**	**445**	**508.33**	**611.2**
SD	**96.56**	**71.64**	**71.29**	**152.79**	**198.2**

5.5.1 Vibrotactile Messages preference

Observed results provide a general indication on the preference of participants on the set of haptic messages proposed to convey a risk level under the foot. Among the six vibrotactile messages presented, participants had to select four and then. The results (Table 5.2) show that the participants had a similar preference in the choice of vibrotactile messages. We observed, for the four risk levels of falling low, medium, high, and very high, participants have generally associated vibrotactile messages W_6, W_2, W_1, and W_3 respectively.

5.5.2 Observed Reaction Times

Individual results showed that the smallest RT was 252.5 msec. observed for the participant B on the Concrete soil. The highest RT was 907.5 msec. observed in participant C on the Sand soil. Mean RT results are found in (Table 5.2). On average, the fastest RT can be observed on the Concrete soil (390 msec.) and the slowest RT is observed on the Sand soil (611.25 msec.). All these results revealed that the RT varies according to the types of soil.

We also analyzed conditions for which participants did not perceived the vibrotactile messages. In general, five (5/6) participants did not perceive the vibrotactile messages on three types of soil (Foam, Gravel, and Sand). The breakdown is as follows: (3/6) concerning the Foam, (4/6) concerning the Gravel and (4/6) concerning the Sand. On the other hand all participants were able to identify vibrotactile messages on the Concrete and Carpet types of soil. The results also showed the mean RT were different according to the type of soil.

Tableau 5.3: Additional statistic test.

Group	Soil pair	Type of test	P-value
1	Concrete - Sand	Tukey	0,04
1	Concrete - Sand	Bonferroni and Holm	0,02
1	Concrete - Sand	Fisher	0,034
2	Sand - Concrete	Fisher	0,006
3	Sand - Carpet	Fisher	0,012

5.5.3 Statistical Analysis

We performed an ANOVA with repeated measure on the mean RT (Table 5.3). Factors are the types of soil and its associated levels are Concrete, Carpet, Foam, Gravel, and Sand. Our assumption for the ANOVA was the homogeneity of variance, we supposed that variance in different levels of each independent variable was equal. The significance level (α) is 0.05. The p-value corresponding to the F-statistic of ANOVA ($F(4, 25) = 2.92$, $p < 0.05$) was lower than 0.05, suggesting that one or more mean RTs across types of soil were significantly different. To identify which of the pairs of soil is significantly different from the others, the Tukey HSD test, Bonferroni and Fisher's least significant difference (LSD) were performed. Results of these additional tests are reported in Table 5.3. We can observe that the pairs 1, 2, 3 are significant from each other. Thus, we can reject the null hypothesis and confirm the alternative hypothesis. No other statistically significant difference was found, but from data collected in our post-experimental interview, a simple contrasts indicated that vibrotactile RTs were much longer for soft or irregular surfaces according to the rank ordering of the surfaces causing concerns in Table 5.4.

Tableau 5.4: Types of soil causing perception difficulties.

Level of difficulty	Type of soil
Low	Concrete
	Carpet
Medium	Concrete
	Sand
High	Foam
	Sand
Very high	Gravel
	Sand

Additional question on the survey about the device revealed that 66.66% of the population feel uncomfortable with the device while walking.

5.5.4 Discussion And Limitations

Overall results suggest a significant effect of type of soil on RT to vibrotactile message. The factors that most influence the RT to a vibrotactile message is when participants walk on the Sand and on the Gravel.

Vibrotactile RTs were longer on deformable surfaces. A possible explanation for that is that when walking the pressure exerted on the surface induces deformations that introduce perceptual conflicts in the understanding of proposed haptic messages. As result, vibrotactile messages are thus better perceived on non-deformable soils (Concrete, Carpet) when compared to deformable ones (Foam, Gravel, and Sand). Moreover, based on, our post-experimental interview, we observed that most participants (83.33%) had experienced some difficulties to walk on these soils. They categorized them as types of soil with very high-risk difficulty (Table 5.4).

The main limitation of this study concerns the participants; it focuses on two aspects that will be investigated in future work. The first is related to the limited number of participants in the study. Although we had significant results, the sample being very small, it will be important to repeat the experiment with more subjects. The second limitation concerns the representativeness of the sampling. The purpose of this study was to validate the possibility of using vibrotactile feedbacks to transmit messages under the foot plantar during walking. This step now taken, we will need to validate this possibility with the population targeted by the designed instrumented footwear (Menelas and Otis, 2012). More particularly, we will have to experiment with the possibility of use and perception of these messages with elderly people.

5.6 Conclusion

This paper aimed at evaluating the RT to vibrotactile messages when walking on five types of soil. We analysed the time needed to react to a vibrotactile message sent to the foot plantar, using an enactive sole, while walking. Two main results have been noted. First, we observed that the RT was significantly longer on deformable surfaces compared to non-deformable surfaces. Second, results and answers to the post-experiment interview showed that the information (the risk of falling) conveyed through vibrotactile messages is better perceived on non-deformable surfaces. It thus appears that types of soil can influence the perception when walking. But, to increase the significance of our results, an extension of this work will be to use an apparatus adapted to improve the user experience when walking, increases the number of participants (fallers and non-fallers / youth and elderlies), and finally study the positioning of the Haptuator on the body.

Chapter 6

Response Time to a Vibrotactile stimulus presented on the Foot at Rest and During Walking on Different Soil

6.1 Abstract

This study investigates the Simple Reaction Time (SRT) and Response time (RT) to a vibrotactile stimulus presented on two body locations at the lower extremity of the foot on different types of soil during walking. We determine the effect of RT while walking on Concrete, Foam, Sand, and Gravel soil. Also, for RT, we evaluated two vibrotactile stimulus (VS) locations on the lower extremity, the ankle (AL) and under the foot plantar (UFP). A total of 21 young adults participants (n=21) aged mean (24±2.9 yrs.) took part in two session experiment with two main conditions (at rest and while walking on four types of soil). The control session includes 2016 repeated measures with a one-way and two-way ANOVA analyses. The findings have consistently revealed slowness of RT to VS, in particular on Sand and Gravel soil. In

addition, we found that body location has a significant effect on RT in certain soil. These results showed that RT increased with the environment changes during dual task.

6.2 Introduction

Humans use their sensory-motor channels to perceive and to interact with their environment. For example, touch is fundamental to elaborate motor tasks of daily activities. During walking, neural systems process different information, like vestibular, mechanoreceptor, visual, or auditory input, in order to continuously adapt walking patterns with the environment (Rossignol et al., 2006). The real-time processing of this information is thus crucial for an adequate gait. As demonstrated by Mathis et al., visual information from at least two step lengths ahead is needed to guide foot placement when walking over a complex terrain (Matthis and Fajen, 2014). However, health problems are more common among older people, specifically falls that represent a large proportion of them. In fact, a recent study by the Canadian Health Agency reported that almost a third of people over 65 fall at least once a year, and this is responsible for 60% of injuries in this age group (Scott et al., 2005). Even without injury, these falls can lead to psychological impact, temporary or permanent, owing to the fear of falling again (Ganz et al., 2007; Greenberg, 2012). Falls are a social and economic health problem, especially in the elderly. Moreover, Lajoie and Gallagher Lajoie and Gallagher (2004) found that old people who tended to fall in nursing homes had a significantly slower reaction time (RT) than those that did not. All these observations highlight the need to develop a means of preventing falls by evaluating RT. In fact, such observations have been a driving force for the study of RT or response time in cases of balance disorders.

In prior work, to prevent accidental falls, we designed an augmented shoe aiming at assisting a user when walking (Menelas and Otis, 2012). To that end, we crafted a serious game dedicated to learning of the risk level of falling represented by four vibrotactile messages. That first step significantly confirmed the idea that vibrotactile messages can function in communicating the level of risk. Thereafter, we designed a new study aimed at designing a set of four tactons to communicate a risk level using an enactive shoe (Tchakoute et al., 2018). However, participants remained in the rest position and the influence of the environment was not evaluated. Next, in a second study, we evaluated the impact of the environment when communicating the risk level (vibrotactile message). Firstly, we evaluated the impact of auditory distractions when stimuli were presented to the foot on various types of soil (Chapwouo Tchakoute and Menelas, 2018). We found that auditory distractors significantly influenced the perception of vibrotactile messages. Secondly, we investigated the RT with respect to vibrotactile messages presented at the foot plantar (FP) on different types of soil Tchakoute and Menelas (2018). The findings consistently revealed a decrease in RT to vibrotactile messages when walking on three deformable soils (foam, gravel, and sand). In addition, other research has shown that the physical properties of types of soil can influence the risk of falling Otis et al. (2016) and the type of ground increases the imbalance (Ayena et al., 2015). Consequently, all these studies showed that some cueing, especially vibrotactile stimuli (VS), could favorably influence or reduce the risk of falling on unstable ground. Thus, it is important now to evaluate the RT to VS unstable soils. Indeed, if the time required to react to a VS is too long, the risk of falling increases as the user is more likely to have lost balance. In this study, we sought to evaluate RT to VS presented to the foot while walking on unstable soils.

Aaron et al. defined RT as the time elapsed between the onset of a stimulus and the response to that stimulus (Rossignol et al., 2006). Several types of RTs are defined related to their associated stimuli. For instance, the auditory stimulus takes 8-10 msec to reach the brain (Kemp, 1973) and mean auditory RTs are 140-160 msec (Galton, 1890; Kosinski, 2008; Welford, 1980a). In addition, visual stimuli take 20-40 msec to reach the brain with mean visual RTs being 180-200 msec (Kosinski, 2008; Marshall et al., 1943). Yet, RT to touch with the hand is intermediate at 155 msec (Kosinski, 2008; Robinson, 1934). Nevertheless, numerous factors, such as the environment, sensory motor diseases, fatigue, and age can influence RT and increase it, just as reported by Kosinski (2008) whom presented a review on RTs mentioning that age, especially aging, is a factor affecting RT. Neuropsychologists have named three basic kinds of RT experiments. In addition to the simple reaction time (SRT), there are also recognition reaction time (RRT) and choice reaction time (CRT) (Galton, 1890; Welford, 1980a). As opposed to a SRT that implies only one stimulus and answer, in RRT experiments, there are stimuli that should be responded to and certain distracting stimuli that should receive no answer. The user has to react only to the right stimulus. In a CRT experiment, there are multiple stimuli, and each requires a different answer. Apart from these three basics kind of RT, there may be a combination of SRT and CRT, as in the case of the probe reaction time (Probe RT) suggested by Posner and Boies (Posner and Boies, 1971). The Probe RT requires subjects to perform simultaneously a CRT task (primary task) with one hand and a SRT task with the other hand (secondary task). Based on the definition of RT provided in (Kosinski, 2008), we will situate our evaluation within the framework of a RRT. RT has been employed to collectively refer to all components of time required to complete a task after the appearance of a stimulus (Klavora et al., 1995; Wilkerson et al., 2017). However, in the present project, the term RT is rather inappropriate because we mainly measure the response time during a task where the central nervous system is already engaged. For the purpose of this study, we used the term RT to refer to response time during dual tasks (for instance, during walking and pressing a button on a smartphone), and the term SRT refers to RT in the rest position.

In the elderly, many falls occur on different types of soil Kosinski (2008) or when walking on a stairway (Ayena et al., 2015). We then hypothesize that possibly because of aging and the time to readjust the postural control, the information perceived by some mechanoreceptors among others could influence the RT of the person as well as the types of soil on which they are walking. If falls are a major health problem, then a first study might be to evaluate young people and RT could be a solution to see how a healthy person responds to stimuli on different types of soils. In fact, certain studies have improved the usability of RT in response to haptic stimuli. Cinaz et al. designed and evaluated a wearable device in order to assess RT to an haptic stimulus (Cinaz et al., 2011). Their study was performed with 20 subjects in an idle condition and under cognitive load. They measured the RTs of 10 subjects from a desktop-based RT test in the first half of the experiment. In the second half, they performed the wearable RT test. They observed that, in both experimental conditions, individual changes in RTs were augmented with cognitive load. Moreover, Ivorra et al. implemented a haptic stimulus to investigate the central nervous system in a minimally obtrusive way (Bolanowski Jr et al., 1988). In a first feasibility study, they showed that a SRT test can be continuously administered throughout the course of normal life activities. Recently, Peon and Prattichizzo studied the RTs to visual, auditory and haptic stimulus while transmitting information (Peon and Prattichizzo, 2013). They compared different sensory modalities (vibratory, auditory and visual) and employed two intensities for the auditory and haptic modalities. For the visual modality, they used a screen in front of the users showing two colors - black and white - until the user retracted the tool. The results demonstrated that the haptic channel can provide faster RTs than the auditory one.

All these studies evaluated various aspects affecting RT, like age as presented in (Kosinski, 2008; Fieandt, 1956), or like comparisons between different stimuli, as in (Peon and Prattichizzo, 2013). Yet, a potential limitation for RT measure evaluation is related to the constraints of conveying VS when walking on various flooring surfaces. In fact, the relationship between RT and risk of falling is very complex. To the best of our knowledge, there is very little research concerning the RT to a VS when walking on various types of soil. Moreover, a feasibility of technological measure of RT to VS is not elaborate enough, particularly when walking is divided by increasing the difficulty of the task of changing flooring surfaces. Therefore, it could be that some cueing, especially VS, could decrease or increase the risk of falling, especially on unstable soils. We addressed research questions utilizing a new wearable enactive shoe capable of induction and measuring RT to VS on four types of soil. Next, the present study investigated the SRT and RT to a VS on two body locations at the lower extremity of the foot on varying types of soil during walking. Specifically, the purpose of this study is to assess factors affecting the RT while induced VS at the foot when walking on four types of soils. We also wanted to compare RT to VS at two different positions.

6.3 Apparatus: Enactive Shoe

6.3.1 Characterization of The Haptuator

We characterized our device to evaluate its physical properties that could influence RT. Each engine produces an acceleration before reaching steady state. This latency can have a great influence on the perception of the stimulus, therefore on RT, as well. We sought to determine the time that the engine takes before reaching its cut-off frequency and is stabilized. For this, we powered the motor (haptuator) by a function generator with an impedance of 10 ohms, providing a stable signal of 3.3 volts at a frequency of 100 Hz. The voltage (shown in yellow in Figure 6.1) is read by channel 1 of the oscilloscope. The current (in blue in Figure 6.1) equivalent to the motor torque read on channel 2 of the oscilloscope and is programmed with an amplification at an input of x100. The current is measured across a shunt resistance of 0.01 ohms in series with the motor. The display of the voltage of channel 2 therefore corresponds to 1mV = 1mA.

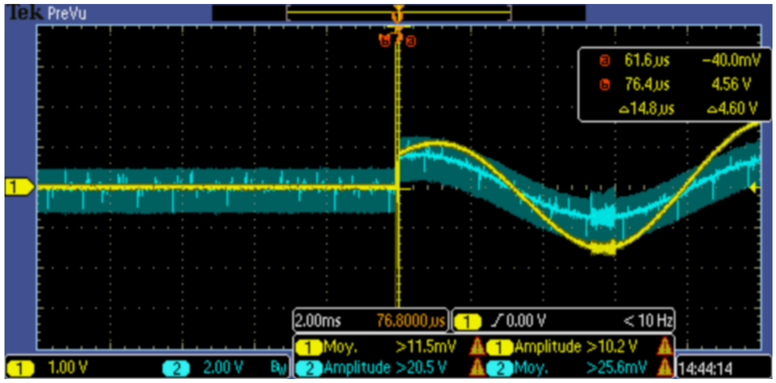


Figure 6.1: Characterisation test of the device displayed by an oscilloscope.

We can ignore the first impulse that is a "bounce" (a noise generated when the function generator is turned on). We can see that there is a delay (Figure 6.1) between the start of the signal (cursor a) and the initial rise of the motor current (corresponding to starting inertia). The current reaches its maximum at cursor b. This delay is approximately 19.6μsec. Further, this device characterization test revealed that the Mark II haptuator has a latency of 0.0196 msec. However, such a delay is relatively minimal in terms of being able to influence RT, so that is why we decide later if we had to take it into account or not.

6.3.2 Positioning of The Haptuator On a Specific Body Location

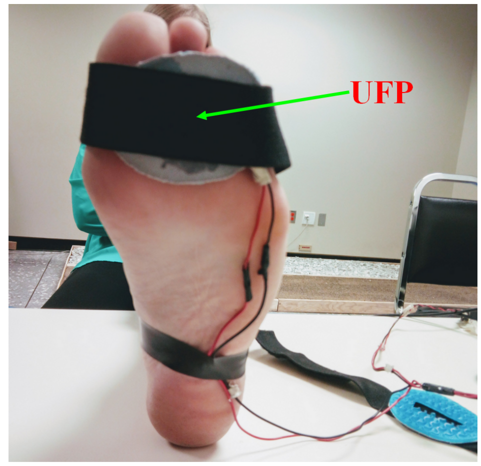
Regardless of the limited research concerning the foot, it is known that the haptic modality is a bidirectional modality providing coupled and distributed returns across our body through the skin, muscle and joint receptors (Coren et al., 1999). To ensure this, we must make certain the sender transmits the message to the correct recipient on the appropriate channel using the code known by the sender and recipient. To ensure information communication, this model suggests identifying the components involved in the transmission of our VS, namely: communication device, the body location (point of contact of the stimulus with the skin) and the information to be transmitted. We know that VS can be transmitted through various body locations according to various devices (Menelas and Otis, 2012), but it is important to specify the location of the stimulus. In fact, the sensory physiology of the FP is similar to that of the skin of the hand with the same types of tactile mechanoreceptors. There are mainly four types of mechanoreceptors: slow-adapting type I (SA-I), slow-adapting type II (SA-II), fast-adapting type I (FA-I) and fast-adapting type II (FA-II) (Kennedy and Inglis, 2002; Kikuchi, 2013). Various FA mechanoreceptors are located on lower extremity, for instance under the arch of the second toe and at the ankle. Our aim is to evaluate the RT to a VS using an enactive shoe embedding a haptic actuator (in this case, haptuator). It is a robust means to identify a specific body location of the stimulus such that the user must respond as quickly as they perceive the stimulus. For this, FA seemed to be suitable as we needed a fast transmission and rapid RT.

Previous studies have demonstrated that VS can be perceived through the foot. For instance, through an array of 16 dots of actuators, Velázquez et al. have shown that certain forms could be discriminated (stereognosia) in order to direct a blind person while walking (Velázquez and Pissaloux, 2008). Visell et al. investigated human differentiation and identification of haptic stimulus via the foot with vibration elements, like voice-coil actuators (Visell et al., 2009). Recently, Velázquez et al. studied the communication of information and tactile-foot perception capability through human feet for assisting navigation (Velázquez et al., 2015). The results show that subjects were capable of following directional instructions useful for navigating spaces. As such, the foot appears to be a suitable body location for haptic interaction and communication. Given this, FA-I were used to convey the stimulus as suggested in (Velázquez and Pissaloux, 2008) and (Meier et al., 2015a), and we selected two body locations where the fast mechanoreceptors (FA-I and FA-II) are more dense:

- The ankle (AL), especially between the lateral ankle joint (just behind both malleolus) and the Achilles tendon (Figure 6.2a - a)
- Under the FP, especially under the third toe of the foot (Figure 6.2b - b).

For the comfort of the user, the underside of the second toe of the foot is a hollow area, so the thickness of the actuator will have a less painful effect when walking.

(a) AK location



(b) FP location

Figure 6.2: The device is wear on the left foot and a strap holding the haptuator is located a two lower extremities where the fast mechanoreceptors (FA-I and FA-II) are more represented in order to render VS. (a) In the first half of the experiment, the haptuator is located at the lateral ankle joint; (b) in the second half, haptuator is located under the arch of the second toe.

6.3.3 Materials

In a previous study, we evaluated the impact of auditory distraction on the identification of VS presented under the FP (Chapwouo Tchakoute and Menelas, 2018). We assessed whether having auditory disturbances would increase the learning time of vibrotactile messages. The VS was rendered throughout an enactive shoe having two haptuators. The findings highlighted the negative effect of auditory distractions on the number of iterations and completion time to recognize VS. The device was connected to the power outlet and participants were at the resting position. In addition, it was not possible to position the device at different places on the body. However, in walking, a wearable functionality device is necessary to ensure accuracy in conveying information using haptic modality when walking outdoors. Indeed, Yang et al.

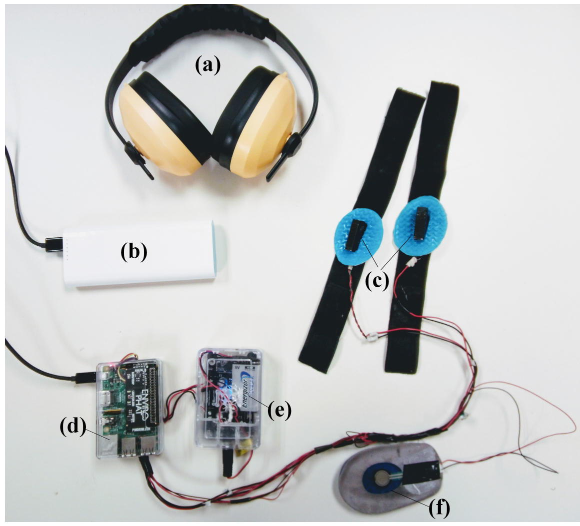


Figure 6.3: Enactive wearable and removable insole: (a) ear protection; (b) Power supply of 5v; Haptic system [(c) Mark II haptuator mounted on strap; (e) Bluetooth amplifier with a battery;] Computing system [(d) Raspberry + EnviroPhat; (f) Force sensitive resistor]

reported that wearables are mobile electronic devices that are worn on the body, or can be attached or embedded in clothes and accessories, such as Google Glass, or incorporated into the body, such as via smart tattoos, to supply a functional, portable and mostly hands-free electronic system (Yang et al., 2017).

For the purpose of this study, we designed a wearable device with a mini-computer embedded in sensors and actuators that can display, process or gather information, and have wireless communication capabilities. It can be spotted on the body, communicate wirelessly with smartphones via the Bluetooth and Wi-Fi protocols and convey VS when walking at a specific location on the body. To this end, we employed certain components, mainly subdivided in two modules (Figure 6.3). Firstly, the designed requirement is portability. As such, the device has to be attached or mounted on the body during the experiment because participants are walking. Secondly, the VS has to be induced and perceived on a specific location on the foot while allowing movements of the foot. Thirdly, because of foot size variability and, as previously noted in Section (4.1), we designed a device with two enclosures separately as suggested in (Zanotto et al., 2014). Each enclosure is a module with a specific function (haptic and processing). In the first enclosure, the haptuators are mounted on removable straps that can be placed directly on a specific location. In the second, a computing unit is mounted. Each plastic enclosure of the device can be attached to the foot of the participant with a strap. The dimensions of each enclosure (Figure 6.3 [d and e]) was: Width $\times$ Length $\times$ High (90mm $\times$ 55mm $\times$ 30mm). The main function of each module follows:

The Haptic System (Figure 6.3 (c)-(e)):)

The haptic system is responsible for transmitting the VS at a specific location of the body. The system consists of an Android application on a smartphone and a Class D Bluetooth Amplifier powered by a 9v lithium rechargeable battery of 600 mAh. The input audio signal is transmitted by Bluetooth from the computing system. Then, it is amplified with a gain of 26 decibels before being sent to the two stereo outputs. At each stereo output, we connected a second-generation Mark II haptuator from TactileLabs (TactileLabs, 2012). Each haptuator measures (32 mm x 9 mm x 9 mm) with a frequency range between 90 to 1000 Hz, an impedance of 5.5 Ω, a maximum input voltage of 3.0 v, a maximum input current of 0.5 A and a weight of 9.5 g. The maximum acceleration (7.5G) is reached with a 3 v voltage. TactileLabs (TactileLabs, 2012) reported that they provide an accurate signal and a faster time response ($\approx$ 1msec.). The equipment is fixed on a body location of the participant and signal-driven wirelessly from the smartphone. The measurements are performed at 121 Hz as the optimal response of the FA mechanoreceptor (Pacinian corpuscles) is noted to be at frequencies between 10 – 500 Hz (Bolanowski Jr et al., 1988).

The Processing System (Figure 6.3 (d)-(f)):

The processing system is a built-in application with the main task of sending VS at the foot. The processing system consists of five main units:

(a) The Raspberry Pi 3 B (Figure 6.3 - d): The Raspberry Pi 3 Type B motherboard is a powerful and affordable solution for all types of compact or embedded systems. It is equipped with a powerful Quad-Core ARM Cortex-A53 1.2 GHz processor (Broadcom BCM2837), 1024 MB RAM and a Dual-Core VideoCore IV GPU capable of decoding 1080p HD video streams.

(b) Power supply (Figure 6.3 - b): We used a TP-LINK power bank model TL-PB15600 with dual-flexible output ports. It is powered with a 5 v rechargeable battery featuring an enormous capacity 15600 mAh power bank.

(c) The EnviroPhat (Figure 6.3 - d): Is the analog unit used to recover the signals from the force-sensitive resistor as well as the accelerations when the participants are walking.

(d) Force sensor (Figure 6.3 - f): Interlink 402 Force-Sensitive Resistor (FSR) with a detection range of 10 g up to 10000 g for a resistance of 100 KΩ to 100 MΩ. There are two FSRs, and both are positioned at the heel of the foot (rear FSR) and under the big toe (front FSR).

(e) The smartphone running an Android application is used to record response time measures when the participant presses on the tactile screen.

Figure 6.4 illustrates a detailed view of the circuit diagram of the whole system.

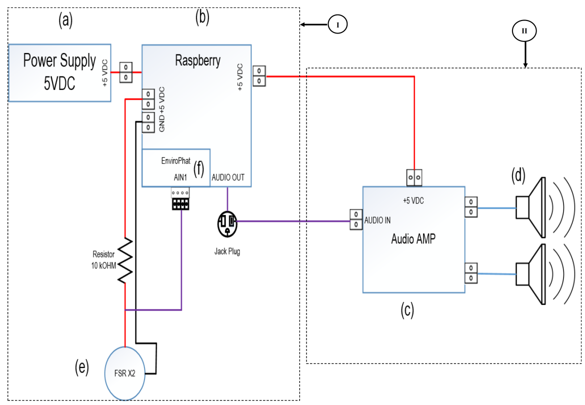


Figure 6.4: Circuit diagram of the device. I- computing system (a- Power supply, b- Raspberry; f-EnviroPhat; e-FSR); II-Haptics system (c- Audio amplificator; d- haptuator)

6.3.4 The VS Embedded in The Device

One VS' of one second from a previous study evaluating SRT within the foot Tchakoute and Menelas (2018) is utilized. This stimulus was designed according to various studies of psychophysical perception reported in (Visell et al., 2009) and (Bricker, 1955). To meet the goal of the current work, we chose a pure sinusoidal wave with a waveform described by equation 6.1 because the signal is elicited at 121 Hz as the optimal response of the vibration receptors (Pacinian corpuscles) is reported to be at frequencies between 10 – 500 Hz (Bolanowski Jr et al., 1988).

$$W = asin(2pi121t), \tag{6.1}$$

6.4 Experiment

In this experiment, our objective was to investigate factors influencing RT to a VS while walking on four types of soil with the enactive device. During the first half of the experiment, the stimulus is sent at the AL (Figure 6.2a - a) and we evaluated RT. Within the second half,

Tableau 6.1: Participant's characteristics

Participants	Value
Age (Y)	24.42 ± 2.87 *
Height (cm)	168.47 ± 10.64 *
Weight (kg)	68.24 ± 11.66 *
Gender	Men (N = 8)|Women (N=13)
* Values are represented as Mean ± Standard deviation (SD).	

the stimulus was sent to the FP (Figure 6.2b - b).

6.4.1 Participants

Twenty-eight students aged from 20 to 28 (24.2+/-2.9 yrs.) that were healthy without musculoskeletal problems from the University of Quebec at Chicoutimi (UQAC) participated in the study. They were recruited by means of accidental sampling after written electronic invitation to participate in a study related to the RT and response time of a VS. All participants attended the session voluntarily and informed consent was obtained before experimental sessions. All assessments were performed in a controlled laboratory environment. Further, all participants were novices to haptic technologies and they were followed up with by an interview before the beginning of the session by filling out a short questionnaire on their health history along with touch inspection surrounding their foot sensitivity. In the case of any foot sensitivity problem, the person was excluded from the study - seven participants were removed because of this reason. Finally, only 21 participants without any sensorimotor deficits were retained because they presented tactile foot acuity and were provided their consent (Table 6.1). The experiment and consent form had been previously approved by the local ethics committee (certificate number: 602.434.01). To achieve the study goal, one experiment was carried out.

6.4.2 Experimental Setup

What follows is the description of the setup including conditions.

Test Environment

The experimental phase took place in a calm space, specifically in our laboratory at UQAC, equipped with chairs and a table for preparation of the participants. The laboratory was equipped with the flooring surface conditions and a hygienic kit to clean the device after a session was finished. This environment remained constant during the experiments.

Types of Soil

The first factor (first condition) of the experiment was a set of several types of soil representing the natural flooring surface materials commonly found in the daily life, such as concrete (Figure 6.5. - 1), foam (Figure 6.5. - 2), sand (Figure 6.5. - 3) and gravel (Figure 6.5. - 4). As shown in (Figure 6.5.), we designed a longitudinal and wooden partitioning device to accommodate the gravel and sand soils (length=350 cm; width=71 cm; height=7.5 cm). With this, foam soil is a little bit longer and less thick (length=370 cm; width=71 cm; height=4.5cm). Overall, all soil signified each of the five steps of the walking cycle. In particular, we filled each partition with real materials. The setup was the actual volumes of the corresponding materials (real gravel, real sand, etc.) placed in a longitudinal box.

6.4.3 Experimental Protocol

Our protocol is resumed in Table 6.2. Generally, we had two main sessions that are described as follows:

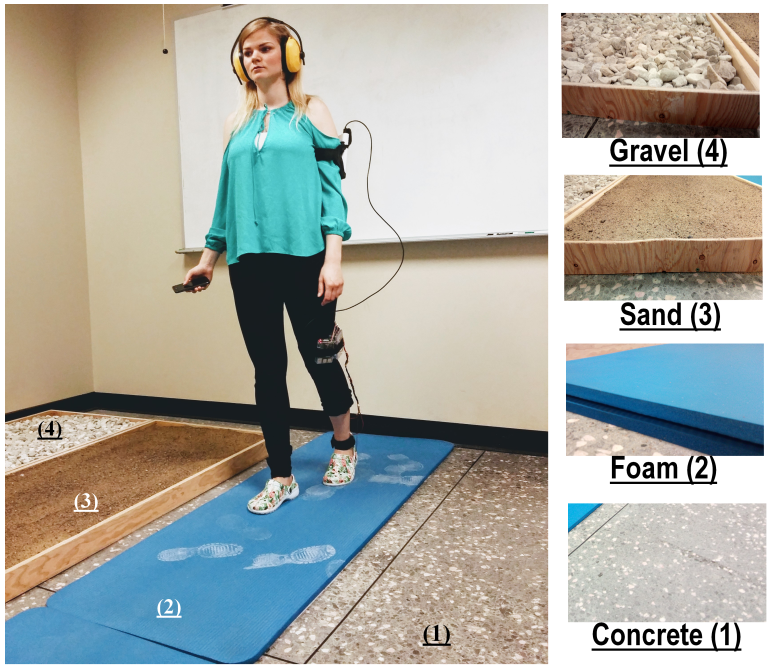


Figure 6.5: A participant performing the test wearing enactive device and ear protection. The task consists of walking, focusing on the black spot on the opposite wall and performing the RT test on the foam soil. Four types of soil named: concrete (1), foam (2), sand (3), and gravel (4).

Experiment Sessions: Baseline and Control

To achieve the goal of this study, the experiments were concerned with two sessions. The first concentrated on baseline treatment and the second session was focus on the control treatment. The baseline is the session where we collected SRT at a resting position on the concrete soil whereas the control was the session where we collected RT on four types of soil during walking. Each session (baseline and control) featured familiarization followed up with a test phase. The first half of each test phase was concerned with collected measures when the stimulus location is at the AL (Figure 6.2a - a). During the second half, we changed the stimulus location toward the FP (Figure 6.2b - b). Within the entire session for each participant during each phase, we used two specific locations to apply the VS successively. When the stimulus was applied at the AL level, the RT collected were named RTs at the AL (RT_AL).

Tableau 6.2: Experiment protocol summarize

Sessions	Conditions				
	At rest	Walking			
	C	C	F	S	G
Baseline	Familiarization phase *				
	Test phase				
Control		Familiarization phase *			
		Test phase	Test phase	Test phase	Test phase

** Familiarization was made only on the Concrete soil for all sessions.*
C= Concrete, F = Foam, S = Sand, and G = Gravel soil.

Under the arch of the second toe of the FP, the RT collected were dubbed the RTs of the FP (RT_FP). The order of stimulus location (AL and FP) was alternated for each participant between the sessions.

The control test for different types of soil was made up with 2016 measures (21 participants $\times$ 3 trials $\times$ 4 types of soil $\times$ 4 identifications $\times$ 2 positions $\times$ 1 vibrotactile stimulus). The overall length of a session was 45 minutes with a break of 5 minutes between the two sessions.

Familiarization Phase

The familiarization phase was concerned with the explanation and demonstration of the participants getting in touch with all aspects of the experiment. During this phase, the participants were at rest in a chair, wearing ear protection and hosting the tactile device on the left foot. To avoid false-positive perceptions on different types of soil, participants were encouraged to detect the VS in order to be familiar with them. A demonstration of the expected flow is located in Figure 6.6. Thereafter, we cleaned and reinstalled the system. The participants fixed a black spot on the opposite wall in order to be outside the field of vision of the screen in hand. When they perceived VS on the foot, they pressed the smartphone screen as quickly as possible, and the time taken was stored. We recorded 25 measurements and generated a training chart of all RT measures. Once the participant was trained, they began with the testing phase.

The Test Phase

The test phase that includes the baseline session was performed at rest, with the participants sitting on a chair as shown in Table 6.2. However, the control session of the test phase was conducted while the participants were walking on the four types of soil (Figure 6.5.). At this stage, participants donned ear protection. For each trial walk, at the initial time (t1), the processing system sends the VS four times. As soon as the participant perceived the VS, they pressed the smartphone screen. Thereafter, the identification time (t2) was saved and the processing system computed the $RT_i = T_{i2} \breve{} T_{i1}$ ($i <= 4$), where i represents the number of identifications per trial on one type of soil. When measures are completed on the type of soil, the participant was invited to move on to the next type of soil. The trials on the different soils were counterbalanced (random) between participants. A synopsis of the trial with one type of soil is found in Figure 6.6.

6.4.4 Results and Discussion

Twenty-eight participants took part in this experiment to evaluate RT to VS, but seven participants were removed before the test because they have documented sensitivity issues, limitations of the haptuator technology for haptic stimulation or both. We used a wearable haptic device to convey the VS to two locations (FP and AL). All remaining participants went through the experiment successfully. On one hand, we observed the fastest RT_AL (98.79

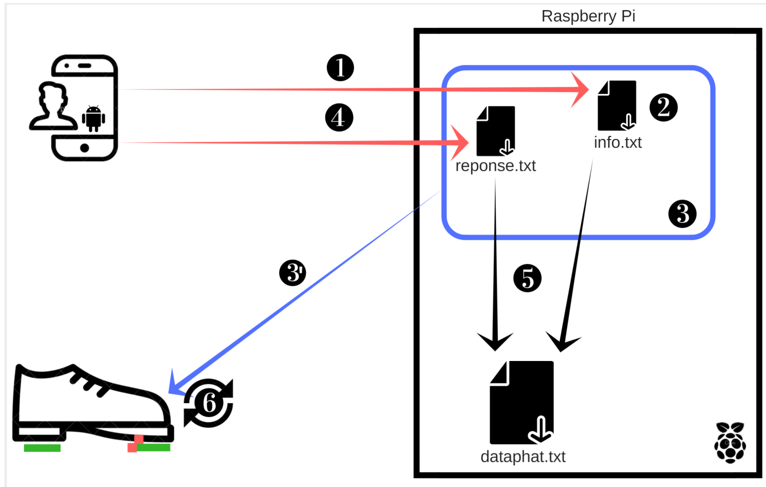


Figure 6.6: Experiment synopsis. 1. Sending the parameters of the experiment and information regarding the user in the processing system; 2. Saving settings and information in information.txt; 3. The processing system waits for the user to perform the first step; 3. The processing system detects the step and transmits FSR actuated to the haptic system, which sends the first VS (t1) and commences a delay of 5 seconds; 4. The user presses the screen and the time (t2) is recorded in the file reponse.txt; 5. The processing system retrieves the response, calculates the SRT and records it in dataphat.txt; 6. The processing system waits for the next step that will actuate the FSR.

msec.) for participant, N (male), on the concrete soil and the fastest RT_FP (96.75 msec.) for participant C (female). On the other hand, the slowest RT_FP (600 msec.) was observed for participant T (female) on the gravel soil and the slowest RT_AL (595 msec.) was observed for participant G (female). Observations of the mean results are presented in Table 6.3. let us says that the fastest means were RT_FP (mean=392.6; SD=70.29) and RT_AL (mean=465.43; SD=80.02). Both these RTs were observed on gravel soil. Yet, the slowest means were RT_FP (mean=146.62; SD=32.21) and RT_AL (mean=118.8; SD=32.13). Both RTs were observed on concrete soil.

To meet the goal of this study, we were looking for the effect of each independent variable within each condition of the experiments. We were concerned especially with three assumptions:

Tableau 6.3: Means and standard deviations of reaction time showing results when reaction time is obtained at rest position and when they are walking

		At rest	Walking			
		Concrete	**Concrete**	**Foam**	**Sand**	**Gravel**
FP[1]	**Mean**	169.5	146.6	186.2	311.3	392.6
	SD[3]	24	33.2	56.3	68.5	70.2
AL[2]	**Mean**	161.4	118.8	156.6	305	465.4
	SD[3]	15.9	3.1	42.2	53.7	80

[1] *FP = RT obtained when stimulus is presented at the FP.*
[2] *AL = RT obtained when stimulus is presented at AL.*
[3] *SD = standard deviation.*

- First (H_1): Do types of soil have any effect on the RT?
- Second (H_2): Do types of soil and location interactions have any effect on RT?
- Third (H_3): Is the SRT at the rest position for concrete soil different for FP and AL?

We assumed that for the null hypotheses H_{01}, H_{02} and H_{03}, all means were equal, and for the alternative hypothesis (H_{a1}, H_{a2} and H_{a3}), at least one mean was different from another. Our significance level is (alpha) = 0.05. The dependent variable is RT and our independent variables are types of soils and stimulus location. We have more than two groups and the variables are quantitative. All tests were performed using GraphPad Prism version 5.02 for Window (GraphPad PRISM San-Diego, CA, USA). All analysis of variance (ANOVA) evaluations were performed with post-hoc Tukey HSD (Honest Significant Difference) tests. Our input data were k=4 independent first group factors, concrete, foam, sand and gravel. The second group factors were FP and AL. The sample observation was N=21. The data satisfied the conditions to justify the use of ANOVA. All Tukey comparisons are illustrated in Figure 6.7.

Figure 6.7. show that there is a strong trend for SRT at rest is slower (about 20%) than response

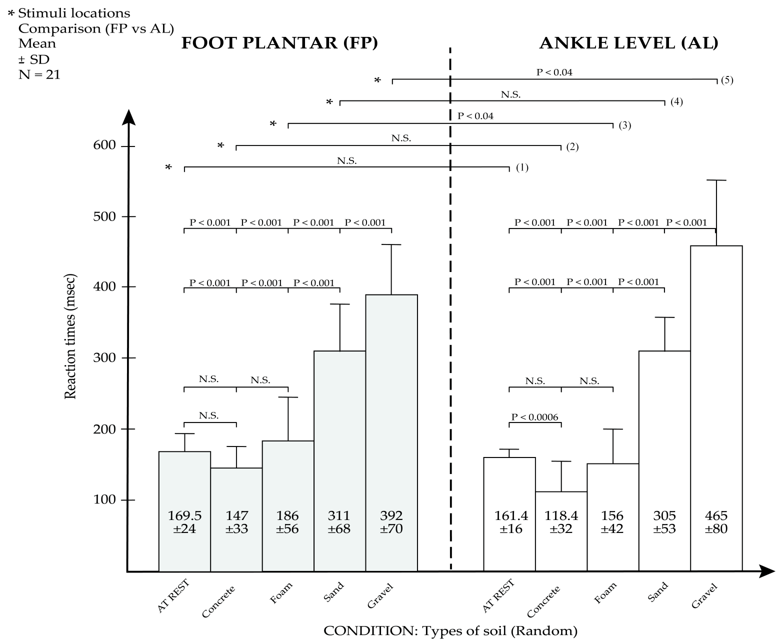


Figure 6.7: Comparison of reaction times on young participants at two location of stimulus (FP and AL). * are results from turkey comparison for the two way ANOVA.

time when subjects are engaged in a complex motor task such as walking. Figure 6.7. also shown that the response time is considerably slower when subjects are walking on Sand (by about 225%) and gravel (by about 311.6%). The VS location site either at the FP or at the AL has only a significant effect on the RT by 50% on FP condition and 93% on AL condition.

Tableau 6.4: Two-way ANOVA results

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Locations	1	215	0.01%	215	215	0.07	0.797
Types of soil	3	2307063	79.56%	2307063	769021	236.99	0.000
Locations * Types of soil	3	73210	2.52%	73210	24403	7.52	0.000
Error	160	519190	17.91%	519190	3245		
Total	167	2899677	100.00%				

Tableau 6.5: Two-way ANOVA coefficient: distance between factor levels and the overall mean

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	260.36	4.39	(251.68; 269.04)	59.24	0.000	
Locations						
AL	1.13	4.39	(-7.55; 9.81)	0.26	0.797	1.00
FP	-1.13	4.39	(-9.81; 7.55)	-0.26	0.797	*
Types of soil						
Concrete	-127.65	7.61	(-142.68; -112.61)	-16.77	0.000	1.50
Foam	-88.88	7.61	(-103.91; -73.84)	-11.68	0.000	1.50
Gravel	168.66	7.61	(153.63; 183.69)	22.16	0.000	1.50
Sand	47.86	7.61	(32.83; 62.89)	6.29	0.000	*
Locations*Types of soil						
AL Concrete	-15.04	7.61	(-30.07; -0.01)	-1.98	0.050	1.50
AL Foam	-15.94	7.61	(-30.97; -0.90)	-2.09	0.038	1.50
AL Gravel	35.28	7.61	(20.24; 50.31)	4.63	0.000	1.50
AL Sand	-4.30	7.61	(-19.33; 10.73)	-0.56	0.573	*
FP Concrete	15.04	7.61	(0.01; 30.07)	1.98	0.050	*
FP Foam	15.94	7.61	(0.90; 30.97)	2.09	0.038	*
FP Gravel	-35.28	7.61	(-50.31; -20.24)	-4.63	0.000	*
FP Sand	4.30	7.61	(-10.73; 19.33)	0.56	0.573	*

Effect of Types of Soil on RT(H1): Do Types of Soil Have Any Effect on the RT?

To evaluate hypothesis H_1, One-way ANOVA was conducted for the two conditions (FP and AL) with repeated measures. Results from the ANOVA-FP test showed that the p-value corresponding to the F-statistic of the one-way ANOVA was lower than the α level [F(3,80)= 77.46, $F_{critical}$ =2.72, p < 0.0005, Effect sizes (η^2_{ufp}) = 0.75], suggesting that one or more soils were significantly different when the stimulus was presented at the FP. Moreover, results from the ANOVA-AL test showed that the p-value corresponding to the F-statistic of the one-way ANOVA was lower than the α level [F(3,80)= 174.45, $F_{critical}$ =2.72, p < 0.0005, Effect sizes (η^2_{ufp}) = 0.75], suggesting that one or more types of soil were significantly different. These results are also reported in Figure 6.7, uncovering that types of soil have a significant effect on RT. RTs were faster on concrete and foam soils, but on sand and gravel soils, RTs were slower.

This indicates that certain soils have more of an influence on RT than others. However, one could consider the influence of double tasks (walking and pressing a button with one's hand) to explain the slowed RT on sand and gravel soils (Figure 6.7). That said, we believe that a number of variables, like visual, vestibular, and auditory sensory systems, and others such as verbal instruction, were not controlled for this study and can explain the difference in RTs on various types of soil. Indeed, during the experiment, we noted that participants tended to look at the soil for a few seconds when they were walking and sometimes slightly lost balance owing to the accidental flooring surface and gait disturbance. This indicates that the RT would have been influenced by a visual and external stimulus (Tchakoute et al., 2018; Tchakoute and Menelas, 2018). Moreover, this is why we suggested the implication of neurocognition (variables such as a difference in knee muscle extension strength and proprioception, haptic touch, balance and interlimb coordination) that elucidates the differences observed between experimental conditions, in particular by divided attention and the possibility of risk of falling. All this suggests RT is influenced by the ability of subjects to pay attention (divided attention) and concentrate on the dual task, but also increase the difficulty of the task (walking on various types of soil) with a potential increase in risk of falls in young participants.

Stimulus Location and Types of Soil (H2): Do Types of Soil and Locations Interaction Have Any Effect on RT?

To evaluate the hypothesis, H2, two-way ANOVA was conducted for the two conditions - the stimuli location (FP and AL) and types of soil (concrete, foam, sand and gravel) with repeated measures. Furthermore, we assessed the positioning of the haptuator when walking on four types of soils. For the two-way ANOVA results, there was no significant difference for location of the stimulus, $F(1, 160) = 0.07$, $p = 0.797$. Yet, there was a statistically significant difference between various types of soil factor means, [$F(3,160)=236.99$, $p < 0.0005$]. In addition, there was a significant interaction between the effects of location and types of soil on RT, F (3, 160) = 7.52, $p < 0.0005$. The results (Tables 6.4 and 6.5, Figure 6.7. suggest that stimulus location (FP or AL) had no influence on RT ($p>0.05$) when participants walked on concrete or sand (Figure 6.7. – (2) and (4)). This is based on the fact that on sand, participants tended to have almost the same mean RT (FP mean RT = 311+/-68 msec.; AL mean RT = 305+/-53 msec). However, interactions between the locations and other soils (foam and gravel) revealed significant results (Figure 6.7. - (3) and (5)). As such, this demonstrates a weak significant effect for the interaction between stimuli location and types of soil. However, this is not really surprising. We suggest that the complexity of the walking task on sand can reduce tactile perception. For the between concrete and stimulus location, the explanation could be that concrete is a form of hard-flooring surface where one has almost the same average speed when walking. In addition, the level of difficulty is almost nill because people are used to walking on that type of flooring surface every day. Moreover, for both locations, the covered distance of the VS (conduction time) was about +/- 17-20 cm between the two stimuli locations. Hence, if the density of haptic receptors were similar on both sides and the nerve conduction velocity (sensory and motor) was 100 m per second, this variation in RT would be relative, between 15-20 msec, because of the difference in distance between stimulus location sites. This variation represents a very small effect and it is lost in a global variability of RT. Yet, all participants have almost the same RT mean and standard deviation on sand owing to the balance on this type of soft soil that has the same level of difficulty for all participants. Indeed, the shorter RT found here confirmed that the FA mechanoreceptor of the foot (FP and AL) (Figures 6.2a. and 6.2b.) are robust locations for stimulation to evaluate RT.

SRT at Rest (H3): Is the SRT at the Rest Position on Concrete Soil Different on FP and AL?

To evaluate hypothesis H3, a one-way ANOVA was conducted for the two conditions (FP and AL) with repeated measures. The statistical results according to Figure 6.7 – (1) performed to analyze SRT at rest were not significant (p-value > alpha-level). The SRT were collected on concrete soil at rest. This means that the SRT did not change while in a static position, even if we modified the location of the haptuator. This is the first study of the researcher's knowledge to examine SRT to VS stimulation at the lower limb extremities (short vibration at the foot). In the past, one of us (Tremblay, 2009) measured the SRT at rest in 10 young adults without musculoskeletal problems following a short burst of 100 Hz electrical stimulation (ES) of 50 msec at a two-time threshold of sensory detection. The ES was made on the skin in the forefoot in level five (L5) dermatomes. The voluntary response of dorsal foot flexion was recorded using electromyography (EMG) activity in extensor digitorum brevis muscle. Though, in the present work, the SRT for FP was 169+/-24 msec and for AL was 161.4 +/-16 msec. This suggests that measurement of new technologies is valid. However, we cannot propose a different haptic density of the haptic receptors between FP and AL (concrete = 147+/- 33 vs. 118+/-32) in RT conditions to compare (169.5+/-24. vs. 161.4+/-16) in SRT conditions to explain the significant difference in concrete soil in terms of AL and FP stimulation.

Comparison of SRT and RT

Results from the ANOVA-FP testing showed that the p-value corresponding to the F-statistic of the one-way ANOVA was lower than at the α level [$F(3,80)= 77.46$, $F_{critical} = 2.72$, $p < 0.0005$, Effect sizes (η^2_{ufp}) = 0.75], suggesting that one or more soils were significantly different when stimulus is presented at the FP. In addition, results from ANOVA-AL testing indicated that the p-value corresponding to the F-statistic of the one-way ANOVA was lower than the α level

[F(3,80)= 174.45, $F_{critical}$ =2.72, p < 0.0005, Effect sizes (η^2_{ufp}) = 0.75], suggesting that one or more types of soils were significantly different. These results can be explained as follows.

Response time for the concrete soil during a dual task (walking and pressing a smartphone) when we consider both sites of VS was on average 20.2% significantly (147+/-33 msec vs. 118.4+/-32 msec) shorter than SRT at rest. It is different than in the literature where the complex RT was habitually longer than SRT (Kosinski, 2008; Bricker, 1955). However, in our methodology, the physical environment and instructions were controlled. We believe that during walking, the neurocognitive attentional process was under dynamic engagement of the central nervous system (frontal lobe) facilitating sensory-motor cortex (afferent and efferent information systems), brain stem and spinal cord response (already in action) for movements (walking).

Walking is a complex motor act, a multi-segmental task and a semi-automatic control of rhythmic movements by the central nervous system. Indeed, it is under cortical control, but also of the cerebellum, pedunculopontine nuclei in the upper brainstem and local interneuron network in the spinal cord. This implies that sensory information (haptic and other) coming from lower limbs reach in real time and continuously, during walking, the sensory cortex, SI and SII, and then the motor cortex, MI and MII, and almost simultaneously, the prefrontal cortex (cognitive and attentional process) to analyze and execute correctly the directive of pressing the smartphone screen quickly after haptic feeling on the foot, and, thereafter, motor cortical and the sub-cortical efferent response reach motor spinal cord pathways. This latency represents the response time. During motor action (walking), this neurological network is facilitated during vibrotactile stimulation and explains why RT is shorter than SRT, or, in other words, during walking, the time for motor preparation and movement initiation were facilitated. Moreover, in a preliminary study Tchakoute and Menelas (2018), we investigated six young adult subjects with a similar protocol except that subjects feeling VS could lift the foot (dorsal flexion) as quickly as possible. The experiment was interesting because this task represented the motor preparation and motor initiation of movement during motor conflict during the gait cycle. The subjects must assure safety balance before lifting the foot and avoid the risk of falling. Our results demonstrated that the response time, respectively, for lifting the foot quickly and pressing the smartphone after VS perception during walking were: on concrete soil - 147+/-33 msec and 118.4+/-32 msec; on foam - 186+/-56 and 156+/-42 msec; on sand - 311+/-68 msec and 305+/-53 msec; and on gravel - 392+/-70 msec and 465+/-80 msec. Nevertheless, in the prior study, where participants had to lift the foot quickly after perception of VS, we observed great variability of the mean RT and standard deviation compared to the present study because a lengthy duration was necessary to analyze, in a timely fashion, walking safely with respect to balance. We suggest that the long time for analyzing is to avoid or reduce the risk of falls.

The protocol involved with lifting the foot quickly after the VS Tchakoute and Menelas (2018) represented principally a walking perturbation compared to the present study. During a perturbation process, we used other neurologic strategies to resolve the situation. As such, we corrected the motor task by including a hand task as the dual task. In our opinion, this preliminary study suggests that RT is not a stereotyped response and that environmental information is more important than haptic information for control of movement, such as walking.

Overall, the significant results showed that the RT varied according to the type of soil with a major propensity for gravel while there was a minor propensity observed for concrete. We also found that another factor influencing the RT to VS is the stimulus location. These two factors (type of soil and stimulus location) can be added to the list of factors influencing the RT found in the literature (Kosinski, 2008). However, it was found that hand RT reduced relative risk of falls using a visual stimulus and a finger-press response by 21% Lord et al. (2003) and 31%

Taylor et al. (2017), respectively. Nevertheless, in the present study, the VS was presented at the foot level and the RT mean was not higher than for studies Lord et al. (2003) and (Taylor et al., 2017). Therefore, as our mean RT values were fast on certain types of soil, we suggested that evaluation of RT to VS on the foot can be interpreted as a physiological characteristic of humans to diminish fall risk. Finally, we know that RT slows with age; RT involves both motor and cognitive processing, and a short RT is required for responding to environmental changes or perturbations of the center of mass (Taylor et al., 2017).

6.5 Conclusions And Future Works

The main objective of this study was to investigate, for the first time with new technologies, the simple RT (at rest) and the response time while walking to a short haptic stimulus on the lower limb. The results revealed the feasibility of using a new device (enactive shoe and smartphone) capable of conveying VS and recording response time at two locations of the lower limb (AL and FP). The findings suggested that RT is faster on concrete and foam when compared to sand and gravel soil. The SRTs at rest were 20% slower than the response time with regards to the control condition (concrete soil) during dual-task conditions (walking and pressing smartphone). The stimulus location has a weak effect, especially in the gravel condition. One possible extension of this work is to use an apparatus more adapted to convey VS, for instance, adding more Mark II haptuators at different locations under the FP. More people organized in two groups (fallers and non-fallers), the elderly or some motor disease patients with impairment of balance like, Parkinson's disease (PD) patients will be recruited for a future study to increase the significance of results with respect to effect of age and sex. Finally, another possible extension of this study would be to recruit the elderly or some motor disease patients with impairment of balance, like PD patients, and study the impact of age or impairment within two groups (fallers and non-fallers).

Chapter 7

Conclusion

This research concerns the use of an assistive device to reduce the risk of falling in an uncontrolled environment. The use of an assistive device for such a task requires two steps. First, one must compute the risk of falling, and following that, one must alert the user. Our work concerns the second phase of the project. To address this problem considering the advantages that it offers over vision and sound, we choose to exploit the haptic modality as the communication channel.

7.1 Realization of the Objectives

The first phase of this project allowed us to investigate the research context in depth. The context of haptic rendering in communication was explored. Precisely, we have evaluated the potential of tactons to communicate the risk level. In the first study, we presented the results of two experiments conducted to design and evaluate a set of tactons aimed to indicate the risk of falling via vibrotactile actuators embedded in a shoe. The experimental platform, a shoe with two haptuators, has been introduced in a prior work Gagnon et al. (2013c). We reported the results of an MDS study ($N = 14$) designed to find six easily distinguishable tactons out of 36 possible variations. A second experiment was then conducted to evaluate the users' ability to identify 4 of the 6 tactons, selected by each participant ($N = 38$). The participants were asked to identify the tactons in a set of 12 (4 tactons x 3 repetitions) until they reached an accuracy of 95%. The results indicate that all participants were able to reach 95% accuracy in five iterations and that their performance improved with practice. We concluded that it is possible to communicate four risk levels of falling under the foot of the user via haptic modality due to learning.

Following the first study, it was important to evaluate the effects of external perturbations of the perception of haptic stimuli. This has been studied at the second step. Precisely, we investigated the influence of auditory disturbances when communicating vibrotactile messages with the foot at rest position in two conditions (with disturbance and no disturbance). Vibrotactile messages were those from the previous investigation. We designed an experiment with 38 participants with an indoor setup consisting of several trials where the participant seeks to correctly identify the tactons rendered via the enactive shoe. We concluded that the audio distractions do have a significant effect on the number of iterations required to achieve the recognition rate of 95%.

Knowing that the reaction time is decisive to prevent falls, the last phase of this project consisted of validating our haptic system by investigating the variability of the reaction time to four vibrotactile messages during walking on five types of soil. To this end, we designed a new wearable haptic device using the haptic rendering from the first investigation. The setup consisted of a common environment of daily life, for example, walking on different types of soil. The question was whether people could perceive the haptic rendering, but above all, what was their reaction time under these conditions. We came to two conclusions. First, the reaction time was significantly longer on deformable surfaces compared to non-deformable surfaces.

Second, based on a post-experiment interview, vibrotactile messages are better perceived on non-deformable surfaces.

7.2 Research Questions

The identification of these problems allowed us to ask some research questions introduced in the first chapter that can be addressed in the following ways.

- *What might affect haptic communication?* In Chapter 2, we described the initial stages of haptic perception while reviewing the literature. We identified three main factors that might affect such a communication. The first regards the haptic interface (communication system) encompassing the design of the signal and the device (material). The second concerns the influence of the environment (context). The third is the limitation characteristics of the user while interacting with the communication system.

- *Is it possible to communicate the risk of falling through a haptic modality? If so, how can this be done?* In Chapter 3, we described the results of two perceptual experiments where distinguishable design parameters, (waveform and amplitude) were used to design stimuli. The results revealed the usability of the stimuli (tactons) to communicate four risk levels of falling using the foot via a haptic modality. Then, it is possible to use haptics to communicate the risk level. We can use the foot as a body contact interaction to perceive the stimuli.

- *What factors can disrupt communication of the risk level in moving?* We argued that the competition of information communication with some external resources could disturb the perception of haptic stimuli. Through the process of designing and building a prototype capable of use in various situations, like in moving, we study auditory disturbance during the haptic communication process. Through an experiment in Chapter 4, we addressed the evaluation of auditory distractors. We discovered external auditory stimuli are capable of distracting the perception of the risk of falling. Then, one factor to consider is auditory distractors.

- *What is the effect of the physiological characteristics of humans during haptic perception?* Haptic perception may be limited by the human physiological characteristics. In Chapter 2, we identified reaction time as an element that can characterize the limitations of haptic perception in humans. We were able to highlight this theory. In the first experiment in Chapter 5, we found that types of soil can influence the reaction time. In addition, with a device suitable for walking in Chapter 6, we also found that reaction time was influenced and varied by soil type. Thus, reaction time is a significant human physiological characteristic for the perception of information via haptic modality.

In summary, the answers to these questions allow us to validate a possible haptic communication system to inform the user of the risk level of falling.

7.3 Known Limitations

Despite the promising results obtained during our experiments (Chapters 3, 4, 5, and 6), we believe that our work still requires some years of research.

Particularly, our communication system has been globally evaluated with healthy young people and adults. Considering that the target population in this thesis research is elderly, this population must be evaluated. However, initial assessments have allowed us to set the premises regarding haptic perception. Another drawback of our communication system is that we did not assess the set of factors identified in Chapter 2 that can disrupt haptic communication. For instance, we did not evaluate cognitive distractors and motor distractors like walking. In addition, a joint assessment of these two factors will complete our work on haptic information communication in a mobile context.

The last limitation of our research thesis is that we have not evaluated or characterized the perception thresholds at the contact points at the foot. In our opinion, although the communication system proposed here has provided significant results, it does not fully exploit the physiological potential of the human and the diversity of the environment.

7.4 Prospects and Future Work

7.4.1 Objective

Our past work focused only on young people and adults, but the target population was seniors. My future work is in a multidisciplinary field. They will involve preventing falls to seniors and we plan to use the haptic channel which is a rich and varied channel. The guiding objective of this project is the communication of a risk level of falling among elderly people who are healthy and those who are not healthy. A context-sensitive support tool will be designed and should be able to counteract slowness, possibly improving walking and preventing falls.

7.4.2 Methodology

Initially, the project consists in measuring the slowness of the participants and comparing them to healthy control subjects by measuring their simple reaction times (TRS), their motor responses (TRM) in mobility and performing another task (dual task) following lower limb (foot) stimulation involved in walking using specialized mechanoreceptors (Chapwouo Tchakouté et al., 2018). Now, we plan to evaluate these measures with the target participants. A mobile application embedded on a smartphone will be developed to automate the process. It will be connected remotely to the haptic device. For the TRS, the challenge is to measure the RT at rest and the TRM to measure the TRM during walking (double task) and even triple task either during the Time Up and Go (TUG) test. Also we will evaluate the cognitive load with various test. At this step, it will be interesting to use distractor sounds that require constant concentration, for example a discussion to listen to.

- Classic TUG without stimulation = measure of slowness,
- Classic TUG with stimulation,
- Manual TUG = to wear a cabaret with a glass of water half full,
- Cognitive TUG = countdown by 7 starting from 100.

The first step will be to measure TRS and TRM during a disordered automatic task in participants and control subjects. We could add some tasks by inducing at a specific moment a mini perturbation while the walking cycle (chosen at random). At this time, we will look for correlations with the different TUGs and falls (evaluated by the fear of falling test and by questionnaire on their falls history of the last month). The walking route is based on the difficulties of daily life as validated by Ziegler et al. (2010) (Figure 7.1) and will run two or three times. The first time is performed without disturbance. Five minutes later, the participant restarts the test, but this time with the haptic device.

In a second step, we will try to check if we can improve TRS and TRM in participants by repeating the experiment under the influence of rhythm or attention exercises. The aim here is to evaluate the influence of slowness and the incidence of falls after home training with the device for 4 or 8 weeks. Row data and measures collected via remotely via a network architecture will be analyzed in real-time and send to a health professional. These steps have to be validated before using a low-cost network and software architecture implemented during

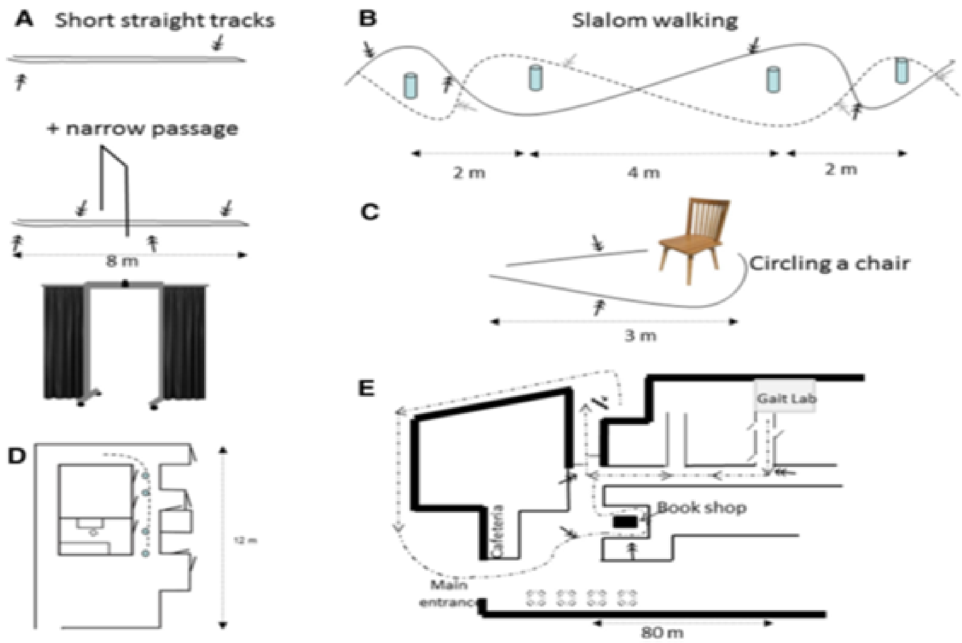


Figure 7.1: An example of a course simulating a daily activity.

the project and deployed at home to reduce slowness and falls. At this point, participants could increase their mobility and quality of life wherever. Some companies will be contacted to ensure the opportunity to make patents and market our solution to the general public.

To achieve our goal, we will recruit seniors participants (fallers / non-fallers) also those with low mobility will take part on the first part, such as those with Parkinson's disease (PD). Next, the experimental method will be to do a preliminary survey of the recruited participants. Then a set of successive experiments with clear objectives and indicators will be conducted. Here are some steps that will be covered by our project:

- Recruit participants of balanced (equal poupulation of men and women). The participants recruited for this project will be divided into three groups:
  - Control group: non-faller seniors
  - Experimental group 1: faller seniors

  - Experimental group 2: seniors with PD

- Define the experimental framework to accommodate the participants,
- Propose an experimental setup with types of soil that reproduce different daily situations,
- Conduct a survey on the perception threshold at the foot plantar with a users preference choice of haptic message. This step can be achieved in two situations at rest and in a mobile context,
- Propose a new haptic device adapted for mobility according to the frequency range found,
- Major lower limb tests will also be performed,
- Evaluation of the haptic signals and the proposed device,
- Design a new device adapted for context awareness and mobility
- Design adapted haptic signals for the senior,
- Intensity modulation of the haptic stimulus designed according to the type of soils,
- Parameterization of the haptic stimulus according to the participants (preference by default and personalized),
- Adaptation of the stimulus according to the context
- Different test groups as well as the repetition of the test after a few days to ensure the reproducibility of our method,
- Deport the methodology to an external context (real life) thanks to a network architecture to send information and collect measure remotely regardless of the location and the distance of the participant,

- Design a network and software architecture for the mobility, presence, and availability of the solution,
- Integrate experimental Group 2,
- Validate our method with the general public thanks to mobile computing techniques,
- Validate the adaptability of the solution to the real environment of use of the participants,
- Integrate experimental Group 3,
- Evaluate reproducibility of the methodology,
- For each phase of our protocol, the performance indicators will be the papers produced at each stage.
- Finally, we will look forward to evaluate the possibility of using the new haptic stimulus to guide users or informing them of the direction with the foot.

7.5 Scientifics Contributions

The results of this work have been published in the following papers:

1. **Peer reviewed journal articles**

    - Landry Delphin Chapwouo Tchakouté, Louis Tremblay, Bob-Antoine Jerry Ménélas: Response Time to a Vibrotactile stimulus presented on the Foot at Rest and During Walking on Different Soil. MDPI, Sensor (2018)
    - Landry Delphin Chapwouo Tchakouté, David Gagnon, Bob-Antoine Jerry Ménélas: Use of tactons to communicate a risk level through an enactive shoe. J. Multimodal User Interfaces 12(1): 41-53 (2018)

2. **International conferences with reading committee**

    - Landry D. Chapwouo Tchakouté, Bob-Antoine Jerry Menelas: Reaction Time to Vibrotactile Messages on Different Types of Soil. VISIGRAPP (2: HUCAPP) 2018: 155-161
    - Landry D. Chapwouo Tchakouté, Bob-Antoine Jerry Menelas: Impact of Auditory Distractions on Haptic Messages Presented Under the Foot. VISIGRAPP (2: HUCAPP) 2018: 55-63
    - Johannes C. Ayena, Landry D. Chapwouo Tchakouté, Martin J.-D. Otis, Bob-Antoine Jerry Ménélas: An efficient home-based risk of falling assessment test based on Smartphone and instrumented insole. MeMeA 2015: 416-421

7.6 Personal Assessment on this Research

In conclusion, I would like to present a brief personal assessment of my initiation to the world of research. The journey made throughout this project was quite challenging and constant work. However, it was very rewarding and worthy of all these short nights for which I traded hours of sleep for acquisition of new precious knowledge in the targeted area of expertise of HCI and virtual reality, especially in haptics. I was able to successfully conduct this project because of its stimulating nature. As a member of a formidable multidisciplinary team, I have been lucky enough to participate in multiple projects and activities with peers from different fields.

This experience allowed me to develop important new skills, such as a rigorous research methodology and communication skills. I had to master many different areas ranging from electronics to artificial neural network to haptics communications theory. Finally, all the work done for this thesis or to improve my skills in order to succeed this thesis have allowed to write several scientific publications greatly improving my skills in English. This rewarding experience also allowed me to make a few contributions to the scientific community in my field of research that were presented at famous international conferences (Ayena et al., 2015; Tchakoute and Menelas, 2018; Chapwouo Tchakoute and Menelas, 2018) and journals (Tchakoute et al., 2018; Chapwouo Tchakouté et al., 2018). After such a positive introduction to research, I look forward to beginning a career as a researcher and pushing the limits of science into new territories. My last words go to all the persons that supported me, one way or another, intentionally or not, in my quest to obtain expertise, new skills, and priceless knowledge: thank you.

**

Appendix A - Approval of the ethics application obtained before the start of experiments

UQAC
Comité d'éthique de la recherche
Université du Québec à Chicoutimi

APPROBATION ÉTHIQUE

Dans le cadre de l'*Énoncé de politique des trois conseils : éthique de la recherche avec des êtres humains 2* (2014) et conformément au mandat qui lui a été confié par la résolution CAD-7163 du Conseil d'administration de l'Université du Québec à Chicoutimi, approuvant la *Politique d'éthique de la recherche avec des êtres humains* de l'UQAC, le Comité d'éthique de la recherche avec des êtres humains de l'Université du Québec à Chicoutimi, à l'unanimité, délivre la présente approbation éthique puisque le projet de recherche mentionné ci-dessous rencontre les exigences en matière éthique et remplit les conditions d'approbation dudit Comité.

Responsable(s) du projet de recherche : *Monsieur Landry Delphin Chapwouo Tchakoute, étudiant*
Doctorat en sciences et technologies de l'information, UQAC
Département d'informatique et de mathématique,

Direction de recherche : *Monsieur Bob-Antoine-Jerry Ménélas, professeur*
Département d'informatique et de mathématique, UQAC

Projet de recherche intitulé : *Évaluation d'un dispositif haptique pour l'amélioration de l'interaction en mobilité*

No référence : *602.462.01*

Financement : *CRSNG-Subventions à la découverte de M. Ménélas ayant pour titre Exploitation d'interaction 3D multimodales pour remplacer ou renforcer un retour visuel dans un environnement non-contrôlé*

La présente est valide jusqu'au 30 avril 2018.

Rapport de statut attendu pour le 31 mars 2018 (rapport final).

N.B. le rapport de statut est disponible à partir du lien suivant : *http://recherche.uqac.ca/rapport-de-statut/*

Date d'émission initiale de l'approbation : *18 mars 2015*
Date(s) de renouvellement de l'approbation : *6 avril 2016, 10 mai 2017*

[redacted]

Nicole Bouchard,
Professeure et présidente

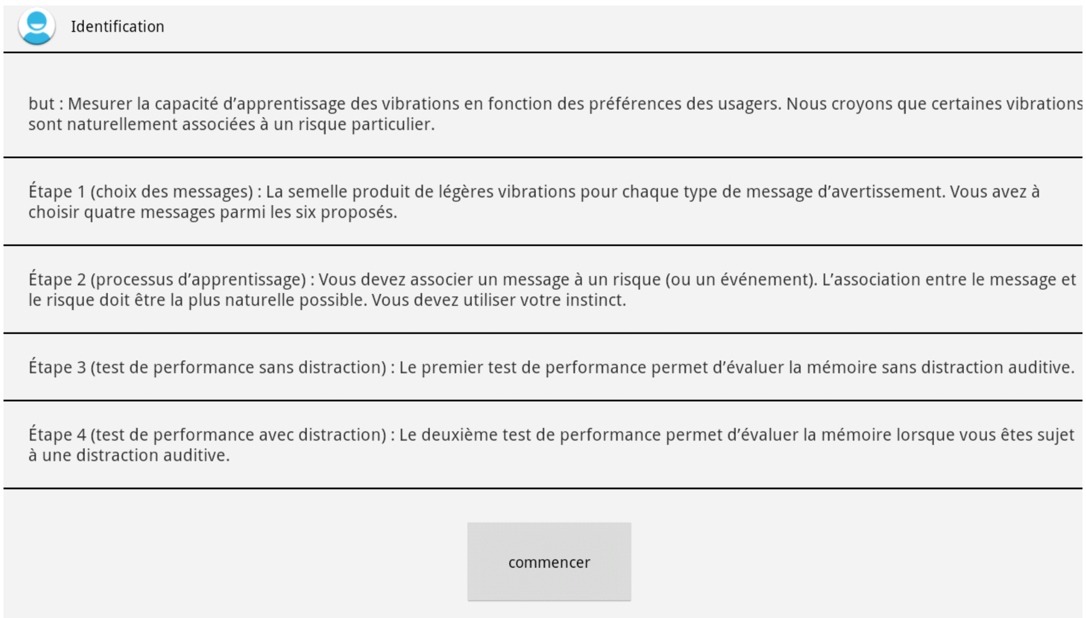
Appendix B - Questionnaire 1

Questionnaire

Le questionnaire prend la forme d'une application informatique s'exécutant sur une tablette *Android*. Avant l'utilisation de l'application, chacune de ses fenêtres sera expliquée au participant. L'application a cinq fenêtres différentes, tel que présentées ci-dessous.

Introduction

Les différentes étapes de l'expérimentation sont présentées sommairement. Le participant peut appuyer sur le bouton « commencer » pour débuter la procédure.



Sélection des messages tactiles (3)

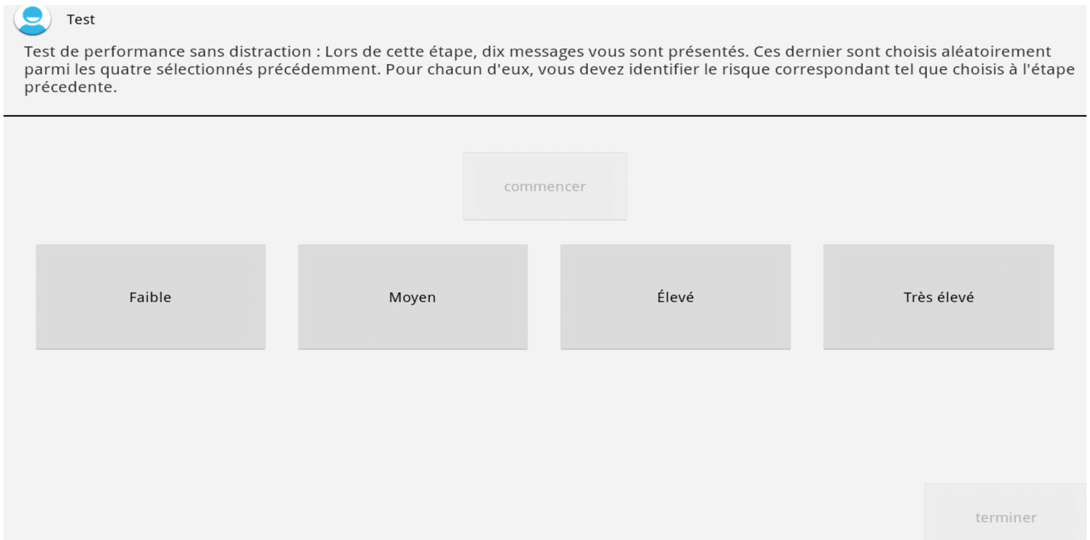
À cette étape, le participant est invité à ressentir chacun des messages tactiles en appuyant sur les boutons correspondant. Il doit par la suite en sélectionner quatre avant de passer à l'étape suivante. Il sagit ici du point 3 de l'étape 1 tel que présenté dans le formulaire de consentement.

Association des messages à un risque (4)

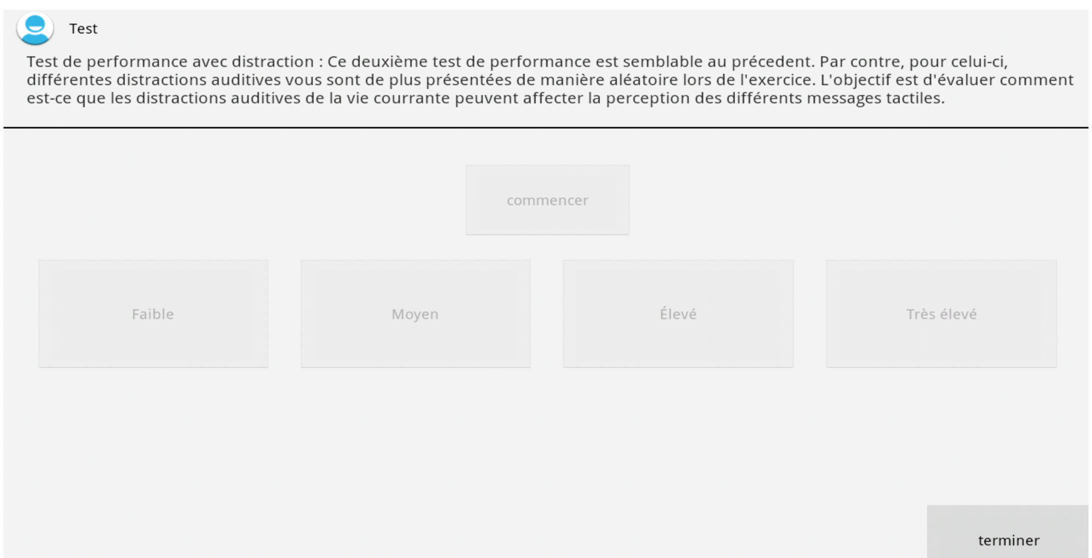
Pour associer les messages sélectionnés à un risque, le participant doit lier chaque message à un risque différent. Les messages peuvent être ressentis à nouveau en appuyant sur les boutons correspondant. Une fois les quatre associations complétées, le participant peut passer à la prochaine étape. Cette étape correspond au point 4 de l’étape 2 tel que présenté dans le formulaire de consentement.

Tests de performances (apprentissage) (5a, 5b)

Les deux tests de performance assis utilisent la même fenêtre. Dès que le participant appui sur le bouton « commencer », un signal tactile choisi aléatoirement parmi ceux sélectionnés est envoyé au participant. Ce dernier doit ensuite sélectionner le risque correspondant tel que défini à l'étape d'association. Chaque test comprend dix messages. Un score de zéro à dix sera compilé à partir des réponses du participant. **Le participant n'aura pas accès à son score.**



Le deuxième test est identique au premier, à la seule différence que pour celui-ci, une distraction auditive sera ajoutée.



Ces deux tests correspondent respectivement au point 5a et 5b de l'étape 2 tel que présenté dans le formulaire de consentement.

Test de performance lors de la marche (6)

La performance lors de la marche est évaluée à l'aide de la même interface que le test de performance assis sans distraction auditive (5a). Or, pour ce test, c'est l'évaluateur qui manipulera l'interface alors que le participant marchera selon la trajectoire défini. Pour chacun des stimuli tactiles présentés lors de la marche, le participant devra identifier à vive voix le risque associé et l'évaluateur appuiera sur les boutons correspondant. Tout comme les tests précédents, un score de zéro à dix sera compilé à partir des réponses du participant. **Le participant n'aura pas accès à son score.** Cette étape correspond au point 6 de l'étape 3.

Appendix C - Questionnaire 2

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Chicoutimi le …..../……/…..….

QUESTIONNAIRE ADMINISTRÉ

PAR LE CHERCHEUR

Avant l'expérimentation

1- Caractéristiques du participant

Participant N°	
Âge (ans)	
Sexe (M/F)	
Taille (cm)	
Poids (Kg)	

2- Questions

2.1- Aviez-vous déjà consulté un médecin pour la sensibilité à la plante du pied?

☐ Non

☐ Oui

2.2-Aviez-vous du mal à marcher dans des conditions normales (sans un obstacle environnemental ?

☐ Oui

☐ Quelques fois

☐ Non

3- Présentation et explication des séries d'expériences à effectuer au participant

<u>Pendant l'expérimentation (voir déroulement du test dans le formulaire de consentement)</u>

4- Prise de mesures quantitatives du participant :

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À CHICOUTIMI

QUESTIONNAIRE POUR LE PARTICIPANT

Rappels et compréhension des termes au participant

La perturbation au sol consiste à l'utilisation de six différents types de sol, à savoir le béton, le gravier, le sable, le parquet et le tapis en mousse. Le stimulus haptique utilisé est une vibration envoyée à la plante du pied.

N°	La liste des cas d'expériences effectuées
1	Apprentissage et familiarisation avec les Tactons (vibrations) en position statique assise
2	Test d'évaluation des Tactons en position statique debout sur le béton
3	Test d'évaluation des Tactons en position mobile (marche) sur le béton
4	Test d'évaluation des Tactons en position mobile (marche) sur le Tapis
5	Test d'évaluation des Tactons en position mobile (marche) sur la mousse
6	Test d'évaluation des Tactons en position mobile (marche) sur le gravier
7	Test d'évaluation des Tactons en position mobile (marche) sur le sable

1- Parmi les six types de sols, sur lequel ou lesquels aviez-vous éprouvé des difficultés à marcher ?

☐ Béton ☐ Tapis

☐ Mousse ☐ Sable

☐ Bois ☐ Roche

2- Quelle pourrait-être selon vous le niveau de resentis des vibrations sur chacun des sept types de sol ?

Expérience : Les vibrations sur les sept types de sols	Perception de la vibration	
Béton	☐ Aucun ☐ Faible ☐ Modéré	☐ Élevé ☐ Très élevé
Mousse	☐ Aucun ☐ Faible ☐ Modéré	☐ Élevé ☐ Très élevé

Bois	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Polymère	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Tapis	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Sable	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Roche	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré

3- Quelle pourrait-être selon vous ce niveau de risque dans chacun des cas suivants ?

Expérience : La marche sur les six types de sols	**Niveau du risque**
Béton	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Mousse	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Bois	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Tapis	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Sable	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré
Roche	☐ Aucun ☐ Élevé ☐ Faible ☐ Très élevé ☐ Modéré

4- Quelle type de vibration est la mieux perçue pour chaque type de sol ?

Expérience : Les vibrations sur les sept types de sols	**Type de vibrations**
Béton	☐ M1 ☐ M4 ☐ M2 ☐ M5 ☐ M3 ☐ M6
Mousse	☐ M1 ☐ M4 ☐ M2 ☐ M5 ☐ M3 ☐ M6

Bois	☐ M1 ☐ M2 ☐ M3	☐ M4 ☐ M5 ☐ M6
Polymère	☐ M1 ☐ M2 ☐ M3	☐ M4 ☐ M5 ☐ M6
Tapis	☐ M1 ☐ M2 ☐ M3	☐ M4 ☐ M5 ☐ M6
Sable	☐ M1 ☐ M2 ☐ M3	☐ M4 ☐ M5 ☐ M6
Roche	☐ M1 ☐ M2 ☐ M3	☐ M4 ☐ M5 ☐ M6

5- Seriez-vous d'accord pour son utilisation de l'haptique dans la vie quotidienne pour transmettre des informations sur un niveau de risque quelconque lors de la marche ?

Totalement en désaccord				**Totalement en accord**
1	2	3	4	5
○	○	○	○	○

<u>Auriez-vous un commentaire à nous communiquer à ce propos ?</u>

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