Assessment of the neck as a haptic surface for displaying vibrations for emotional responses

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Abstract

Haptic technology is used in the game and media industry to augment a user's presence through touch related sensations. Affective haptic studies haptic feedbacks to elicit humans emotion but, so far, no shared framework exists that states how to achieve this. By exploiting the correlation between the physiological changes in the body induced by the autonomic nervous system is a promising method but requires expensive and obtrusive devices. Striving for devices that are relatively inexpensive and easy to replicate we focus our study on the neck. We argue that the neck has the peculiarity of being completely exposed and intimate hence the haptic feedback provided by vibroelectric motors are sufficient to trigger an emotional response in a user. To test our assumption we created a haptic device and a haptic dataset. We proved that our setup was indeed sufficient to elicit different emotional states in a user as meant by the circumplex model of emotion. We found that the *intensity* of vibration and the *sequence* in which the actuators are driven affect the *arousal* but not the *valence.* Instead the *vibration* affected both the *arousal* and the *valence.* We discussed these limitation and offered a set of guidelines on haptic stimuli meant to ease the design of affective feedback for devices that employ an array of actuators.

Preface

This document was written in fulfillment of the requirements for the Master degree in Gamed and Media Technology at the University of Utrecht. The purpose of this report is to present the results of an experiment that assesses the neck as an eligible surface to perceive vibrotactile stimuli meant to convey emotional states. This document reviews each of the phases that lead to its final implementation.

The major outcome of my research is a scientific paper which cane be read as a stand-alone article and can be found at the end of this thesis (Chapter 5). The rest of this document is complementary to it and its structured as follows: the first chapter contains a detailed literature study that constitutes the theoretical background of this work. Here a brief definition for *affective haptic* as well as several techniques to implement it are presented. The chapter ends with a brief summary of the covered topics and a research question is stated. The second chapter provides a description and the motivation that leads to the design of a neck device used in the experiment. Here its main components are described highlighting advantages and disadvantages of our design choices. Chapter 3 and Chapter 4 review the two preparation studies conducted to define the parameters for vibrotactile stimuli tested in the main experiment. The former exploits the *Method of Limits* to assess the neck's sensitivity regarding the highest non-perceivable vibration and the lowest perceivable vibration that is not experienced as irritating by a user. The latter consisted in a *Discrimination Task* between vibrotactile stimuli that have been created by combining together custom design parameters. The aim of this experiment was to validate the design of the custom designed parameters and to create an haptic dataset populated by perceptually different vibrotactile stimuli. Finally, Chapter 5 contains the aforementioned stand-alone scientific paper summarizing the major results of the thesis. It combines the findings of the previous experiments to assess the affective value of the elements belonging to the haptic dataset through a 3 way within subjects *MANOVA*.

Contents

Chapter 1

Literature Review

1.1 Introduction

Information technology has recently been addressed with the lack of emotional expressiveness in human computer interaction. Consequently, researchers in computer science, cognitive science and psychology shared ideas giving rise to affective computing which aim is to study and develop systems that can detect, display, elicit and communicate affects (Eid and Al Osman 2016).

Measure Emotions
Given the nature of this recently born field of study and since emotions are expressed subjectively, there is not an agreed definition of what an emotion is (Picard and Picard 1997) nor a shared framework that assesses how to elicit them. Among others, Ekman (Ekman 1992) proposed a discrete model of emotion which adjudges six basic emotions (i.e. anger, fear, disgust, happiness, sadness, surprise) as a set shared across all the cultures; each basic emotion is distinct and it has its unique physiological, expressive and experiential properties and all the other emotions can be created as a combination of those.
Advocates of the dimensional model of emotion refute this discrete view arguing that basic emotions are a result of our experiences and as such they are not congenital. They claim that emotions are not distinct states but rather overlapping dimensions in human emotional space, which are propelled by valence, arousal and dominance. Based on this ratings the self-assessment manikin model (SAM) (Bradley and Lang 1994) have been proved to be a valid way to measure emotion-related experiences. Lastly, the circumplex model of affect (Russel 1980) proposes a view in which affective experiences are driven by valence and arousal, but labeled with a discrete emotion once we interpret them.

Multi Modalities
Visual and auditory stimuli represent the main medium through which emotions are elicited, as research in haptic technology was initially focused on others cognitive aspects of haptic stimuli. These studies aimed to convey information without overloading the visual and auditory channel to aid blind or visually impaired people, to alert a user, to provide spatial information and to present abstract information on the skin (Lylykangas et al. 2009). Nonetheless, the sense of touch is the earliest sense to develop in a human embryo and the human skin has specific reception to process affective touch (Erp and Toet 2015). Consequently, researchers in affective computing started to investigate up to which extent haptic technology can be exploited in the process of detecting, displaying and communicating affects. This field is known as affective haptics and it has several application ranging across health care and assistive technology for children with autism, affective and collaborative entertainment and gaming, online communications and social and inter-personal communication (Eid and Al Osman 2016).

1.2 Previous affective haptic applications

Within the field of affective haptics, we are interested in affective touch, which studies how participants emotionally react to haptic stimuli and explores the quality of experience measuring methods (Eid and Al Osman 2016).

1.2.1 James Lange Theory

One way is to exploit the correlation between the physiological changes in the body induced by the autonomic nervous system. As such, advocates of the so called James Lange theory, have developed ad hoc devices to assess if a physical reaction induces an emotional experience. For example, Fukushima (Fukushima and Kajimoto 2012), forced the piloerection on a user arm, and by measuring the skin conductance reaction (SCR), found out that this reaction enhances the feeling of surprise; Ueoka (Ueoka, AlMutawa, and Katsuki 2016) imposed a fake heartbeat, felt under the sole of the feet through a silent subwoofer, and recorded the heart rate variability (HVR). They found out that the real heart beat was affected by the modulation of the fake one enhancing the feeling of being scared in a VR experience. Also Tsetserukou (Tsetserukou, Neviarouskaya, and Terashima 2013) developed some tools to enhance social interactivity and emotionally immersive experience in real time messaging. These tools are

- HaptiHug: a wearable haptic display generating forces similar to those of a human hug on the back of a user.
- HaptyButterfly: a tool, shaped like a butterfly, that is developed to evoke joy. It reproduces ”butterflies in your stomach” on a user’s abdomen.
- HaptiShiver and HaptiTemper: these two work together to evoke fear. The former sends a shiver up and down your spine through a row of vibration motors while the latter sends chills up and down, to the same area, through both cold airflow from a fan and the cold side of a Peltier element.
- HaptiTickler: evokes joy by tickling a user’s ribs. It includes four vibration motors reproducing stimuli similar to human finger movements.

Lemmens (Lemmens et al. 2009) created a haptic jacket with 64 ERM motors, divided in 16 strings, to add vibrotactile stimulation attempting to create emotionally fully immersive experience while watching a movie. This configuration, allowed them to create vibrotactile patterns abide by the James Lang theory and more abstract pattern such as ”a comforting arm around a shoulder”. Also Arafsha (Arafsha, Alam, and El Saddik 2012) built a prototype of a haptic jacket designed to enhance video gaming and movie watching experience. Their setup is composed of six haptic components (i.e. chest and neck vibration, neck warmth, heartbeat simulation, arms vibration and shivering) and it includes 35 vibrotactile units as well as thermoelectric coolers and temperature sensors to evoke emotions by inducing physical body reactions.

1.2.2 Tangible Interfaces

Other researchers exploited tangible interfaces as mediating tool to help a user to reach a specific emotional state. Yu (Yu et al. 2015) designed a device that simulates humans breathing movements through the shape of an inflatable airbag to minimize the cognitive workload in relaxing exercises; Aslan (Aslan et al. 2016) presented two tangible somaesthetic designs: the former resembles a real heart and the latter is a stuffed animal which is capable to breathe synchronously with a user. These are hand-held tangible artifacts that provide haptic sensations by changing their shapes which guide a user’s attention away from their body helping them in inward listening tasks.

1.2.3 Pure Vibrotactile

Although it seems intuitive that haptic stimulation works better when coupled with other senses (Wilson, Romeo, and Brewster 2016) we are mostly interested in pure vibrotactile sensation as a more compact and feasible design is required to investigate its correlation with emotional states. In this field Salminen (Salminen et al. 2008) developed a friction-based horizontally rotating fingertip stimulator to investigate emotional experiences and behavioral responses to haptic stimuli when the burst length, the continuity and the direction of the stimuli are changed. They discovered that all the four parameters of the SAM model (i.e. pleasantness, amorousness, approachability and dominance) were affected by the rotation style while the burst length was not significant. Ur Rheman (Réhman and Liu 2010) rendered emotional information, extracted from the humans lips movement, into vibrotactile patterns on mobile phones: the frequency of the vibrotactile stimuli rendered the emotion type (i.e. happiness, surprise, disgust and sadness) while the magnitude coded the emotion intensity. In their tests, users were able to recognize the emotions presented to them after a little training. Rantala (Rantala et al. 2013) studied if vibrotactile stimulation, that imitates human touch, conveyed intended emotions (i.e. the feeling of being unpleased, pleased, relaxed or aroused) from one person to another. They used a device, previously designed by Rantala (Rantala et al. 2011), that converts touch gesture of squeeze and finger touch from the sender into vibrotactile stimulation perceived from the receiver. Both of them evaluated the stimulation using rating scales for valence and arousal. By matching the senders' intended emotion and the receivers' interpretation they found that the squeeze gesture is better at communicating unpleasant and aroused emotional intention, while the finger touch was better at communicating pleasant and relaxed emotional intention.

1.3 Research Question

Through this review of affective haptic studies, we can infer that it is possible to evaluate changes in the emotional state of a person through self assessment form. These emotional states can be evoked and affected through a haptic medium (Smith and MacLean 2007) and several techniques and haptic interfaces exist to reach this goal.

We first focused on experiments abide by the James Lang theory which states that a specific emotional state is evoked by inducing a physiological response to a specific location of the body. Although their results seem convincing, reproducing those sensations leads to an obtrusive and complicate set up. Indeed, different parts of the body need to be stimulated by haptic patterns which mimic real physiological reactions. These patterns require a large amount of vibrotactile actuators often coupled with other haptic devices to convey, for example, thermal stimuli or to create tangible interfaces.

Then, we discussed those studies that investigated the relation between emotions and vibrotactile stimuli. Driven by their results we argue that it is possible to evoke emotional states in a user by exploiting pure and abstract vibrotactile information. Patterns that fit this set are composed by stimuli generated solely with vibrotactile actuators and that do not attempt to mimic human gestures (i.e. a caress) and do not attempt to recreate physiological reactions as intended in the James Lang theory. The main advantage of these patterns is that their implementations require a more compact and simple design compared to the ones discussed so far. The inevitable trade-off, given the intrinsic limitations of this technology, is the limited amount of different patterns that it is possible to convey.

We want to investigate the neck area as an eligible location to receive tactile information that elicit emotional states in a user. We argue that the neck, even if its skin has no substantial difference compared to others part of the body, has the peculiarity of being simultaneously completely exposed and intimate. Hence, by exploiting this intimacy, we speculate that simple vibrotactile stimuli, conveyed by an array of eccentric rotating mass (ERM) motors, are sufficient to create patterns that trigger an emotional response in a user while keeping the design compact and simple. Therefore our research question is:

> *"Is it possible to elicit emotions belonging to the four quadrants of the circumplex model of emotions through simple vibrotactile stimuli conveyed on the neck?".*

For this reason, our study is structured in three phases: in the first we assess the range of vibration's intensities that can be felt on the neck using our device. Then we conduct an experiment to create an haptic dataset populated by variations that are perceptually different. Finally we tested the emotional response related to these elements.

Chapter 2

Apparatus

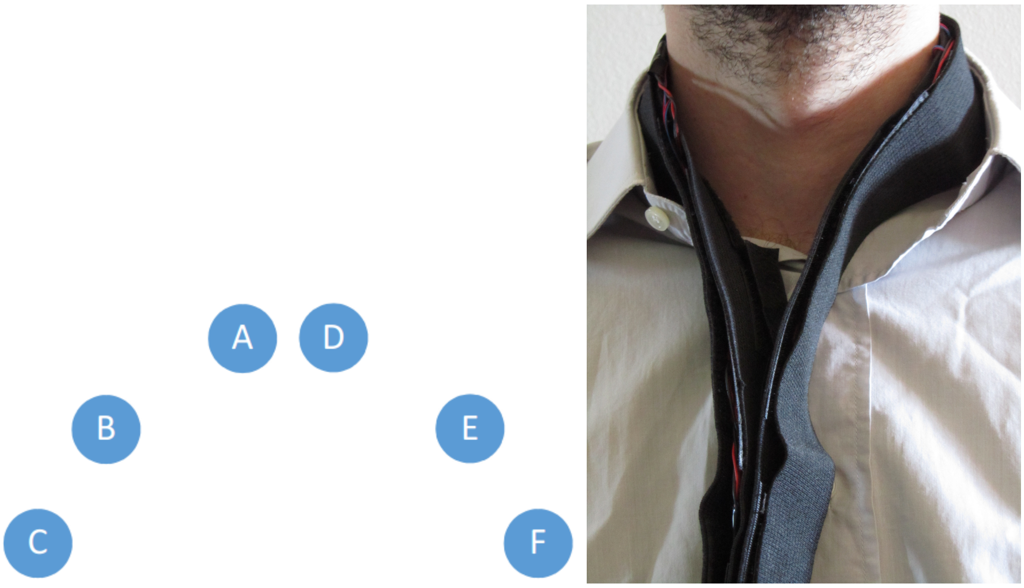
To test whether the neck is an eligible haptic interface where simple vibrotactile vibrations can be used to elicit emotional status, we need to design a device that is comfortable and reasonably inexpensive. The vibrotactile units must be light, small and they have to be displaced so that it is possible to perceive each of them as a distinct *"Buzz"* on the skin. At the same time we require them to be close enough to create what we call a *"Smooth"* vibration, where the intensity of the vibration is increased from an actuator to the other resulting in a stimulus that is perceived as a continuum along the neck. This is required as we want to compare our results with Seifi (Seifi and Maclean 2013) and Yoo (Yoo et al. 2015) which assessed that the roughness of an haptic stimulus influences both the rating for *Valence* and *Arousal*.

2.1 Introduction

In Chapter 1 several studies have been reviewed but either their design was too complicated, either they embedded the actuators in clothes either they combined vibrotactile feedback with thermal stimuli. To the best of our knowledge Taghavi (Taghavi 2011) is the only that offers a design for an neck haptic device that makes use of vibrotactile actuators. Since their study investigated directional cues conveyed on the neck, we had to to adapt their design for our purposes. Specifically the position and the distance between the actuators was inspired by this study. Indeed they used 12 actuators each sharing a distance of 2.5cm and with this configuration the participants to their experiment were able to locate the position of the actuator that vibrated within a range of ± 1 actuator. Also they found that vibrations perceived on the front of the neck are less recognizable. To cope with these issues we choose a design that involves 6 actuators divided in two groups on each side of the neck (i.e. actuators ABC and DEF in Figure 2.1a). Actuators belonging to a group share an intra distance of 5cm, while the two extremities (i.e. actuators A an D) shares a distance of 1.5cm. This way the distance covered by the actuators sums up to 23cm which permits to comfortably position the device around an average size neck. Furthermore a distance of 5 cm allows to perceive the actuators distinctly while conveying a sense of direction when they are driven in sequence. Since it wasn't possible to replicate their frame, we opted for a solution which involved two simple elastic bands covered in Velcro strips. Although this design is extremely simple it offers several advantages in terms of comfort, safety and ease of repair (Figure 2.1b). Indeed, the elastic band can be worn around the neck and closed in the front without risking to choke a participant. Furthermore the wire cables that connect the actuators to the board are contained within the two elastic bands and there is no direct contact with a participant's skin. Finally the velcro strips allow to easily adjust the position of the actuators.

For the hardware we opted for an ArduinoMega board mounting the necessary circuitry to drive six vibration motors. We had already experience with this set up and it perfectly fit our needs in terms of cost efficiency and easiness to use. Hence the device is composed by the control unit mounting six screw terminals driving six ERM actuators soldered to a 100cm long kynar wire. Each actuator is glued to the center point of a Velcro square (1cm side) to facilitate the placement of the motors on a 90cm long elastic band covered with Velcro strips. To protect the cables, another elastic band of the same length is attached through Velcro strips on the back of the other.

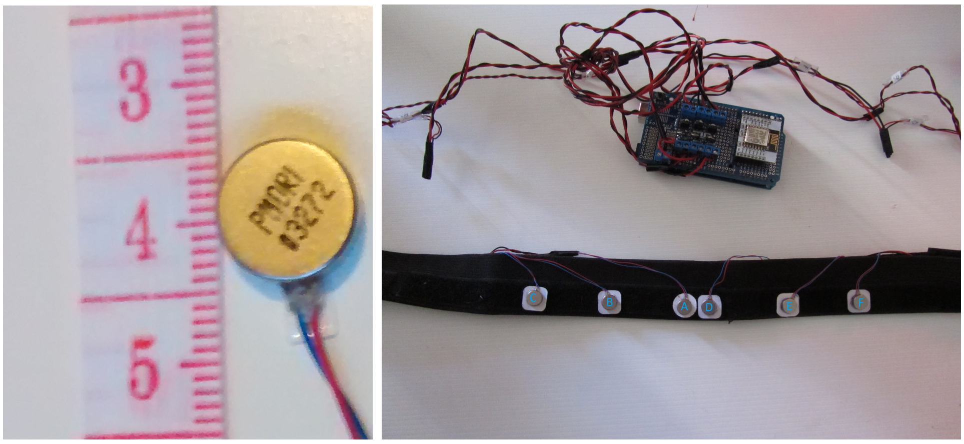
The actuators are attached to the Velcro strip so that the first two actuators (i.e. actuators A and D in Figure 2.1a) share a distance of 1.5 while being symmetrical with respect of the last cervical vertebra of the spinal cord. The others are spaced by 5 cm. The device is illustrated in Figure 2.2.



(a) Schematic representation of the actuators around the neck.

(b) The device worn on the neck.

Figure 2.1: Actuators Configuration



(a) Precision Microdrives's vibration motor Model 310-113 (Precisionmicrodrivescom 2016).

(b) The Device.

Figure 2.2: Apparatus. We can clearly distinguish all the pieces that compose the device: in the center, the ArduinoMega with the PCB mounted on top. On this, there are soldered the ESP8266 and the power shield. Six kynar wires connect the actuators to the device. Around it, the elastic band.

2.2 Board Communication

A printed circuit board (PCB) mounting an ESP8266 WIFI module and the necessary circuitry to drive several ERM motors with pulse width modulation (PWM), is stacked on the top of an Arduino MEGA. A user can send instructions to this device either via the UDP protocol over WI-Fi or via a serial connection with a baud rate of 38400. This rate allows to send up to 38400 bits per second. We use a set of instructions formatted as a string of text which are on average 10 characters long: since each character is 8 bits, we are able to send up to 480 instructions per second to a single actuator or $\frac{480}{N}$ instructions per seconds to each of the N actuator. To convey information with a temporal pattern, the time between signals must be at least 10ms for a burst duration of 10ms (Van Erp 2002). This means that a user is virtually able to distinguish up to 50 instructions per second. Hence, our solution is more than acceptable. Also we can precisely increase or decrease the intensity at which the actuators vibrate by exploiting the interrupts on the Atmega2560 micro controller's timers: if we increase the intensity linearly over a period of time, we can create a smooth transitions from one PWM level to another; if it goes up in the shortest amount of time to the desired intensity, it will be perceived as a buzz vibration.

2.3 Vibration Motors

The vibrotactile signal is created using ERM motors, model 310-113 Precision Microdrives (Figure 2.2a) which are light, little and relatively inexpensive, but it is not possible to separate the frequency at which the unbalanced shaft rotates from the perceived amplitude of the vibrotactile stimuli. Driven at the maximum voltage (i.e. 3.6V) the unbalanced mass rotates at 203Hz which is perceived on the skin as an acceleration of 1.8G. For the sake of simplicity we will refer to those quantity as *Intensity* of the signal, which has a maximum value of 100. All the specifics for this vibration motor are reported in Figure 2.3.

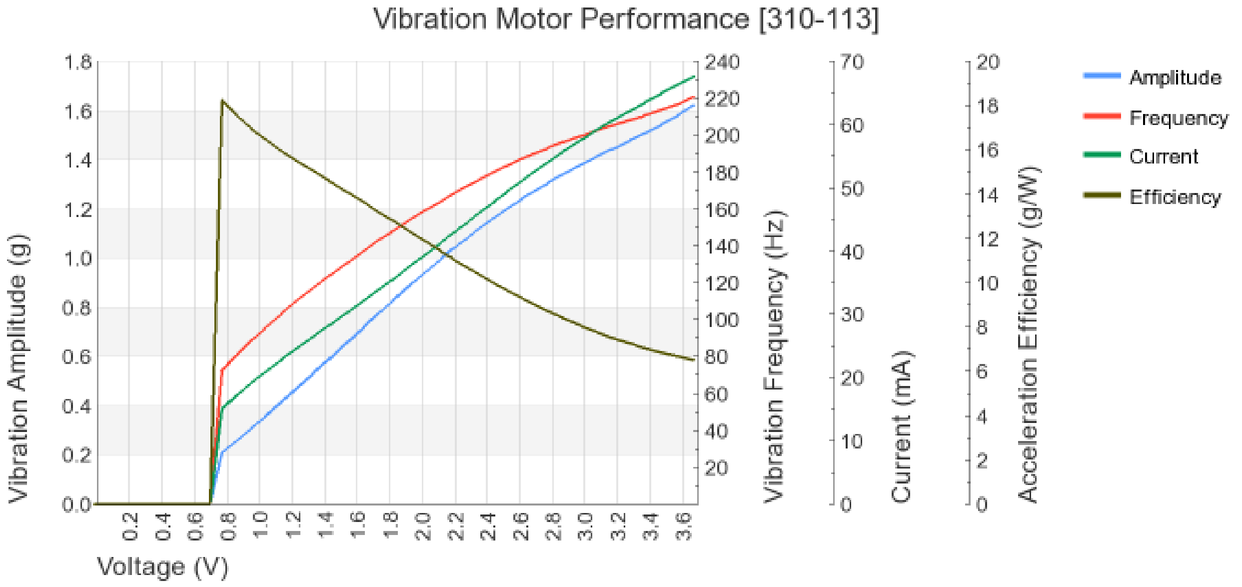


Figure 2.3: Typical Vibration Motor Performance Characteristics: Here are represented the typical performance characteristic for the Precision Microdrives's vibration motor Model 310-113. In particular it is represented the linear proportionality between the Amplitude and Frequency of the Vibration (Precisionmicrodrivescom 2016).

Chapter 3

Experiment 1: The neck's skin sensitivity

3.1 Introduction

The aim of this experiment is to gain insight into users' sensibility regarding vibrotactile stimuli on the neck. In particular we want to assess the lower and upper boundaries for the range of intensities that can be perceived on the neck using our device. This is necessary so that we can compare our results with other studies that employ different haptic devices. Specifically we are interested in finding a range of vibrations that can be perceived on the neck. Also this experiment allow us to validate the design of our apparatus (Chapter 2). Indeed, through this experiment, we are implicitly testing the ability of a user to perceive the vibration on six different positions around the neck for a prolonged period of time without irritating a participant. Consequently, as it is always true for other parts of the body, we are assuming that above a certain intensity value a vibrotactile stimulus conveyed on the neck is perceivable.
Hence, our hypothesis is that two sensory thresholds exist for vibrotactile intensities conveyed on the neck, namely:

- The lower threshold separates the intensities that are non-perceivable from the ones that are perceivable.
- The upper threshold separates the intensities that are perceivable from the ones that are irritating. Every intensity that causes annoyance to a user it is considered "Irritating".

3.2 Experiment

SERIES	Variation	Starting Value	S0	S1	S2	S3	S4	S5	Final Value
Descending	-3	30	P	P	P	P	N		18
Non-Perceivable to Perceivable	+3	7	N	N	N	N	P		19
Perceivable to Irritating	+3	45	P	P	P	P	P	I	60

Table 3.1: Example for the three series are presented. *Variation* refers to quantity that is added or subtracted from the *Starting Value* at each Step S_i depending on the type of Series. **P**erceivable, **N**on-Perceivable or **I**rritating represent the answer of a user. A series ends when there is a change in the answer.

We used the device described in Chapter 2 to test users' perception of vibrotactile stimuli by changing their intensity. We measured the absolute thresholds by a modified version of the method of limits.

According to our hypothesis a user had to choose between three options for each stimulus, namely: *Non-Perceivable*, *Perceivable*, and *Irritating.* Therefore three series were created:

- **Descending Series:** this series starts with an intensity above the range of non-perceivable values (i.e. *Perceivable*). At each steps, the intensity decreases until a user reports the disappearance of the stimulus (i.e. *Non-Perceivable*).
- **Ascending Series - Non-Perceivable to Perceivable:** this series starts with an intensity below the range of perceivable values (i.e. *Non-Perceivable*). At each steps, the intensity increases until a user reports the presence of the stimulus (i.e. *Perceivable*).
- **Ascending Series - Perceivable to Irritating:** this series starts with an intensity in the range of perceivable values (i.e. *Perceivable*). At each steps, the intensity increases until a users reports irritation (i.e. *Irritating*) or the maximum value is reached.

Examples for each series are provided in Table 3.1. The transition point between two different states was considered as an estimation of the threshold. Therefore, the lower boundary is designed as the average of each estimation of thresholds from the first two series. The upper boundary is designed as the average of each third series' estimation of thresholds.

For each series, five repetitions were created for each actuators, resulting in 90 total series. To prevent *errors of habituation* and *errors of expectation* each series started with a pseudo randomly generated value and they were presented to a user in a pseudo random order. The range of starting values for each series were selected in an informal experiment testing six subjects.

3.2.1 Methodology

10 voluntary participants (7 females, 3 males) in the age group of 23 to 27 were tested. Each participant was instructed about the purpose of the experiment and asked to listen to white noise through headphones to mask any source of noise. The tester put the device around the neck of a user so that the actuators were symmetrical with respect to the most superior cervical vertebra of the spine. The tester made sure that a user felt comfortable. Finally, a user was asked to look at a laptop's screen to interact with the experiment's GUI.

Before the actual experiment began, a user was asked to complete the training phase. A user clicks the Test button until it was disabled. Each time a different actuator was driven for half a second at a value of 50 which was the half of the maximum intensity. Then it stopped and a dialog box appeared. A user closes the dialog box to perceive the next actuator. This was repeated until each actuator was driven exactly once. Then the experiment started.

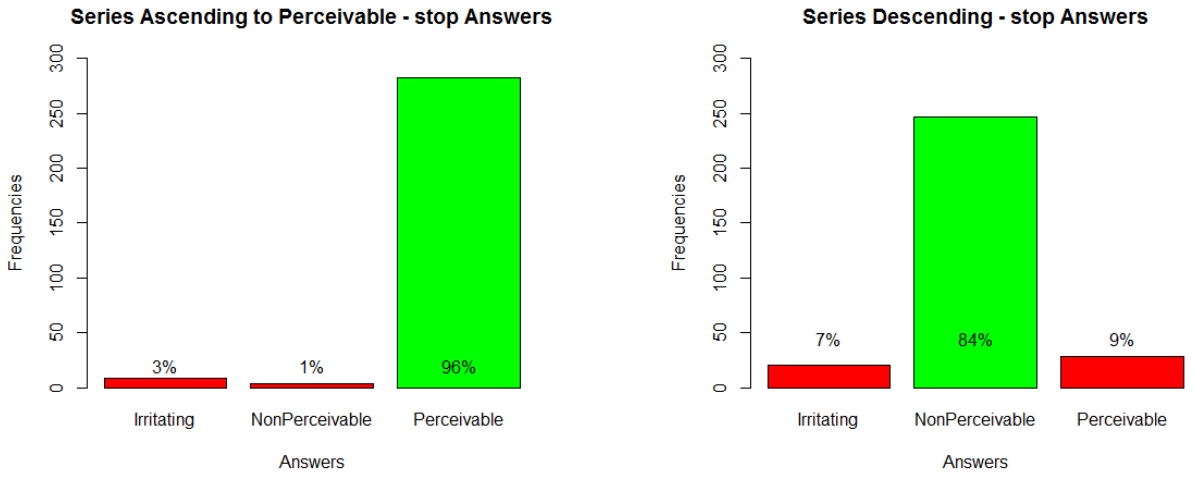
A user clicks the Experiment Button. After half a second, a dialog box appeared and a user had to rate the stimulus. Three options were provided: "Non-Perceivable", "Perceivable", "Irritating". Once a choice was made, the next stimulus was conveyed and the whole procedure was repeated until there was a change of answer or the maximum intensity was reached. Then a series ended and a user had to select the Experiment Button again. The whole was repeated 90 times for each user. The average time to complete the experiment was approximately 30 minutes.

3.3 Results

8705 answers from 10 participants were collected, but only 8403 were used as the actuator A stopped working during the experiment of one participant. This was due to a bad electrical contact that was fixed after the experiment ended.

3.3.1 Lower Boundary

4183 answers were collected: 1913 from the series ascending to perceivable and 2270 from the descending series. A modified version of the method of limits was used to assess the lower boundary's value as described in the previous section. Hence we obtained 590 values but only 529 were used as described below.



(a) Series Ascending to Perceivable: the series started as *Non-Perceivable* and in the 96% of the cases ended as *Perceivable*.

(b) Series Descending: the series started as *Perceivable* and in the 84% of the cases ended as *Non-Perceivable*.

Figure 3.1: Lower Boundary: the green color represents the answers that have been used to compute the Lower Boundary. The red color were those that have been discarded. The name of the columns represents the answer that terminated the series.

Ascending Series - Non-Perceivable to Perceivable

The 96% of the 295 answers collected were used (Figure 3.1a Perceivable column) to compute the lower boundary according to the method of limits. The remaining 4% have been discarded as it follows:

- 75% of the stimuli (Figure 3.1a Irritating column) were rated as *Irritating*. These are composed by a 25% of cases where the initial intensity was perceived by the user due to exceptional sensitiveness. As the series was ascending the value was increased until it was perceived as *Irritating*.
  In the remaining 75% the series was perceived as *Irritating* due to the actuators' hardware failures. Indeed the voltage applied to the actuator was not enough to win the inertia to move the shaft less motor which causes the vibration. When the voltage was high enough a user perceived a vibration which was well above the non-perceivable intensity and the series ended as *Irritating*.
- 25% of the stimuli (Figure 3.1a Non-Perceivable column) were rated as *Non-Perceivable* as the user selected the wrong answer.

We obtained a mean intensity of *21.79*.

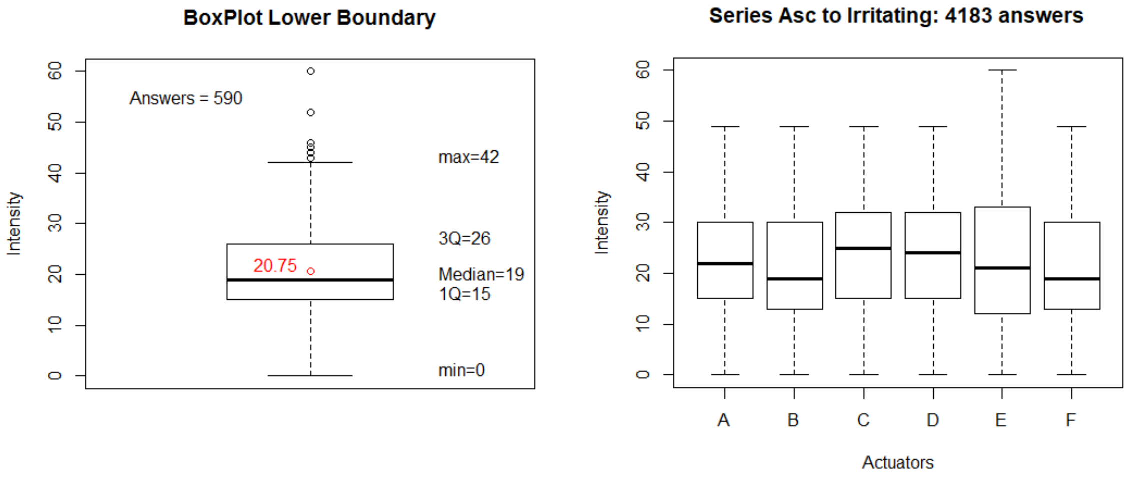
Descending Series

The 84% of the 295 answers collected were used (Figure 3.1b) the remaining 16% have been discarded as it follows:

- 42% of the stimuli (Figure 3.1b column Irritating) started as being *Perceivable* and ended as *Irritating*. Among these, 20% of the cases a user selected the wrong answer.
  The remaining 80% was unexpected. Indeed, we expected that stimuli that are *Perceivable* would end as *Irritating* only when the intensity of the stimulus increases.
- 58% of the stimuli (Figure 3.1b column perceivable) started as being *Irritating* and ended as *Perceivable*. Hence the range of starting value for the Descending series was not set up correctly as it included intensities that were perceived as *Irritating*.

We obtained a mean intensity of *19.71*.
Finally we considered the average between these two intensity and we obtained a value for the lower threshold's intensity equal to *20.75*.

Figure 3.2a shows the ending intensities for all the 4220 answers collected for the first two series. The median of the box is skewed toward the first quartile. This means that more than half of the intensities are non-perceivable when the intensity is below 19. Also, the whisker plot is spread and there are several outliers. These exist because of intrinsic differences among the actuators. Indeed, the rated start voltage of the actuators ranges from 1.2V to 2.3V (Figure 2.3) and it is not possible to know this in advance. In Figure 3.2b we can see that actuators *C* and *D* operated consistently different from the others. Nonetheless we can conclude that our first hypothesis has been confirmed: a threshold that separates intensity that are non-perceivable from the one that are perceivable exists. It's value is *20.75* which is equal to a vibration's amplitude of *0.33G* with a frequency of *45,7Hz*.



(a) BoxPlot Lower Boundary: The red dot indicates the mean value of the 590 intensities collected with the method of limits.

(b) All Answers Lower Boundary.

Figure 3.2: Lower Boundary

Upper Boundary

4220 answers were collected from the ascending perceivable to irritating series. A modified version of the method of limits was used to assess the upper boundary as described in the previous section. Hence we obtained 295 values, but only 165 were used to compute the upper boundary (Figure 3.3). These are composed by all the 155 series that ended as *Irritating* and 10 out of the 140 series that ended as *Perceivable*. Consequently, 130 out of 295 answers were discarded as they rated a stimulus as always *Perceivable* and, therefore, they weren't useful for our analysis. No stimuli were rated as non-perceivable which means that the intensities tested were above the *Non-Perceivable* level and all the actuators worked correctly.

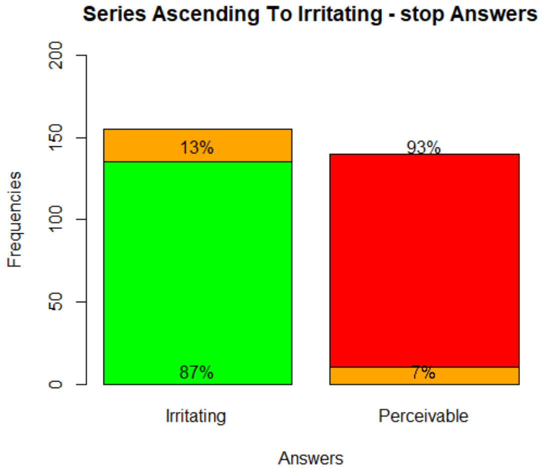


Figure 3.3: Upper Boundary: The green bar represents the answers that have been used to compute the Upper Boundary. The orange bars, those for which only the first answer is considered. The red bar, those that have been discarded. The name of the columns represents the answer that terminated the series. In particular: 1) 13% of the stimuli were always perceived as *Irritating* 2) 87% of the stimuli started as *Perceivable* and ended as *Irritating* 3) 93% of the stimuli were always perceived as *Perceivable* 4) 7% of stimuli started as *Irritating* and ended as *Perceivable*.

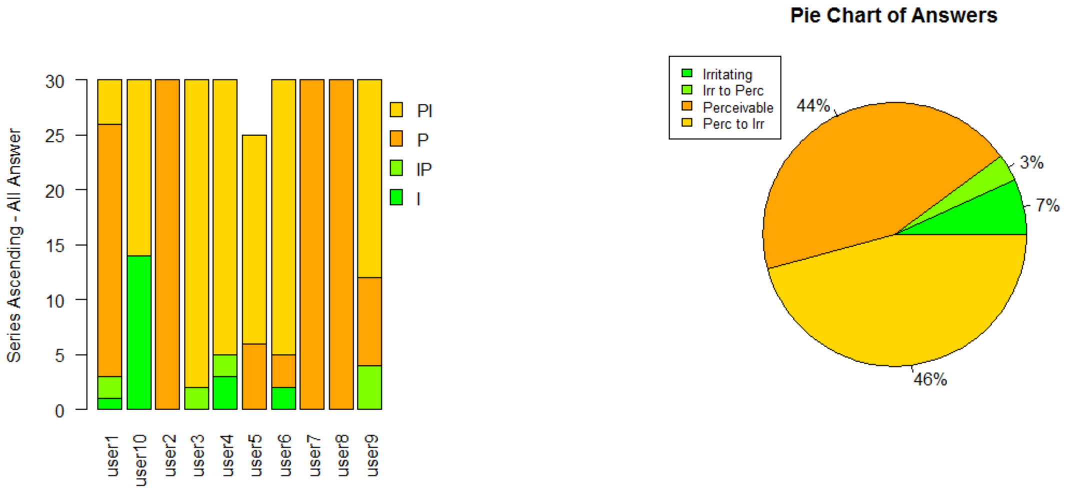
Among the answers that used to compute the upper boundary we considered:

- The starting value of the stimuli whose intensity were perceived as *Irritating* during the whole series and the starting value of the stimuli whose starting intensity were perceived as *Irritating* and ended as *Perceivable*
- The mean of the last two values of the series whose starting intensity was perceived as *Perceivable* and the ending intensity was rated as *Irritating*.

By taking the mean of these values we obtained an intensity of *61.04*. Since we discarded almost half of the data in this series (Figure 3.4b *Perceivable* slice), our assumption was not satisfied as it was not possible to clearly define a value above which a stimulus is perceived as *Irritating*. In Figure 3.4a we have plotted for each user the answers they gave at the end of a series. We can see that

- 6 users felt most of the stimuli as *Irritating* when the intensity grew.
- 4 users out of 10 felt most or all the stimuli as *Perceivable* regardless of their intensity.
- 1 user felt almost half the stimuli as *Irritating* regardless of their intensity.

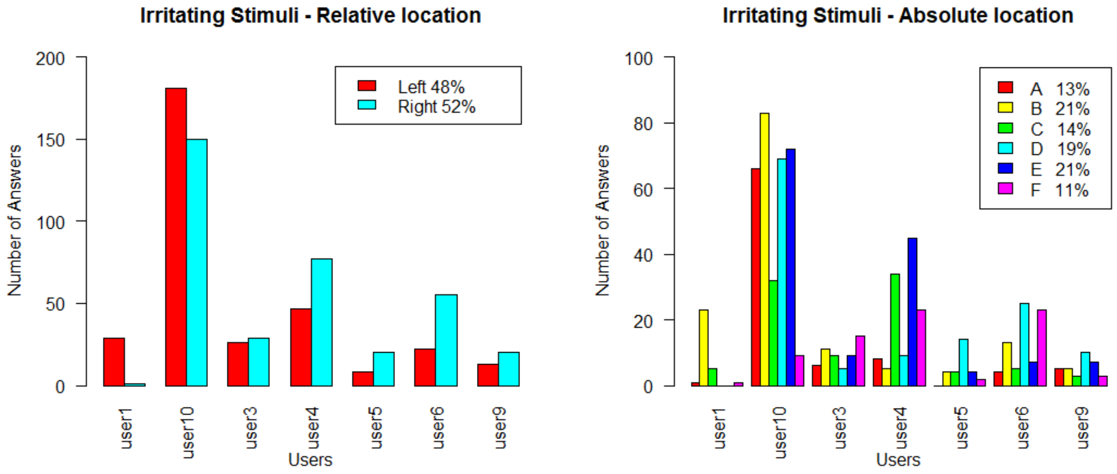
To understand which factors played a role in a user perceiving a stimulus as *Irritating* we plotted the relative position of the actuator (i.e. if it was on the left or on the right side of the neck) (Figure 3.5b) and the absolute position of the actuator (Figure 3.5a). The overall amount of stimuli perceived as *Irritating* is almost the same on both halves of the neck, but for each user it is different. Also, if we consider the irritating stimuli based on the absolute position of the actuators results are even less homogeneous among the users.
Therefore our assumption was not satisfied as it was not possible to clearly define a value above which a stimulus is perceived as *Irritating*. Nonetheless no user felt pain during the experiment, therefore we made a conservative decision and we set the intensity for the upper threshold at *60* which is equivalent to a vibration's amplitude of *0.96G* with a frequency of *132Hz*.



(a) Compare answers: for each user all the answers are presented. we can see that user2, user7, and user8 never felt a vibration as *Irritating*, while the opposite was true for user3.

(b) Percentage of Answers: here all the answers are grouped together according to four categories.

Figure 3.4: The answer for each series provided by each user are presented and divided in 4 labels: *PI* are those series where the starting intensity is rated as *Perceivable* and that ends as *Irritating* while the lable *IP* represent the opposite situation. *I* are those series in which the vibration is always perceived as *Irritating* and the label *P* represent the discarded data, as the series were always rated as *Perceivable*.



(a) Irritation Answers - Sides of the Neck.

(b) Irritation Answers - Actuators.

Figure 3.5: Upper Boundary Analysis

3.4 Discussion

Through our study we obtained the following important results:

- First of all we were able to find a threshold that discriminates between intensities that are perceivable from the ones that are not. Its value it's is *20.75* which is equal to a vibration's amplitude of *0.33G* with a frequency of *45,7Hz* and it is line with results found on other part of the body (Erp and Toet 2015). It is important to notice that driving the actuators at such low intensities, may result in hardware failures as the operating voltage of the actuators may be different.

- We weren't able to unequivocally define a threshold that separates vibrations that are perceivable from those that annoy a user. We identified two main causes:
    1. An issue was to give a user the possibility to choose between three options. Indeed, assuming that the intensity that are perceived as *Irritating* and the ones that are *Non-Perceivable* are well separate, the experiment could have been conducted by implementing a two mutually exclusive choices. This way, for the first two series a user has to choose between *Non-Perceivable* and *Perceivable* and in the last series a user has to choose between *Perceivable* and *Irritating.*
    2. Also the definition of *Irritating* was too vague and each participant may had interpret it according to different standard.

  At this stage we can only conclude that each user has its own sensitiveness and this leads to subjective perception of a vibration as irritating. Furthermore we cannot exclude that some users rated a stimulus as *Irritating* out of boredom. Nonetheless no users felt pain during the experiment which allows us to state that the device can be safely worn around the neck for an extended period of time. Hence we can safely use the vibrations in the selected range in future experiments.

3.5 Conclusion

We performed *the method of limits* to gain insight into users' sensibility regarding vibrotactile stimuli on the neck. We were interested in knowing the lowest perceivable intensity on the neck and the highest perceivable intensity that did not irritate a user. Ten participants were tested on each of the six actuators, but we had to exclude the answers given for an actuator as it stopped working during the experiment. We obtained a frequency of *45.7Hz* for the lower boundary and a frequency of *134.3Hz* for the upper boundary.

We didn't obtain a satisfactory result regarding the intensity's level that a participant may find irritating. Regardless the intrinsic differences between each subjects, a more specific experiment, such as the *Differences Threshold*, should be used. In our experiment this wasn't the main purpose but it should be a crucial component in every study that aims to design wearable neck haptic interfaces meant to be used for long period of time.

At present, a limitation of our work is the lack of generalizability. That is, the results we obtained are generic and can be compared with all those studies that implement similar vibrotactile actuators, but we have tested only a small portion of the neck with a very specific configuration of the actuators. We are well aware that the configuration that we chose, is not the only available. Indeed we voluntarily avoided to place the actuators in proximity of the laryngeal prominence as we assumed that vibrations perceived on this part of the neck would annoy the participants regardless the intensity of the vibration. Also it would be interesting to test other infra space between the actuators to see if it leads to different results.

Nonetheless, these results are solid and they will be used in a next experiment to design an haptic dataset of vibrotactile stimuli that will be conveyed using an identical setup.

Chapter 4

Experiment 2: Haptic Dataset

4.1 Introduction

Haptic interfaces are devices that communicate information exploiting touch related sensations. Whether these are meant to alert a user in a discrete way, whether they are meant to communicate more abstract information, it is paramount that they are distinguishable so that the related messages are recognizable. Most of the studies in this field make use of custom built devices that implement different haptic actuators. Therefore, there are no standardized haptic datasets available, but it is agreed that vibrotactile signals can be created by varying four basic parameters, namely:

- amplitude of the vibration
- frequency of the vibration
- timing
- location

In this study we are using a custom built device (Chapter 2) that has to be worn around the neck. This lead to some limitations on the design space of different vibrotactile patterns. Indeed, the location of the actuators is fixed in a 1 by 6 array configuration (Figure 2.1a). Moreover we are using vibrotactile motors that do not allow to variate independently amplitude and frequency of the vibrotactile signal. In this situation, we can create vibrotactile signals exploiting a limited amount of basic parameters. To overcome this limitation, and to create a haptic dataset that can be used with any set up that shares the same characteristic, we define a new parameter. This is the *pattern's sequence*, which refers to a specific turning on and off sequence of the actuators with respect to their fixed position. We exploited the symmetry of the neck and the number of actuators turned on and off at the same time to define two configurations simple enough to be replicated with any array of actuators while being well distinguishable. Indeed we designed them so that both the number of actuators driven at the same time and the order at which they are turned on and off is different. These are described below:

- *Circular Sequence*: the actuators are turned on and off, one after another in a consecutive order, from one extremity of the device to the other (e.g. F E D A B C but not F E D A C B).
- *Reflection Sequence*: actuators that share the same relative position are turned on and off in pairs from the two extremities of the device to the others (e.g. CF BE AD but not BF CE AD).

Then for each configuration we defined two new parameters with two levels, namely:

- *Pattern's Direction*: Direction1 or Direction2
- *Pattern's Vibration*: Smooth or Buzz

Now that we have defined two new parameters it is paramount to assess if their levels are perceptually different. To this intent we create four variations obtained by combining, for each pattern's configu-

ration, the two levels for vibration and direction.
Discriminating stimuli belonging to different pattern's configurations when the actuators are driven for 200ms is trivial as assessed by conducting an informal experiment with 3 participants to validate this statement: all of them were able to distinguish between stimuli belonging to different sequences. Consequently we divide the experiment in two parts: in the first one (Section 4.2) pairs of stimuli in the circular sequence are compared; in the second one (Section 4.3) pairs of stimuli in the reflection sequence are compared.
Hence, the aim of this study is to assess whether the two levels for direction and vibration, and therefore the variations in each pattern's sequence, are perceptually discriminable. To this intent, we conducted two discrimination experiments by comparing pairs of variations belonging to the same pattern's sequence.

4.2 Experiment 2.A: Circular Pattern Configuration

We used the device described in Chapter 2 to assess whether participants could discriminate between the variations defined in the data set of the circular pattern configuration. A variation is composed by combining the levels of two custom built parameters. These are described and motivated below.

Direction

The way we defined the *Circular Sequence* allows us to define at least two different orientation to drive the actuators. Indeed we want to turn on and off each actuator in a consecutive order and, since there are two extremities, we can easily define two directions as described below.

- **Direction 1: left to right** C B A D E F (Figure 4.1c and 4.1e).
- **Direction 2: right to left** F E D A B C (Figure 4.1d and 4.1f).

Therefore, we are testing a user's ability to perceive the direction in which the actuators are turned on and off when these are spaced by 5cm. Although this topic should require a thorough study, we assume that the shape of the neck and its symmetry with respect to the sagittal plane eases the discrimination task when a vibration is conveyed to one of the sides of the neck.

Vibration

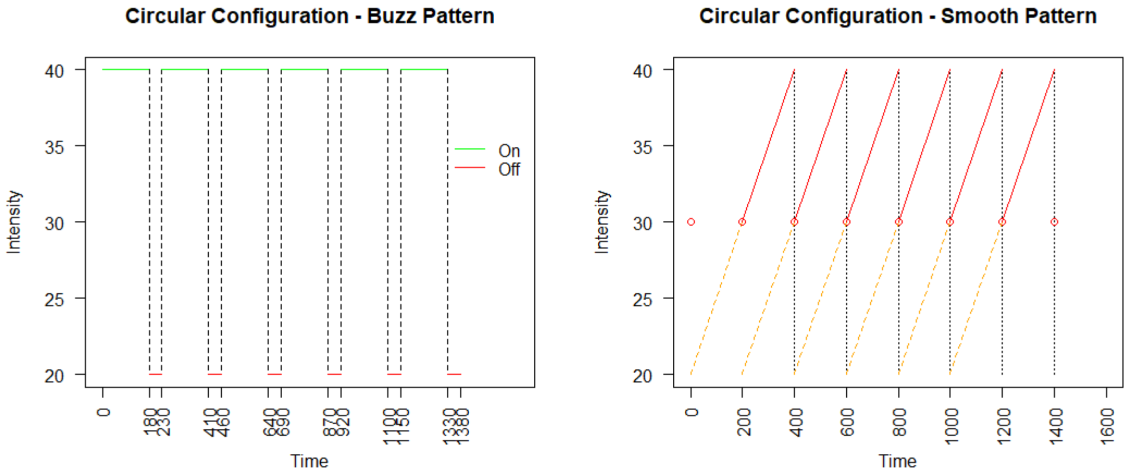
As mentioned before a weakness in the chosen actuators is the impossibility to drive independently frequency and amplitude of the vibrotactile signal. This feature is often exploited by researchers because it allows to create different smoothness levels for a given haptic signal. These levels are then used to communicate different information.
Therefore, we implemented a solution that controls how fast the desired level of intensity is reached. This was used to create two different kinds of vibration which are perceived as two different levels of smoothness, namely:

- **Vibration 1: Smooth**: an actuator linearly increases its value until it reaches the designed value in the specified time. Then it's turned OFF.
- **Vibration 2: Buzz**: an actuator reaches the specified intensity in a time which equal or greater than its lag time (47ms). Then it vibrates for a certain amount of time and then its turned OFF

4.2.1 Variations

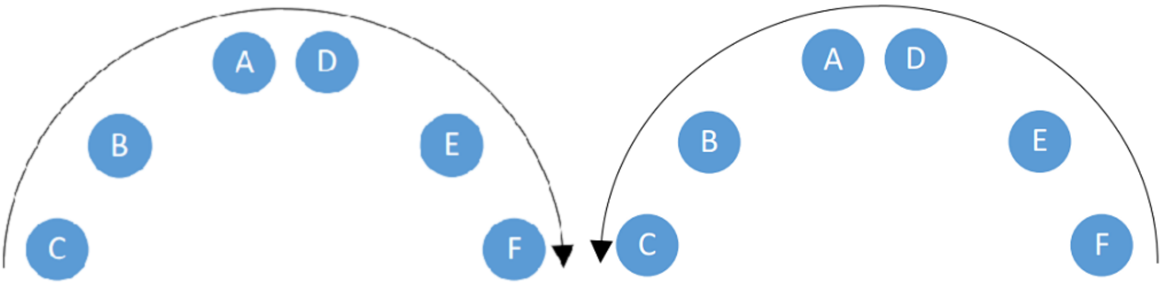
Four different variations have been created for the circular pattern's configuration. These are illustrated in Figure 4.1c to Figure 4.1f. To make the comparison task less trivial, the variations last almost the same amount of time (i.e. ± 20ms). Graphical representations for the execution time of each pattern's vibration variations are provided in Figure 4.1a and in Figure 4.1b.

In the former an actuator is turned ON for 180ms then is turned OFF for 50ms. Then the next actuator is driven in the same fashion until each actuator is driven once. This is equivalent to a waveform with a period of 230ms. In the latter, as we want to convey a smooth sensation, the intensity of the vibration gradually increases from an actuator to the consecutive. Two actuators are perceived at the same time. Indeed an actuator starts to increase its intensity while the previous one is reaching the maximum intensity. This is equivalent to a sawtooth wave with a period of 200ms.



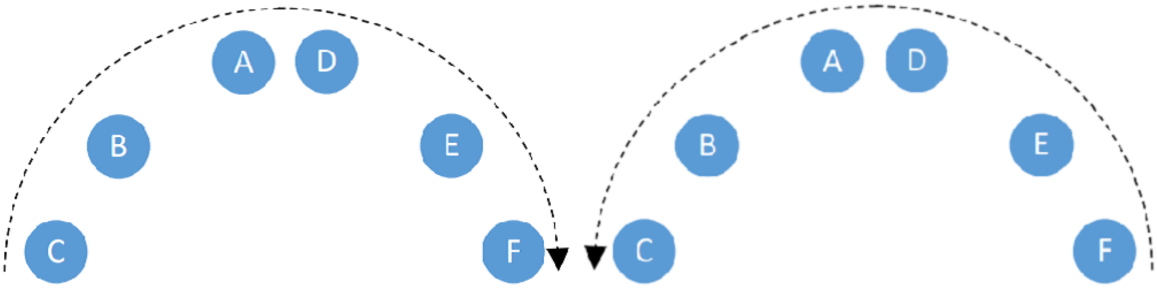
(a) Buzz Pattern: each peak corresponds to a different actuator.

(b) Smooth Pattern: The red dots mark represent the moment where an actuator is driven to reach the maximum value (red line) and the consecutive one starts to increase its value (orange line).



(c) Variaton 0: left to right Smooth

(d) Variation 1: right to left Smooth



(e) Variaton 2: left to right Buzz

(f) Variation 3: right to left Buzz

Figure 4.1: Circular Sequence Variations: a dotted arrow indicates that the variation's vibration is of type *Buzz* and a full arrow indicates that the variation's vibration is of type *Smooth*. The levels of the direction are represented by the direction of the arrow.

Discrimination Task

We have now defined two types of directions and two type of vibrations: by combining them it is possible to create four different *Variations* (Figure 4.1c to Figure 4.1f). These are the elements of the data set that we are comparing to assess if they are perceptually different. Since each variation is compared with all the others including itself, there are 16 different comparing pairs that can be grouped in four distinct types of comparison (Table 4.1):

- **Comparison 0 - SAME** a variation is compared with itself and there are no differences.
- **Comparison 1 - DIR** a variation is compared with another. They share the same Vibration but they have different Direction. Since there are two levels for vibration we have:
  - **DIR1:** Direction 1 and Direction 2 are compared while Vibration 1 is kept constant
  - **DIR2:** Direction 1 and Direction 2 are compared while Vibration 2 is kept constant
- **Comparison 2 - VIB** a variation is compared with another. They share the same Direction, but they have different Vibration. Since there are two levels for direction we have
  - **VIB1:** Vibration 1 and Vibration 2 are compared while Direction 1 is kept constant
  - **VIB2:** Vibration 1 and Vibration 2 are compared while Direction 2 is kept constant
- **Comparison 3 - BOTH** a variation is compared with another and they differ both in Vibration and Direction.

We are interested in knowing if the two levels of vibration and the two levels of direction are recognizable. To this intent we consider the proportion of correct answers (i.e. the *Accuracy*) for the comparisons that belong to *DIR 1*, *DIR 2*, *VIB 1*, and *VIB 2*. Comparisons that belong to *SAME* and *BOTH* are the control groups. The first is needed to assess the reliability of responses from the participants, the second is needed to assess the level of attention of each participant during the experiment. Indeed this task is monotonous and we thought that by letting a participant perceive diametrically opposed stimuli (i.e. that changes both in direction and vibration) which are well distinguishable, we make sure that they do not provide random answers.
Therefore our independent variables are **Direction** and **Vibration** and the dependent one is the **Accuracy**.
Since we had more than ten success and failures cases for each comparison we can use the *Z-Test* for comparing the two accuracies corresponding to different types of vibrations and to different types of directions. This provides an insight regarding differences in discriminating between the two levels of vibration and direction. Our null-hypothesis is that the participants would perform at the chance level (accuracy = 50%).

4.2.2 Participants

10 voluntary participants (4 females, 6 males) in the age group of 25 to 28, were tested. Six of them had already experience with the custom built neck device as they also took part in Experiment 1 (Chapter 3).

4.2.3 Method/Procedure

Each user was instructed about the purpose of the experiment and asked to wear headphones to mask any source of noise. The tester put the device around the neck of a user so that the actuators were symmetrical with respect to the most superior cervical vertebra of the spine and the actuators were as close as possible to the collarbones. Finally a user was asked to look at a laptop's screen to interact with the experiment's GUI.
Before the actual experiment began, a user was asked to complete the training phase to get acquainted with the pattern's variations and with the GUI. In this phase a variation was compared with all the others including itself. A user had to click The *Test* button to perceive the first variation. The tester informed a user about the characteristics of this variation (i.e. vibration and direction). Then the button was pressed again to perceive the second variation (i.e. the one to compare) and the tester gave

information about this variation as well. Finally a dialog box appeared asking *"Are they different?"* and two buttons were presented: a green *YES* and a red *NO* button. A user had to close the dialog box by making a choice. This part consisted of 4 comparisons, after which the *Test* button was disabled. Then the experiment started.

For the real experiment part, the task was the same: a user had to click the same *Test* button to perceive the first pattern's variation. Then he had to click it again to perceive the variation to compare. Finally a dialog box appeared and a user stated whether the two pattern were different. Each comparison was repeated 10 times in a pseudo random order leading to a total of 160 comparison. Each variation lasted approximately 1800ms and the mean time to complete the experiment was 30 minutes.

4.2.4 Results

A reliability factor was calculated for each participant as the accuracy obtained for the comparison belonging to the *SAME* group. Since each comparison has an accuracy greater or equal than 90% we can conclude that they all were able to judge the vibrotactile signals. Also the users were able to discriminate between stimuli belonging to the *BOTH* group, ensuring that they were focused during the experiment. The results are reported in Table 4.1. The overall accuracy when discriminating between the two Direction's levels was 89% while for the Vibration's level was 86%. Therefore we can conclude that both the levels for direction and vibration were well recognizable.

Control Group	**Compared Stimuli**	**Parameter Varied**	**Parameter Constant**	**Mean(SD)**
SAME	VAR 0 — VAR 0	None	Dir1 & Vib1	93(26)
SAME	VAR 1 — VAR 1	None	Dir2 & Vib1	90(30)
SAME	VAR 2 — VAR 2	None	Dir1 & Vib2	97(17)
SAME	VAR 3 — VAR 3	None	Dir2 & Vib2	91(29)
BOTH	VAR 0 — VAR 3	Dir & Vib	None	95(22)
BOTH	VAR 1 — VAR 2	Dir & Vib	None	98(14)
DIR1	VAR 0 — VAR 1	Dir	Vib1	89(31)
DIR2	VAR 2 — VAR 3	Dir	Vib2	89(31)
VIB1	VAR 0 — VAR 2	Vib	Dir1	85(36)
VIB2	VAR 1 — VAR 3	Vib	Dir2	87(34)

Table 4.1: Circular Sequence Results

For each comparison we had an expected number of success and failures greater than 10, therefore we were able to use the *Z-test* for comparing the two accuracies corresponding to different types of vibrations and to different types of directions. In Table 4.2 the results of the *Z-Test* are reported. We can conclude that there was a significant difference between the two levels of direction when the actuators were driven with the smooth vibration.

Compared Groups	**Z-Score**	**p-Value**
DIR1 — DIR2	0	1
VIB1 — VIB2	0.41	0.6836

Table 4.2: Circular Sequence Z-Test results

4.3 Experiment 2.B: Reflection Pattern

The goal of this experiment was the same as Experiment A, except we tested the variations belonging to the *Reflection Sequence* data set. Within this configuration, two actuators were driven at the same time, therefore we had to adjust the levels for the parameters defined in the previous experiment. These are described below.

Direction

We were driving a pairs of actuators at the time, hence, among all the possible ways to choose a driving sequence, we chose the ones that go from the two extremities to the others and viceversa. These were:

- **Direction 1: neck to throat** AD BE CF (Figure 4.2c and 4.2e).
- **Direction 2: throat to neck** CF BE AD (Figure 4.2d and 4.2f).

Vibration

In this configuration, the actuators are driven in pairs. We wanted to avoid to drive too many actuators at the same time as this would have led to a strenuous discrimination task. For the *Smooth* vibration (i.e. *Vibration 1*) there was no overlapping effect anymore: two actuator linearly increase their values until they reach a third of the maximum intensity in the specified time. Then they are turned OFF. At the same time, the next pair is driven with a starting value equal to the ending value of the previous pair. This is repeated, until the last pair is driven and the maximum intensity is reached. For the *Buzz* vibration (i.e. *Vibration 2*) there were no difference, except that we were driving two actuators instead of one.

4.3.1 Variations

We kept the same period used in the Circular Configuration. Graphical representations for the execution time of each pattern's vibration variations are provided in Figure 4.2a and in Figure 4.2b. In the former, a pair of actuators is turned ON for 180ms then is turned OFF for 50ms. Then the next pair is driven in the same fashion until each pair is driven once. The latter can be described as three sawtooth waves with a period of 200ms where the starting and ending intensities are consecutively increased.

Discrimination Taks

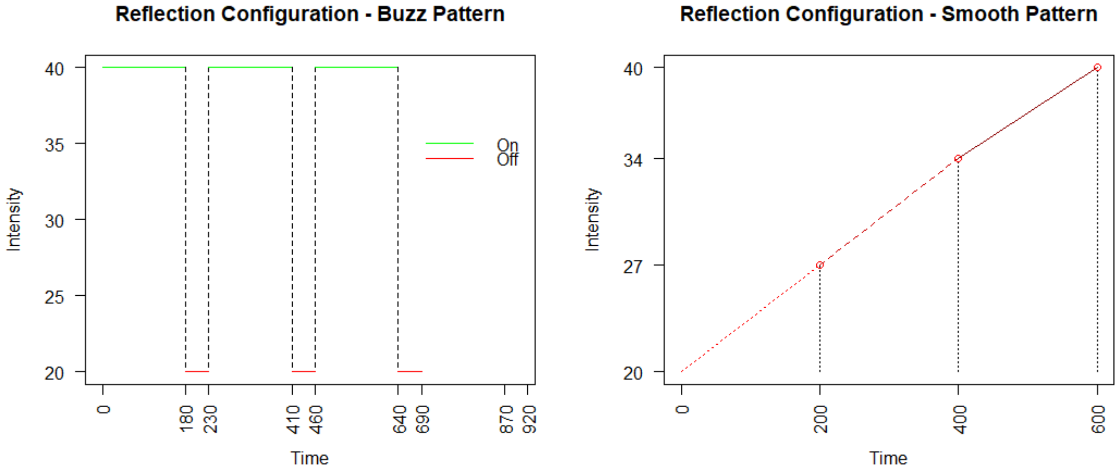
Despite that we changed the definition for the levels of Direction and Vibration, we can still make the same assumption for the discrimination task. Indeed, all the variations can still be grouped in the same four comparisons category (Table 4.3) that we defined in the previous experiment. Furthermore the hypothesis remain the same as well as the dependent and independent variables.

4.3.2 Participants

The same 10 voluntary participants of Experiment A were tested.

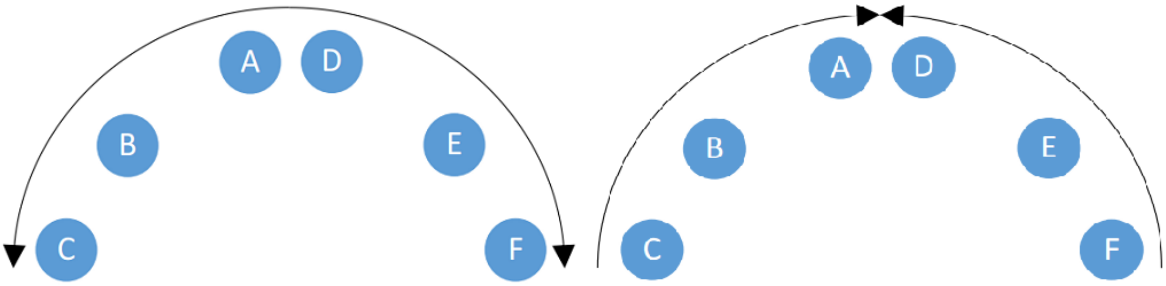
4.3.3 Method/Procedure

The procedure followed was the same as Experiment A. The only difference was the whole duration of the variations that lasted approximately 1000ms; the mean time to complete this part was **12 minutes**.



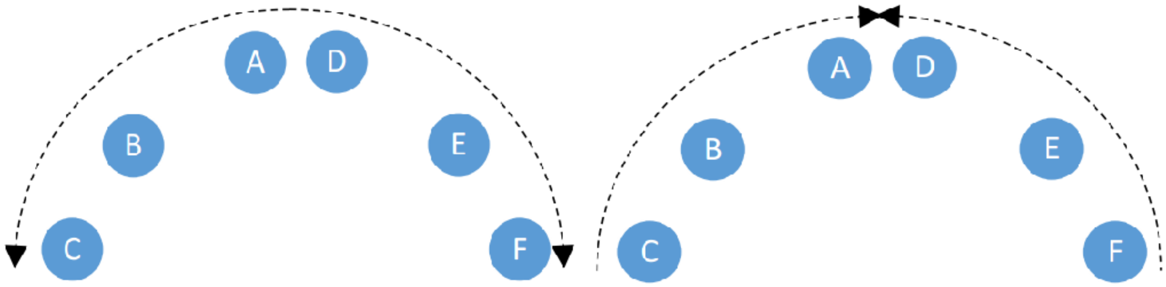
(a) Buzz Pattern: each peak corresponds to a different pair of actuators

(b) Smooth Pattern: each red dot represents the instant where a pairs of actuators is turned off and the next one is turned on.



(c) Variaton 0: neck to throat Smooth

(d) Variation 1: throat to neck Smooth



(e) Variaton 2: neck to throat Buzz

(f) Variation 3: throat to neck Buzz

Figure 4.2: Reflection Configuration Variations: a dotted double heads arrow indicates that the variation's vibration is of type *Buzz* and a full double heads arrow indicates that the variation's vibration is of type *Smooth*. The levels of the direction are represented by the directions of the arrows.

4.3.4 Result

In Table 4.3 the accuracies for the comparisons are reported in the same fashion as Experiment 2.A. The participants were able to discriminate the vibrotactile stimuli in the *SAME* and *BOTH* groups, ensuring that the four variations were well recognizable and the level of attention high. Also they were able to discriminate between the two levels of vibrations when the direction was kept constant. On the contrary, the two levels of directions were discriminate slightly above the chance level.
We ran the *Z-Test* to assess any difference between the accuracies obtained for the two levels for Direction and Vibration. These are reported in Table 4.4.

Control Group	**Compared Stimuli**	**Parameter Varied**	**Parameter Constant**	**Mean(SD)**
SAME	VAR 0 — VAR 0	None	Dir1 & Vib1	74(44)
SAME	VAR 1 — VAR 1	None	Dir2 & Vib1	77(42)
SAME	VAR 2 — VAR 2	None	Dir1 & Vib2	87(34)
SAME	VAR 3 — VAR 3	None	Dir2 & Vib2	83(38)
BOTH	VAR 0 — VAR 3	Dir & Vib	None	89(31)
BOTH	VAR 1 — VAR 2	Dir & Vib	None	95(22)
DIR1	VAR 0 — VAR 1	Dir	Vib1	55(45)
DIR2	VAR 2 — VAR 3	Dir	Vib2	59(45)
VIB1	VAR 0 — VAR 2	Vib	Dir1	83(45)
VIB2	VAR 1 — VAR 3	Vib	Dir2	80(45)

Table 4.3: Reflection Sequence Results

Compared Groups	**Z-Score**	**p-Value**
DIR1 — DIR2	0.57	0.57
VIB1 — VIB2	-0.55	0.59

Table 4.4: Circular Sequence Z-Test results

4.4 Discussion

Accuracy

We found that for the *Circular Sequence* it was possible to distinguish between all the variations well above the chance level. Therefore we can conclude that driving the actuators for a period of 200ms ±20ms, when they are spaced by 5 cm, allowed to distinguish between two levels of directions as defined for the circular configuration. The same was true for the two levels of vibration: increasing linearly the intensity of an actuator was well distinguishable compared to a vibration where an actuator was turned on in the shortest amount of time (i.e. about 47ms).

Variations belonging to the *Reflection Sequence* weren't that easily distinguishable. Indeed users were able to distinguish between the two levels of vibration well above the chance level, but only slightly above the chance level for the two levels of direction. We argue that this was due to a poor design choice. Indeed we decided to drive the actuators for the same amount of time regardless the sequence. This led to a duration time for each variation in the reflection sequence that was about half of the respective one in the circular sequence. Consequently, we can infer that driving simultaneously two actuators that are symmetrical with respect to the sagittal plane for a period of 200ms ±20ms doesn't convey a clear sense of direction as specified in Paragraph 4.3. We assume that the accuracy for this comparison can be easily increased by making the actuators vibrate for a longer period of time in the *Reflection Sequence*.

Z-Test

All the comparisons between the two levels of vibrations and directions in both the *Circular* and *Reflection* sequence, could not be proven significant for $p < .05$. Therefore we can reject the null hypothesis that participants were performing at the chance level when comparing vibrotactile stimuli that differed for intensity or vibration. This means that even when the accuracy was low, such as when discriminating for direction in the *Reflection Sequence* the participants were still able to distinguish the two levels.

These results allow us to justify the design and the choice of our parameters and therefore to validate the haptic dataset.

4.5 Conclusion

Two discrimination experiments were performed to validate the design and the choice of three high levels parameters (i.e. *Sequence, Direction and Intensity*) created to overcome the limitations provided by a custom built neck device and to build a haptic dataset to be used in a future experiment. Each parameters had two levels and we combined them to create a total of 16 vibrotactile stimuli. These were grouped in four different categories based on the differences shared between the stimuli in the pair, namely *SAME*, *DIR*, *VIB*, and *BOTH*. Ten participants took part at both experiments and they were asked to discriminate between pairs of stimuli belonging to the same *Sequence's* level. Each part consisted in 160 comparison: the first part lasted about 30 minutes and the second one 12 minutes for an overall duration of about 45 minutes and a total of 320 comparisons between pairs of stimuli. Results showed that all the participants were able to discern between the stimuli belonging to the *SAME* group regardless of the level for the *Sequence parameter*. Also, participants were able to discern between the two levels of *Direction* and *Vibration* in the *Circular Sequence*. In the *Reflection Sequence* only the *Vibration's* levels were well discernible, the *Direction's* levels were correctly judged slightly above the chance level.

The results highlight several findings. Firstly by dividing the actuators in two groups that are symmetrical with respect of the last vertebrae of the spinal cord and spacing them by 5cm is a good design choice that offers at least two perceptually different ways to drive the actuators. Furthermore, within these sequences, the participants were able to discern the order in which they were driven. These patterns can be exploited to unobtrusively alert a user or to provide spatial and navigation information both in real and VR environments. Secondly, we were able to assess that it is possible to create perceptually different vibrotactile roughness using simple ERM actuators by changing the way they are driven. Especially for mainstream consumer devices, such as smart phones and video game controllers, this finding may lead to new ways of notifying a user without using expensive actuators. However there is a major limitations in the study. Indeed the structure of the device didn't allow to precisely control the position of the actuators around the neck. Hence, although the actuators were always symmetrical with respect of the last vertebra of the spinal cord, their position toward the throat may be different for each user. This limit the comparability of the results among subjects. Since our results were promising we suggest that the neck should be investigate more as haptic surface. Researchers should consider different ways to displace the actuators around the neck, as well as the number of vibrotactile units and their intra distance. We suggest to explore different ways to drive the ERM actuators to understand to which extent it is possible to create levels of haptic roughness. Finally we propose to investigate others sequences to drive the actuators that do not rely on a geometrical order (i.e. a line).

Chapter 5

An Exploratory Study Of The Neck As An Affective Haptic Surface

Abstract

Haptic technology researchers started to investigate how to evoke emotions through haptic devices. Ranging from health care and assistive industry to the game and media services, *affective haptic* is becoming a trending field of research. In this paper we evaluate the neck as a haptic interface to convey affective vibrotactile stimuli. We argue that the neck is both exposed and intimate and simple vibrotactile stimuli are sufficient to elicit emotional responses. We designed a device that employs an arrays of six ERM actuators and built an haptic dataset. Participants were asked to rate the haptic stimuli within two-dimensional *valence arousal* space. We found that the *intensity* of vibration and the *sequence* in which the actuators are driven affect the *arousal* but not the *valence*. Instead the *vibration* affected both the *arousal* and the *valence*. We discuss these limitation and offer a set of guidelines on haptic stimuli meant to ease the design of affective feedback for devices that employ an array of actuators.

5.1 Introduction

Haptic technology has been widely used in the game and media industry to augment a user's presence by recreating touch related sensations exploiting forces, vibrations or motions. Recently, mediated touch feedback have been studied to elicit, enhance, or influence the emotional state of a human giving raise to the field of *affective haptic*. Given the novelty of this field, there is no framework that clearly state how to evoke emotions. Often researchers have been exploiting the correlation between the physiological changes in the body induced by the autonomic nervous system. This solution involves devices that are expensive and obtrusive. Striving for a more compact and relatively inexpensive design we want to evoke emotions exploiting abstract vibrotactile stimuli. In this context, this paper investigates the neck as an eligible haptic affective surface. First we review previous studies, then we describe the apparatus used to carry out the experiment and how it was created. Finally we describe the results and propose future studies.

5.2 Related Works

The studies that aim to improve the emotional communication in HCI through haptic stimuli can be divided in two categories based on the technology and the kind of cues involved. Our discussion focuses on pure vibrotactile cues, but an overview of significant studies for each class is provided to highlight our choice.

Measure Emotions

It is important to consider that, there is no an agreed definition of what an emotion is (Picard and Picard 1997) and, consequently a framework that defines how to elicit them is lacking. Nonetheless, the most accepted model of emotion Russel 1980 allows to define them as a linear combination of two dimension known as *valence* and *arousal* (Figure 5.1). The former provides a way to rate the unpleasantness/pleasantness of a stimulus, while the latter represents upon to which extent that stimulus trigger us (i.e. not at all to really excited). The main advantage of this model is that all kind of stimuli can be subjectively rated through graphic scales (i.e. the self-assessment manikin model (SAM) by Bradley (Bradley and Lang 1994), or with *Likert scale.* Then these ratings are plotted on a two dimensional continuous space which has the advantage of surpassing the ambiguous definition of discrete emotional labels (Ekman 1992).

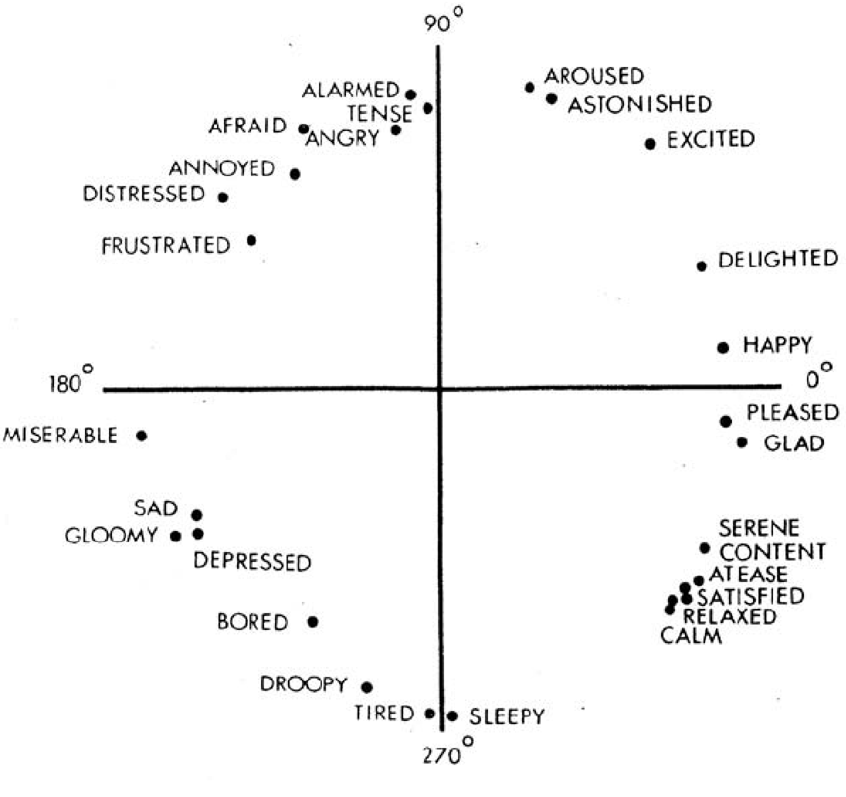


Figure 5.1: Russel's representation of the circumplex model of emotion (Russel 1980)

Physiological responses

Feeling an emotion is a process that manifests itself all over our body. The autonomic nervous system is responsible for this physiological changes. For example when we feel in love, our heartbeat accelerate, the pupils dilate and the skin on our cheeks blushes. Consequently, advocates of the so called *James-Lange theory* (Cannon 1927), exploit the haptic technology to elicit emotion by inducing physiological changes. For example, Fukushima (Fukushima and Kajimoto 2012), forced the piloerection on a user's arm, and by measuring the skin conductance reaction (SCR) found out that this reaction enhances the feeling of surprise; Ueoka (Ueoka, AlMutawa, and Katsuki 2016) imposed a fake heartbeat, felt under the sole of the feet through a silent subwoofer, and recorded the heart rate variability (HVR). They found out that the real heart beat was affected by the modulation of the fake one enhancing the feeling of being scared in a VR experience. Perhaps the most prominent research in this field was conducted by Tsetserukou (Tsetserukou, Neviarouskaya, and Terashima 2013). In this research they

developed six tools to enhance social interactivity and emotionally immersive experience in real time messaging. Each tool was designed to evoke a specific emotion (i.e. joy, fear, happiness, love) and each tool had to be worn on specific parts of the body. Finally Lemmens (Lemmens et al. 2009) created a haptic jacket with 64 ERM motors, divided in 16 strings to add vibrotactile stimulation on the entire upper torso and back and front of the arms. This design allowed them to create emotionally fully immersive experience while watching a movie by recreating patterns to represent real life situations such as "a comforting arm around a shoulder". Also Arafsha Arafsha, Alam, and El Saddik 2012 built a prototype of a haptic jacket designed to enhance video gaming and movie watching experience. Their setup is composed of six haptic components (i.e. chest and neck vibration, neck warmth, heartbeat simulation, arms vibration and shivering) and it includes 35 vibrotactile units as well as thermoelectric coolers and temperature sensors to evoke emotions by inducing physical body reactions.
Although these studies provide promising results, we cannot omit the obtrusiveness and the complexity of such designs which make their use impractical in real life scenario. Not only different parts of the body need to be stimulated but also a large amount of actuators, often coupled with other haptic devices, are needed to mimic real physiological reaction. If the former represent a mere, but not negligible, issue in terms of socially acceptable appearance, the latter poses way more serious complications in terms of power supply. For these reasons we are mostly interested in pure vibrotactile sensation as a more compact and feasible design is required to investigate its correlation with emotional states. A review of significant studies is provided in the next section.

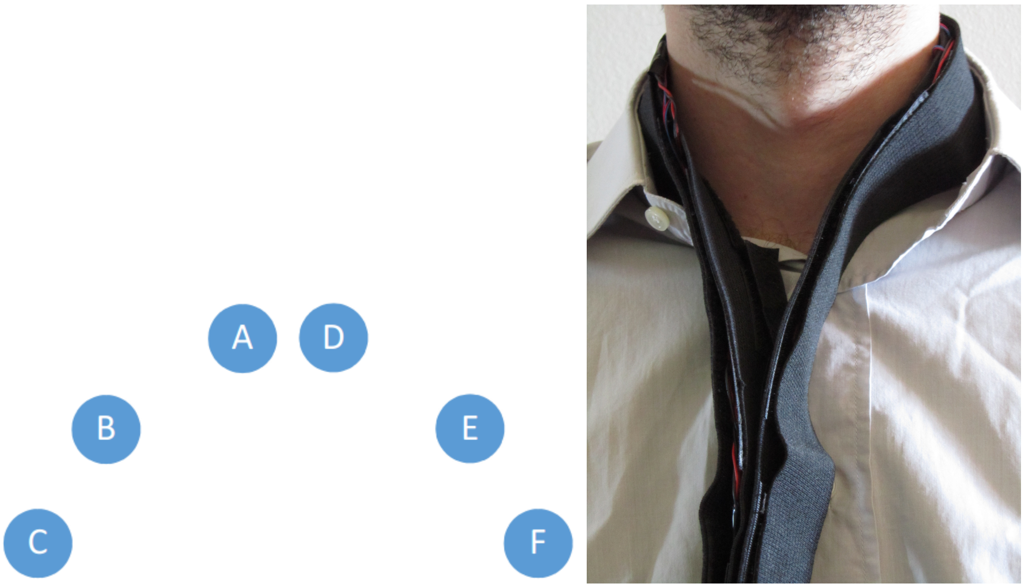
Pure Vibrotactile Pattern

In this section we review studies that make use of pure vibrotactile patterns to elicit emotion. In this category we consider those haptic patterns created solely by vibrotactile stimuli that do not attempt to mimic physiological responses. We are mostly interested in pure vibrotactile sensation as a more compact and feasible design is required to investigate its correlation with emotional states. Indeed vibration motors are largely used in mobile phones and other mainstream devices and as such it is worth to study to which extent they can convey emotional information.
In this field Salminen (Salminen et al. 2008) developed a friction-based horizontally rotating fingertip stimulator to investigate emotional experiences and behavioral responses to haptic stimuli when the burst length, the continuity and the direction of the stimuli are changed. They discovered that all the four parameters of the SAM model (i.e. pleasantness, amorousness, approachability and dominance) were affected by the rotation style while the burst length was not significant. Rehman (Réhman and Liu 2010) rendered emotional information, extracted from the humans lips movement, into vibrotactile pattern on mobile phones: the frequency of the vibrotactile stimuli rendered the emotion type (i.e. happiness, surprise, disgust and sadness) while the magnitude coded the emotion intensity. In their tests, users were able to recognize the emotions presented to them after a little training. Rantala (Rantala et al. 2013) studied if vibrotactile stimulation that imitates human touch conveyed intended emotions (i.e. the feeling of being unpleased, pleased, relaxed or aroused) from one person to another. They used a device, designed in a previous study by Rentala (Rantala et al. 2011), that converts touch gesture of squeeze and finger touch from the sender into vibrotactile stimulation perceived from the receiver. Both of them evaluated the stimulation using rating scales for valence and arousal. By matching the sender's intended emotion and receiver's interpretation they found that the squeeze gesture is better at communicating unpleasant and aroused emotional intention, while the finger touch was better at communicating pleasant and relaxed emotional intention.

Through this review of affective haptic studies, we can infer that emotional states can be evoked and affected through a haptic medium (Smith & MacLean, 2007) and several techniques and haptic interfaces exist to reach this goal. Having such a sparse amount of devices is an issue as the results obtained in one study are difficult to compare with others. Nonetheless several studies provide formal guidelines about the characteristics that a vibrotactile stimulus must have to obtain certain ratings for valence and arousal. Seifi (Seifi and Maclean 2013), Yoo (Yoo et al. 2015), and Obrist (Obrist et al. 2015) find that short vibrotactile pulses are highly arousing; increasing frequency and amplitude of the vibration lead to an increase of both arousal and valence; increasing the perceived roughness of a vibration increases the arousal but decreases the valence. Following these guidelines allows to compare results obtained with different devices. Another issue is the amount of different patterns that is possible to convey with these kind of devices and consequently the range of emotions that these can elicit is quite limited. Indeed Yoo (Yoo et al. 2015) points out that, with respect of the circumplex model of emotion, most of the ratings belong to the first two quadrants. We aim to solve these issues designing a device that make use of common vibrotactile actuators and that can be worn around the neck. We argue that the neck has the peculiarity of being simultaneously completely exposed and intimate. By exploiting this intimacy, we speculate that simple vibrotactile patterns are sufficient to trigger emotional states that belongs to all four quadrants of the circumplex model of emotions.

5.3 The prototype

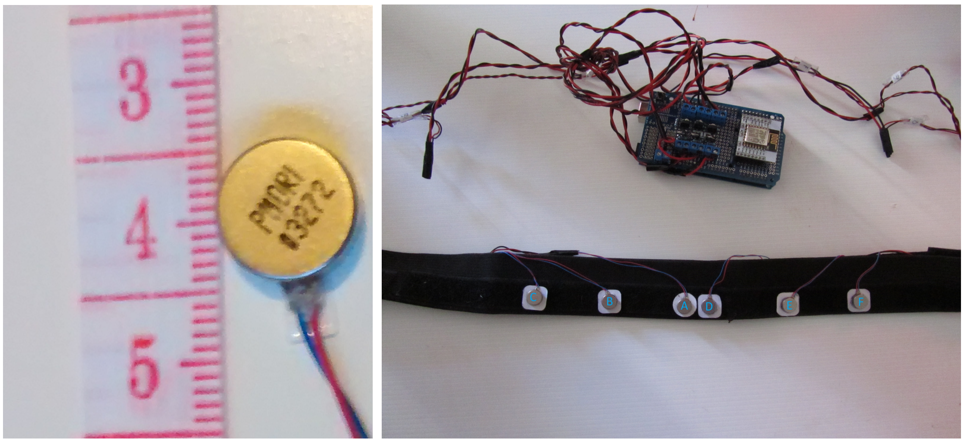
In this experiment we used an ArduinoMega board mounting a power board, and an ESP8266 module (Figure 5.3b) to handle the WIFI communication with an experimental software running on an Acer x54h. The vibrotactile cues were presented from six ERM actuators (Figure 5.3a) soldered to a 100cm long kynar wire. Each actuator was in contact with the skin of a participant and glued to the center point of a Velcro square (1cm side) to facilitate the placement of the motors on a 90cm long elastic band covered with Velcro strips. All the cables were restrained in between the back of the first elastic band and a second one attached through Velcro strip so that they never touched the participants' skin (Figure 5.2b). The first two actuators (i.e. actuators A and D in Figure 5.2a) shared a distance of 1.5cm while being symmetrical with respect of the last cervical vertebra of the spinal cord. The others are spaced by 5 cm. This configuration allowed us to create different vibrotactile sensations as the vibration could be perceived as single "Buzz" or as "Smooth" sensation moving from an actuator to the next. This was possible through a custom program that exploits the interrupts on the Atmega2560's timers. This functionality was implemented in the custom firmware loaded in the micro-controller and allowed us to precisely control the variations in the levels of the PWM signal that controlled the vibration of the actuators. The actuators' intensity was set with instructions in forms of string of text (i.e. 10 characters on average) sent with the UDP protocol over the WIFI network. A baud rate of 38400 bps granted to send 80 instructions per seconds to each actuator.



(a) Schematic representation of the actuators around the neck.

(b) The device worn on the neck.

Figure 5.2: Actuators Configuration



(a) Precision Microdrives's vibration motor Model 310-113 (Precisionmicrodrivescom 2016).

(b) The Device.

Figure 5.3: Apparatus. We can clearly distinguish all the pieces that compose the device: in the center, the ArduinoMega with the PCB mounted on top. On this, there are soldered the ESP8266 and the power shield. Six kynar wires connect the actuators to the device. Around it, the elastic band.

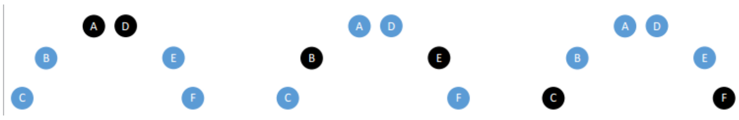
5.4 Experiment 3 - Affective Rating

Previous to this study two preliminary experiments (ten participants each) were conducted. In the first one we assessed the range of intensity that were perceivable on the neck's skin without resulting irritating. In the second one we built an haptic dataset populated by perceptually distinguishable vibrotactile patterns. These are reported in table 5.1. In this experiment we want to prove that it is possible to elicit emotions belonging to the four quadrants of the circumplex model of emotions through the simple vibrotactile stimuli that populate our dataset.

Parameters	**Number of Levels (Values)**
Sequence	2 (**C**ircular: Figure 5.4a — **R**eflection: Figure 5.4b)
Intensity	2 (**L**ow: 40 — **H**igh: 60)
Vibration	2 (**S**mooth —**B**uzz)
Time	1 (455s)

Table 5.1: Final Parameter Levels

(a) Circular Sequence.



(b) Reflection Sequence.

Figure 5.4: Order in which the actuators are driven within each Sequence's parameter

Participants
20 participants (5 females) in the age group of 22 to 28 were tested. Six of them (3 females) already had

experience with the device as they participated to the aforementioned preliminary experiments.

Procedure

Each participant was asked to read and sign a consent form and they were instructed about the goal of the experiment. A definition for *Valence* and *Arousal* were provided. Once they signed the consent form, they were asked to sit in front of a computer and wear headphones playing white noise to mask any source of noise.

Before the actual experiment started, four pictures (Figure 5.5) extracted from the GAPED database (Dan-Glauser and Scherer 2011) were presented. These provided a visual representation of the four levels for the circumplex model of emotion, namely: *High Valence — High Arousal*, *High Valence — Low Arousal*, *Low Valence — Low Arousal* and *Low Valence — High Arousal.* This part was necessary to be sure that each participants fully understood the meaning of these two parameters.

Then they were asked to complete a trial phase to get acquainted with the scoring system and with the graphic interface. They had to rate eight stimuli for both valence and arousal on a 5 point scale (i.e. from -2 to +2) on a dialog box. The users were informed that these data were discarded.

Finally, the real experiment began. The procedure was the same except that each stimulus was repeated 10 times in a pseudo random order, leading to the evaluation of 80 total stimuli. The average time to complete the experiment was approximately 12 minutes. The Independent Variables were the *Sequence*, *Intensity* and *Vibration* parameter shown in Table 5.1 (depending on the combination), while the Dependent Variables were *Valence* and *Arousal* with the 5-point Likert values converted to -2 to +2. We analyzed the data through a three-way repeated-measures MANOVA with Valence and Arousal as combined dependent variables.

(a) H95: Low Valence Low Arousal (b) H22: Low Valence, High Arousal (c) P101: High Valence, Low Arousal: (d) P105: High Valence, High Arousal

Figure 5.5: Gaped: Images Selected

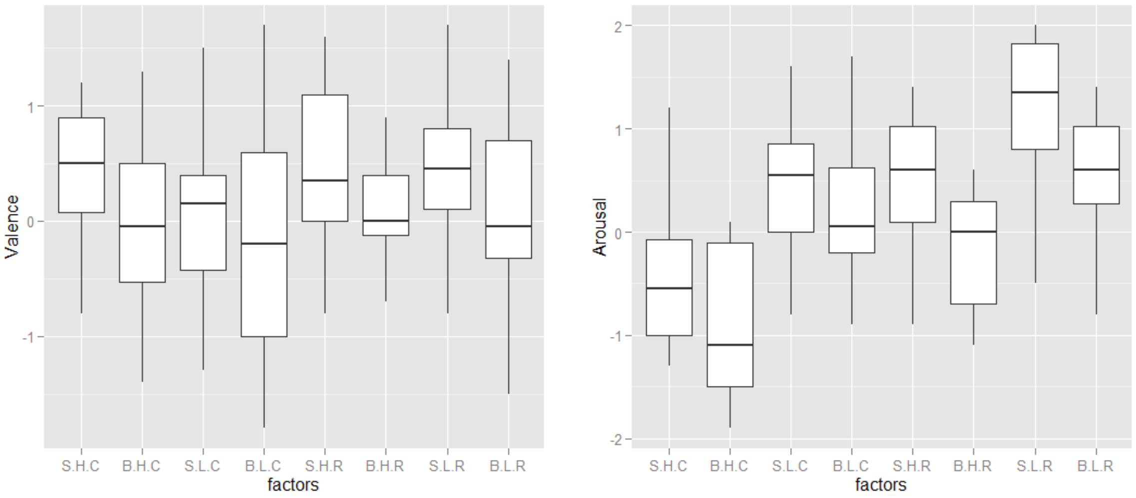
Result

There were no outliers in the data, as assessed by inspection of the boxplots for *Valence* and *Arousal* (Figure 5.6). The results for the MANOVA are reported in Table 5.2. As we can see the interaction between Intensity, Vibration, and Sequence on the combined dependent variables was not statistically significant $F_{(2,18)} = 1.1615$, $p = .226$, Wilks' $\Lambda = .353$, partial $\eta^2 = .152$. Nonetheless there was a statistically significant two-way interaction between each of the independent variables.

In a follow up univariate ANOVA we found a significant main effect of *Sequence* on *Arousal* ($F_{(1,19.53)} = 29.958$, $p < 0.001$, $\eta^2 = .612$). Arousal ratings for the reflection configuration were significantly higher than those for the circular one. *Intensity* had a significant effect on *Arousal* ($F_{(1,19)} = 79.395$, $p < 0.001$, $\eta^2 = .807$). Arousal ratings for the high intensity vibration were higher than those for the low intensity. Finally *Vibration* had a significant effect on both *Arousal* ($F_{(1,19)} = 39.173$, $p < 0.001$, $\eta^2 = .673$) and *Valence* ($F_{(1,19)} = 5.649$, $p = 0.28$, $\eta^2 = .229$). To break down these interactions, simple pairwise comparisons were performed. They revealed that the arousal ratings for the smooth vibration were significant lower than the buzz vibration, while the opposite was true for the valence ratings. These are represented in Figure 5.7.

Effect	Wilks' Λ	F	Hypothesis df	Error df	p	Partial Eta Squared	Observed Power
Sequence	.264	25.071	2	18	0	.736	.293
Vibration	.190	38.378	2	18	0	.810	1
Intensity	.179	41.154	2	18	0	.821	.999
SxV	.716	3.563	2	18	.05	.284	.309
SxI	.640	5.069	2	18	.018	.360	.474
IxV	.711	3.655	2	18	.047	.289	.320
SxVxI	.848	1.1615	2	18	.226	.152	.111

Table 5.2: 3 Way within subjects MANOVA



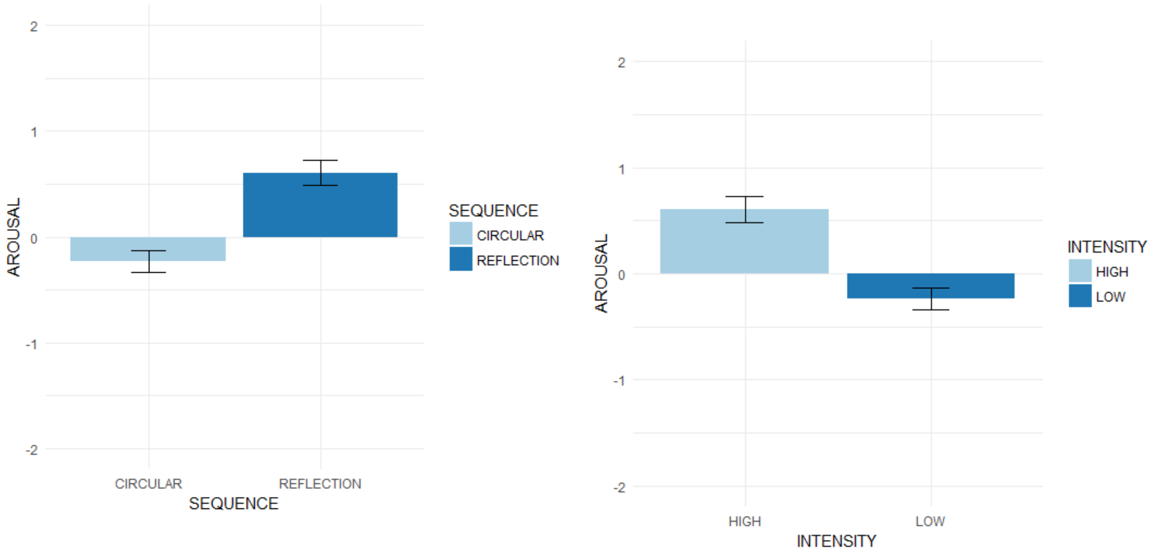
(a) BoxPlot Valence

(b) BoxPlot Arousal

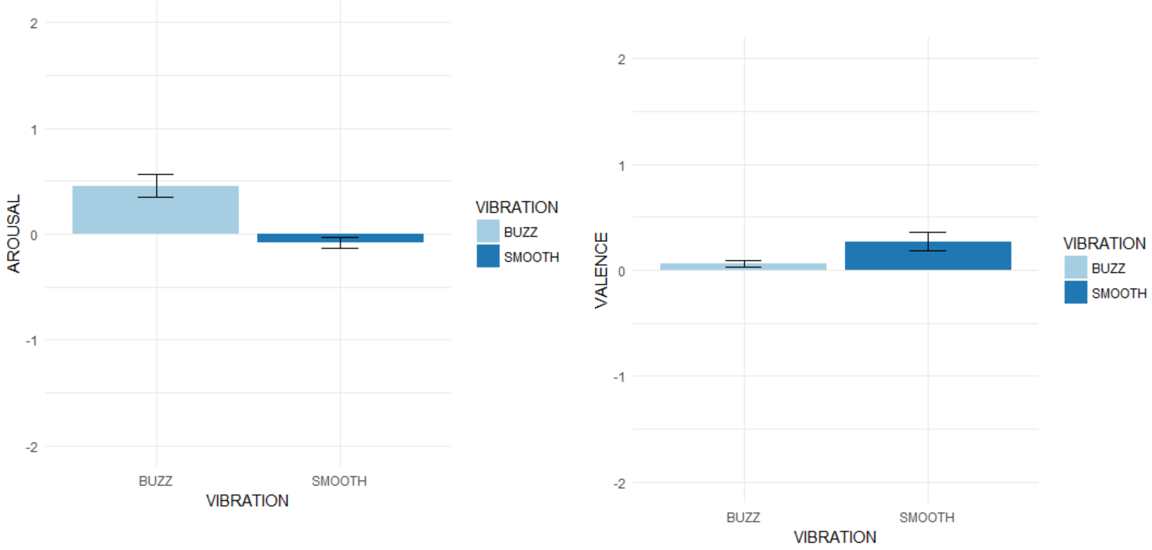
Figure 5.6: Inspection of the data by Boxplot. Each groups is represented. For every parameter there are two levels. *Sequence*: **C**ircular, **R**eflection. *Intensity*: **H**igh, **L**ow. *Vibration*: **B**uzz, **S**mooth

5.5 Discussion

The results revealed no three way interactions. This should not come as a surprise as, while the *Intensity* and *Vibration* parameter were created following guidelines estabilished in previous affective haptic studies, the *Sequence* parameter was created to privilege the perceptually distinguishability between its two levels while keeping the vibrotactile patterns abstract (i.e. they weren't designed to resemble or to recreate any physiological sensation). If the chosen levels for this parameter would have tried to recreate, for example, the scamper of a spider along the neck (i.e. fast buzz vibrations all along the neck) instead of a cat rubbing its head (i.e. smooth slow vibrations on one side of the neck) results may have been different. This highlights a first limitation of our study and of the vibrotactile parameter *Sequence*. When a sequence of vibrations, be they "buzzes" or smooth, is perceived on the neck and it is not coupled with a precise meaning it doesn't convey any significant emotion. At this stage, this is also a limitation for the whole field of haptic technology (Smith and MacLean 2007). In the same way we can justify the significant interactions for all the independent variables with the *Arousal* rating. Indeed most of the participants commented that the experiment felt really relaxing and jokingly asked if they could repeat it. We cannot exclude that this was an effect of the white noise they were listening during the experiment as a mean to cancel the noise made by the vibration of the actuators. Nonetheless it may suggest that they felt the levels in the *Sequence* and in the *Vibration* as a relaxing massage. Indeed the actuators were placed in the area between the splenius muscle and the trapezius muscle, a part of the body which is often massaged to relieve stress. In line with Yoo, (Yoo et al. 2015) who states that most of the vibrations are perceived as arousing, the participants were able to perceive and rate more consistently the *Arousal* rather than the pleasantness (i.e. *Valence*)



(a) Sequence's Mean Arousal (b) Intensity's Mean Arousal



(c) Vibration's Mean Arousal (d) Vibration's Mean Valence

Figure 5.7: Results

of the stimuli. Hence we can infer that each participant has its own sensibility and there is not an agreement upon what is pleasant or unpleasant.

Analyzing the results of the univariate ANOVA we can conclude that our results were in line with those of previous studies. Indeed the "smooth" level for the parameter *Vibration* was perceived less arousing than the "buzz" level, while the opposite was true for the valence (Yoo et al. 2015). This is a significant result for our setup as it proves that it is possible to create different roughness levels utilizing simple ERM actuators. In contrast with results of previous studies, the *Intensity* of the vibration influenced only the arousness of the stimuli, with the higher intensity perceived as more arousing. This result confirms that each participant has its own sensibility on the neck and suggests that affective ratings are sensitive to experimental variability (Wilson and Brewster 2017).

We can conclude that in contrast with our hypothesis the vibrotactile patterns conveyed on the neck didn't elicit the emotions belonging to all the four quadrants of the circumplex model of emotion. Nonetheless the results were promising as, in line with previous studies conducted on other part of the body, we were able to elicit emotions belonging to the first two quadrants (i.e. Low Valence, High Arousal and High Valence, High Arousal). This indicates that the neck is a suitable part of the body to perceive vibrotactile patterns meant to elicit emotional states. These results are in line with those obtained by studies that investigated other part of the body, but to fully assess the potential of the neck as affective haptic surface more studies are required.

5.6 Conclusion and Future Works

In this paper we aimed to cope with the intrinsic limitations of vibrotactile stimuli as a mean to convey emotional states as defined in the circumplex model of emotion by investigating the neck's surface. We chose the neck for its unique characteristics of being both intimate and completely exposed. To this intent we designed a wearable haptic device mounting six ERM actuators and used it to conduct an experiment to assess the ratings for *Arousal* and *Valence* for the elements of a previously created haptic dataset. These elements were created by combining the levels of three custom made parameters: *Sequence, Vibration,* and *Intensity.* Two of those were based on previous studies while *Sequence* was created exploiting the geometry of the actuators along the neck.
Results of a three way repeated measures within subjects MANOVA revealed no significant three way interactions which makes us suppose that the *Sequence* parameter should have been designed more carefully. Nonetheless we obtained results in line with those obtained in previous studies which allow us to validate the design of our device. The results obtained weren't substantially different from those obtained testing other parts of the body, hence we conclude by saying that although the neck shows promising capabilities as haptic surface, the range of emotions that it is possible to elicit are in line with those in other part of the body. This shows a potential for the neck as an affective haptic surface which could lead to further developments in commercial applications such as gaming and multimedia entertaining. Nonetheless the limitations highlighted in this study requires more researches. In particular a more exhaustive study is required to assess different ways to drive the actuators. Since it's not feasible to explore all the possible combinations that allow to drive an array of six actuators and because emotions are inherently subjective, we suggest that the design phase should be a process shared between the researchers and a group of users. Eventually it will be interesting to assess if there is a real difference between the affective ratings of the vibrotactile stimuli perceived on the neck and the one perceived on another parts of the body such as the arms, the hands and the torso. In order to this we propose to build devices that share the same characteristic of the one we built for the neck and conduct an experiment where all these devices are tested, one at a time, on all the participants. Finally we are aware that the way we displaced the actuators around the neck is not the only one possible and, although we obtained significant results, more configurations exist and these should be tested as well.

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