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Issues, Challenges and Practices in Advancing Pervasive Human-Computer Interaction for People with Combined Hearing and Vision Impairments

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Introduction

This dissertation is entirely dedicated to people having some degree of combined impairments of both the visual and the auditory channels and, specifically, to deafblind people. As such individuals are deaf and blind at the same time, they are not able to rely on their sight or on their sense of hearing to communicate with others and to interact with the external world. As a result, they are forced to utilize an alternative channel for achieving communication, interaction and access to information. Among the residual channels, the sense of touch is the best sensory substitute: although it is less performing than vision and hearing, it enables exchanging messages with the environment. Nevertheless, in order to be accessed for exchanging messages (communication) or for acquiring information, people and objects have to be at contact distance. This major drawback can be mitigated by introducing assistive technology (AT) in the form of novel human-computer interfaces that enable individuals to go beyond close proximity and to interact with a world that is, day after day, one step forward.

The purpose of Assistive Technology is providing individuals suffering from many types of different disabilities (e.g., from cognitive problems to physical impairment) with support to individual tasks. Designing an assistive interface implies investigating the relationship between the willingness of using some technology and a temporary or permanent inevitable condition that renders technology compulsory or adds urgency to the need of technological aids. That is, in a scenario of fashion high-tech gadgets, for some people digital devices are not an option. This is the fundamental principle by which interaction designers have the objective of providing people with real support to their basic and fundamental needs.

Nowadays, adaptive technology has a substantial impact on people with sensory, cognitive, and developmental impairments. Also, it has significant benefits for the deafblind: it allows them to achieve communication and to overcome obstacles that seemed overwhelming ten or fifteen years ago. As a consequence of the introduction and the use of technology to close the digital divide with people with disabilities, the deafblind will benefit from more options for education, training, and future employment. Regardless of the complexity and of technology advancement, still individuals will require better systems to be autonomous in communication, to and independently move and interact with the environment, and to get unrestricted access to information. Most importantly, proper technology and training can help them decrease the feelings of isolation, and achieve a complete and fun social life.

In this regard, tactile and haptic interfaces have great potential in rendering computers more accessible to the blind. Particularly, they address specific shortcomings of traditional sensory substitution approaches based on auditory output and, thus, they are especially suitable for the deafblind. However, they have particular requirements in terms of design. In this dissertation, we focus on the several different aspects involved in the design, development and marketing of novel tactile interfaces for the deafblind. We discuss an innovative approach for reducing the prototyping and production costs and for maximizing the performances of assistive technology in terms of acceptability.

Motivation

In the scenario of disabilities and sensory impairments, deafblindness is among the worst-cases. Fortunately, it only affects a small percentage of the population. Being a niche market, in turn, is one of the main reasons why spending in innovation is not considered profitable by both companies and professional investors. Indeed, deafblindness is a rare, challenging, demanding, and urgent situation. Although dealing with this type of disability can be complex, the needs of deafblind people are the very same as that of the sighted: independence, access to information, social integration. And other rights they do deserve. In this regard, the motivation of this dissertation is helping people in particularly demanding situations in gaining back their rights thanks to the use of innovative assistive devices. Authors had no initial personal motivation when they decided to be devoted to this objective, in 2004, and it was a merely technological challenge. Today, this has become more: it is the discovery of unexplored niches of existence that indeed are worth knowing.

Objectives

This dissertation aims at deeply exploring the scenario of assistive tactile interfaces for the deafblind. The objective of our research is five-fold:

1. introduce a description language that can be utilized for rendering touch-based communication methods interoperable;
2. model pervasive interaction based on touch to evaluate the most effective paradigms for accessing the external world, both proximal and distal;
3. innovate the scenario of pervasive interaction with novel devices that can provide users with day-long support to their most common tasks in terms of communication and access to information;
4. identify strategies for improving the design, development and distribution of assistive technology.

Structure of the document

In the first part of this dissertation, we provide an overview of touch-based communication systems, and we identify their major features, and we introduce a meta-language that enables the description of both the static and the dynamic features of touch-based communication systems, in order to enable systems to easily move from one language to another.

The second part of this dissertation is dedicated to innovative devices especially designed for the deafblind; we discuss the challenges in implementing the dynamics touch-based communication systems into interactive devices, and we detail some experiments. Moreover, we discuss the design of a bimodal tactile device meant to enhance content reading with Braille displays; we present a tactile mouse for providing blind and deafblind users with vibrotactile-assisted two-dimension spatial navigation, and for enabling them to interact with WIMP interfaces. Subsequently, we introduce dbGLOVE, a proprietry wearable technology dedicated to the deafblind. Finally, we focus on the evaluation of dbGLOVE, and we introduce some improvements to the performance of the device.

Original contribution

This dissertation reviews original work done in the field of assistive technology for the deafblind since 2004. All the technology discussed in this dissertation is proprietary and original contribution of the author. Particularly, dbGLOVE is an original patent.

Also, we include research studies and experiments realized in collaboration with QIRIS. QIRIS was founded by the author, who is its Chief Executive Officer since 2009. QIRIS (Quality Innovation Research Instruction Safety) is an independent non-profit association for scientific research committed to social interests. QIRIS realizes research projects and technological innovations to improve the quality of life of people in disadvantage (people with disabilities, the elderly and hospitalized patients). Although the focus is human-computer interfaces, this dissertation includes the multidisciplinary contribution of the members of QIRIS, who research in several disciplines, from human physiology to design and electronics.

Limitations of this dissertation

This dissertation is mainly focused on applied research, and on providing the people with tangible innovation. Therefore, we do not introduce any significant discovery from a theoretical point of view. Nonetheless, in this dissertation we introduce novel systems for representing touch-based communication, innovative models for classifying technology for tactile interaction and for rendering it pervasive, inventions patented by the author, new approaches to designing, developing, and marketing assistive technology in niche markets. With respect to the latter, this dissertation is limited in that, as the defafblind represent a very small percentage of the population, it is extremely difficult to retrieve information and data about this domain.

Moreover, some of the methods we introduce could not be extensively experimented on large-scale scientific trials; also, some concepts and theories introduced in this dissertation have not been evaluated. In this regard, we hope this dissertation will contribute to increase attention about the topics discussed here.

Finally, the experimental studies detailed in this dissertation involve healthy participants without any sensory impairments. Intentionally, we did not involve blind and deafblind users because our technology is still to be considered at a prototype leve, and we did not consider it as sufficiently mature to be adequately tested on people with impairments. Although we involved experts and technicians, the results of our experiments have to be validated with real users when our research will receive sufficient funding to take our technology to the next level.

Conventions

With respect to directionality of messages, we intend communication processes as based on the concept of messages being passed from sender(s) to receiver(s). In this dissertation, we apply a user-centric approach and, thus, we will use the following conventions:

- *input system* (*input*) refers to a machine agent capable of receiving messages sent by the human agent, or to the situaton in which the human agent sends messages;

- *output system* (*output*) refers to a machine agent capable of sending messages to the human agent, or to the situaton in which the human agent receives messages;

- *input/output system* (*input/output*) intuitively refers to a machine agent capable of receiving messages from and sending messages to the human agent.

Where not explictly stated, the words *system*, *device* e *peripheral* e *solution* are utilized to refer to the object per se, and they are employed as synonyms, as they do not refer to any specific architecure, operating mode, or communication protocols.

Moreover, when we refer to touch-based communication, our approach is extremely strict: although tactile communication can be associated with spoken language (as in the case of blind people) or visually-perceivable gestures (e.g., in sign languages employed bu the deaf), we only focus on the tactile component of interaction (or communication), and we take less into consideration the visual or auditory elements.

Sources

This dissertation references to articles published and indexed on major scientific conferences and journals. However, given the inherent difficulty in finding extensive information about this particular domain in the scientific literature, alternative sources of information have been explored. These iclude documents published by associations that provide information or assistance to deafblind people (e.g., the American Association of the Deaf-Blind), in addition to other sources considerered as reliable by the community working on deaf-blindness. Also, we decided to include statistical and census data independently processed by municipalities, service centers and other less relevant albeit reliable sources.

Part I

Touch-based communication systems

Chapter 1

An interpretation framework for touch-based communication systems

1.1 Communication using touch

Although the world is perceived as mainly structured into visual and auditory stimuli, the sense of touch plays a fundamental role in human perception, as it enables individuals to communicate with others and acquire a variety of pieces of information about both the environment and the external world. Touch is the first sense being formed in humans: sensitivity to tactile stimulation is already developed at the eighth week of gestation of an embryo [1]. Also, it is among the senses that still are available when sight and hearing start to fade.
Despite its simplicity and its longevity, the sense of touch is not to be conceived as "*primitive*" with respect to vision and audition. In

addition to being an informative and perceptual system of sensing, it includes features that enable bidirectional exchange of information and active communication [2]. Nevertheless, vision and hearing are the major senses through which individuals perceive the world and communicate with others, because they utilize the most convenient perceptual channels in terms of information throughput. As the majority of humans mainly rely on the visual and on the auditory channels to perceive the world, also verbal and nonverbal communication methods usually utilize the sight or the sense of hearing as primary channels for exchanging messages [10]. As a consequence, despite its potential, touch is fundamentally utilized for simply acquiring information about the environment in close proximity, and for manipulating objects in everyday tasks. Eventually, touch-based communication systems receive less attention.

In this dissertation, we will use the terms "*touch-based communication*" in reference to the tactile component of messages, only, even if several communication systems simultaneously use two perceptual channels in order to exchange information. For instance, the sign language utilized by the deaf combines tactile and visual communication; also, blind people utilize tactile displays in combination with auditory output. However, as this work focuses on people with a combined degree of visual and auditory impairments, we will only take into consideration touch. Regardless of the communication system, the majority of purely tactile languages are not utilized by the deaf, who prefer to utilize their vision (or residual vision) to interact with the environment, with computers and with others. Conversely, thanks to the introduction of digital tools for supporting a variety of tasks (e.g., reading books), the blind increasingly utilize auditory feedback instead of traditional touch-based communication systems dedicated to the visually-impaired, such as the Braille alphabet.

Several touch-based systems are available for informative and communication purposes. Specifically, tactile languages allow exchanging messages between individuals, and they are particularly suitable for enriching or complementing verbal communication in situations of impaired sight, if the sense of hearing is affected by some impairment. In general, communication systems based only on touch are utilized when the auditory or the visual channel are affected by noise, such that the reception of the message is compromised to some extent. Furthermore, people who are affected by multiple sensory impairments to the visual and the auditory channels (i.e., the deafblind) have the only choice of using touch for accessing the external world both for communication and for information retrieval purposes.

However, the main issue with touch-based communication systems and, in general, with Augmentative and Alternative Communication systems (AACs) is that, as they are not widespread in the community of non-impaired people, they require the deaf, blind and deafblind to need the constant presence of an assistant who plays the role of an interpreter in situations of interpersonal communication. This, in turn, poses strong limitations to their opportunities in terms of interaction with the external world. Moreover, as there are no official models to conceptualize touch-based communication systems, it is extremely difficult to learn such languages.

In this work, we detail the most important features of each of the aforementioned systems, with the ultimate goal of capturing the characteristics that can be modeled into an Interface Description Language (which will be detailed in the next pages) that can be utilized for designing versatile hardware and software human-computer interfaces dedicated to people with sensory impairments. Therefore, we review current touch-based communication systems in order to extract the main components of the language and to express them into a formal notation. This, in turn, will be utilized as a meta-language for representing the characteristics of tactile communication systems from both a semiotic and mere physical points of view. Such characteristics are crucial for understanding the most suitable methods to be implemented when quantitative requirements, such as reliability, accuracy, and effectiveness have to be met also combining qualitative requirements (e.g., acceptability).

1.2 A framework for touch-based languages

One of the most frequent scenarios in centers devoted to sensory-impaired people involves assistants using several communication systems in order to exchange messages with different users who are deaf, blind, or deafblind. Moreover, caregivers use different methods for interacting with individuals depending on the specific situation of each individual. For instance, the deaf would use sign languages, whereas blind people would speak and read Braille; on the contrary, others would use the Malossi alphabet or print-on-palm, depending if they are deafblind born or have become deafblind in their later life. On the contrary, sensory-impaired children would use objects for communicating, whereas adults with additional impairments at the cognitive level would exchange simple touch cues. It is impressive to see that, although different communication systems help people to interact with the external world, on the other hand, so many languages separate individuals living in the same environment, sharing the same space, and experiencing similar conditions. Nevertheless, regardless of their specific situation, generally, sensory-impaired people are not able to interact with people other than assistants, family members, or close friends who know their language.

Knowing individuals' characteristics and languages, assistants can switch from one communication system to another in order to cope with different requirements and sensory impairments. As a result, they enable communication in a peer to peer fashion. However, they can serve one user at a time, and their services involve additional costs many are not able to pay for. Consequently, they are available for limited time. We envision a system that plays the role of an assistant in interpreting communication from different touch-based systems to written or spoken language, and vice versa. Thus, they enable individuals to autonomously communicate with sensory-impaired people, allowing each to use their own language, without requiring them to learn others' languages. Moreover, rendering communication systems interoperable would help sensory-impaired people interact with the external world, be autonomous and independent in communication, get access to information, and achieve social inclusion.

Although they can easily be formalized into a set of patterns that would simplify their utilization, as Augmentative and Alternative Communication systems represent niche markets, they receive less attention. Consequently, there is poor interoperability between interfaces and assistive devices adopting different languages. Also, this affects the development of new communication technology for the blind, due to increased costs, difficulty in accessing to resources, and lack of scalability. Furthermore, this is the fundamental reason why design patterns, which are widespread in the community of Human-Computer Interaction, are not available in the domain of assistive technology.

Patterns and frameworks are among the most powerful methods for approaching to the design of new solutions. The former consist in couples of items, one representing a typical design issue, and the other element representing a set of key insights to the solution. The latter are conceptual models of a domain that help organize and manipulate knowledge effectively. Both have widely been employed in the development of software systems, and they have been utilized in other domains, such as architecture and engineering, for decades. Patterns and frameworks provide designers and developers with robust solutions to recurring problems, and they allow consistent communication between operators focusing on the same field of study. Moreover, frameworks offer an interpretation tool for new issues, because they can offer an insight to previously adopted methods, they allow to programmatically review the state of the art, and they help anticipate new circumstances. Despite the benefits they may have in the domain of assistive technology, there are only a few conceptualizations, and they mainly focus on the assessment of technology, that is, they regard at the very last stage of the development process. Although they are crucial, proactive frameworks for supporting the initial stage of the design of innovative solutions would be of more support, because they would help close the loop with frameworks that examine assistive technoloy in a reactive fashion.

Several organizations designed and developed frameworks for Augmentative and Alternative Communication systems. Among them, the Daisy consortium is at the most advanced stage, as they are the responsible for the ANSI/NISO Z39.98-2012 Standard, i.e., *Authoring and Interchange Framework for Adaptive XML Publishing Specification* [21]. This, in turn, defines a framework in which to develop XML markup languages to represent different types of information resources (books, periodicals, etc.), with the intent of producing documents suitable for transformation into different universally accessible formats. The standard focuses on accessible output requirements, with the aim of rendering information resources accessible both using current e-book readers and with Braille displays. However, it does not take into consideration communication between individuals, or interaction with a computer.

In this section, we introduce a conceptual framework for the interoperability of touch-based communication systems. Also, we detail a meta-language for describing the so-called Augmentative and Alternative Communication systems [22] based on touch, with the objective of producing their formalization. Moreover, we review the major touch-based methods for exchanging information with the external world, with the purpose of describing their implementation in our proposed framework. Indeed, as the development of standards is an evolutionary process, we introduce some of the elements that aim at giving examples for further research and applications.

Sensory substitution

In case of impairments to one sensory channel, *sensory substitution* is a technique that can be utilized to replace the missing (or less performing) sense with another. As an example, blind people use the sense of hearing as a replacement for vision. Let us define the *level (or degree) of sensory substitution* as the number of perceptual channels that are replaced. Therefore, sensory substitution level 1 applies to the blind and to the deaf: the former increasingly rely on the auditory channel to substitute the sight, whereas the latter replace audition with vision. However, for individuals who are nonverbal (e.g., because they have difficulty in articulating or understanding speech) or suffer from multisensory impairments (e.g., the deafblind), level 1 sensory substitution is not enough. In these circumstances, two degrees of sensory substitution occur. That is, both vision and audition must be replaced. Ultimately, for this category of people, touch is not an option: individuals who are simultaneously blind and deaf need to utilize the sense of touch as the most viable substitute for vision or speech, respectively.

Ultimately, when technology for will be mature enough, touch-based communication systems will be utilized only in the case of level 2 sensory substitution. Therefore, in the next years, despite the blind and deafblind population is expected to increase, the number of people learning tactile alphabets will diminish. As in the case of many other languages, the fact that some touch-based communication systems will disappear has advantages and drawbacks that are beyond the scope of this dissertation. The only touch-based communication systems that will remain are those employed in well-established communities characterized by geography or condition. Sign languages (e.g., sign languages utilized in the deaf community), which are a distinctive feature of communities, are expected to resist to being replaced by technology. Nowadays, given the statistics of the deafblind and the costs of learning touch-based communication systems, only a minority of people with normal hearing and vision know tactile languages (see Section 4.1). This is because of personal factors (e.g., some of their relatives are deafblind) or because of their jobs (e.g., assistants). As a result, touch-based communication systems are basically known by primary users (i.e., blind, deaf, and deafblind), by their family (or their close milieu), and by their assistants, only. In order to communicate with individuals that use tactile languages, people with normal hearing and sight who are not able to utilize any touch-based communication systems require the constant presence of an interpreter who has the purpose of translating communication from the tactile language to verbal communication, and vice versa.

1.2.1 Framework architecture

We propose an interpretation framework for touch-based languages that focuses on the use of technology for interpersonal communication. Although we specifically refer to computer-mediated interaction with the external world, the results can be reused in other domains. To this end, we designed our framework to be compatible with current standards and, specifically, with [21]. Our framework aims at standardizing the way in which different pieces of assistive technology are employed with respect to the languages already known and utilized by their users. The ultimate goal of our framework is to render assistive technology interoperable. To this end, we avoid defining models and architectures for markup languages. Instead, we focus on a general, extensible and highly-adaptable structure in which specific models can be defined. We provide example implementations of several different languages with the only purpose of demonstrating the feasibility and the applicability of our framework to a variety of communication systems, thus, supporting the diverse requirements of blind, deaf and, particularly, deafblind people.

Therefore, our framework conceptualizes touch-based communication methods, and it defines the main architectural requirements for the interoperability of communication technology for people with special needs, without specifying the low-level rules and requirements for the implementation. Particularly, the architecture defines the components that support communication in case assistive technology is employed, but it does not define any rules for describing how messages are exchanged. As in the case of low-level implementation, this is a matter of further standardization.

The primary objective of the proposed framework is to support the development of technology for sensory substitution, by encompassing the alternatives to vision and hearing in a flexible and versatile fashion. Also, it enables the design of new training tools for enabling people to learn and use touch-based communication systems. The proposed framework is particularly suitable for situations in which individuals in different conditions want to interact, each using their own language and device. By defining a model that incorporates and implements several communication methods, it is possible to design an interpretation system that enables the automatic encoding and decoding of messages taking into consideration and adapting to individuals' diverse needs.

Computer-mediated communication based on touch that occurs between two individuals includes the sender and the receiver of the message, the devices through which messages are sent and received, the communication systems (which can be different) utilized by the sender and the receiver, the protocols that rule communication, and the context in which interaction occurs. As a result, the proposed framework consists of the following components:

- *agents*, which represent the humans (or machines) involved in communication, that is, the senders and the receivers of messages;

- *protocols* and languages (rules, conventions, and meanings) that are employed for encoding and decoding messages from one language another, in a bidirectional fashion, and for interpreting them into executable actions, starting from sets of symbols that encode and decode messages;

- *devices*, representing the technology employed to support communication via perceptual channels (i.e., sight, audition, touch); in general, we will refer to touch-based communication systems;

- *contexts* in which communication or interaction occurs; also, this defines states, actions and conditions that affect or rule the functional goals of communication.

Figure 1.1 depicts the architecture of our system. The sender and the receiver are the two endpoints of communication. They may be in or refer to different contexts (see Section 4.1), they may use different languages and different pieces of technology. For instance, sighted senders would type their message in written English using a keyboard, while deafblind receivers would read the message in Braille on a dedicated display. Also, the former could be using a mobile Application, while the latter could be sitting in front of a computer, at a community center. In our framework, language is incorporated into the device. Although this might seem less user-centric, it actually helps represent devices as natural interfaces: they should inherently implement the language already in use by individuals, without requiring users to adapt to technology. Protocols allow functional communication between the sender and the receiver by mediating their messages. The communication protocol is responsible for encoding and decoding message content from one language to another.

Contexts, protocols and devices should be invisible to users, as they are implicit, transparent, and natural, respectively. Specifically:

- *as interaction is situated,* ***users manifest the context in which they operate***: characteristics of individuals' background are defined within instances of user models;

- ***messages are proximal representations*** *of distal intentional meanings*: in the exchange of messages between the sender and the receiver, the syntactic content is the only part to be translated (i.e., encoded or decoded), whereas the semantic component should remain unchanged;

- *as they are natural interfaces,* ***devices expose communication systems without additional overload***: although users interact with tangible technology, they should keep using their language of preference with little or no modification.

As a result, contexts refer to different situations in which individuals may interact with devices (how communication changes depending on the circumstance), protocols regard to the way in which the content of messages are syntactically and semantically structured (how communication is defined by the language), and devices implement the interaction dynamics of languages into technology for communication (how languages are enabled through technology). The latter will be discussed in Section 2.1. This section focuses on language modeling of touch-based communication systems.

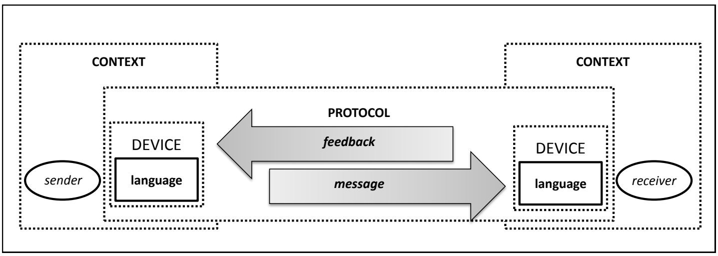


Figure 1.1: Architecture of the proposed framework.

Agents as mediated communication endpoints

In the majority of computer-supported communication, there are two human endpoints mediated by a machine agent, who plays the role of an interpreter. Also, there are circumstances in which users interact with computers, only, which is especially the case of getting access to information. The basic difference between the two situations is in the decoding function, which is left to the receiver in the former case, while in the latter, messages sent by the user have to be interpreted a commands by the machine. Despite the complexity of interpreting users' commands, which also depends on the interaction context (see next section), mediating interpersonal communication is more challenging, as individuals in different situations have diverse needs. Usually, it is assumed that the two communication endpoints utilize the same communication channel (e.g., speech), the same language (e.g., written English), and the same communication device (e.g., voice, or keyboard and screen). Conversely, individuals suffering from sensory impairments need to interact with people having normal sight and hearing, in most of the circumstances. To this end, either the former require the latter to know their communication method, or they need the presence of an interpreter who translates messages for them. Moreover, assistants are needed for interacting with the environment and with the external world. In this regard, methods for exploring the ambience usually have a human communication endpoint, though the environment itself can be conceived as a communication endpoint.

In this dissertation, we will not focus on the conceptualization of agents. Several representations are available for describing human and virtual agents, as well as their characteristics and requirements, and any user model of choice can be incorporated in the framework. As the focus of this dissertation is capturing how communication systems can be mediated by computers in order to be interoperable, we will conceive the sender and the receiver as users of devices each incorporating a communication system. As a result, users can be described as a set of preferences with respect to the languages they know, to the devices they utilize, and to the contexts in which they are. By doing this, it is possible to adapt the specifications of the components of the framework to the different user profiles, and to obtain a fine-level description of language preferences, context intents, and device configurations.

1.2.2 Modeling functional communication by means of protocols

In our framework, we focus on the basic form of communication, the so-called *functional communication*, in which language is simply functional to modifying the environment in a way useful to the sender (or to the receiver) of the message. It is said *functional* because its purpose is in that the result of communication can be predictable or controllable (in some sense) by the sender. A communication system is (said to be) functional if the both of the following hold:

- senders can effectively elicit their needs and their requests;
- receivers can effectively understand the senders' needs and requests.

Moreover, functional communication is *intentional*, that is, messages are transmitted on purpose from the sender to the receiver. Functional communication is based on two main functions:

- using the **receptive function**, receivers are able to decode their messages;
- using the **expressive function**, senders are able to encode their messages.

Although it may seem extremely basic, functional communication plays a crucial role for people with impairments, and especially for those who are not independent. As many of them rely on the presence of others to realize even the most elementary actions, being able to communicate their needs helps them achieve their goal.

In our framework, we model functional communication using Finite State Machines (FSM): it can be regarded as a set of *input events* (i.e., messages) that allow individuals to activate *state transitions* (i.e., actions) that, depending on certain *conditions*, enable switching the *states* in which individuals can be (e.g., thirsty, tired, hungry). Thus, functional communication refers to a system having a limited number

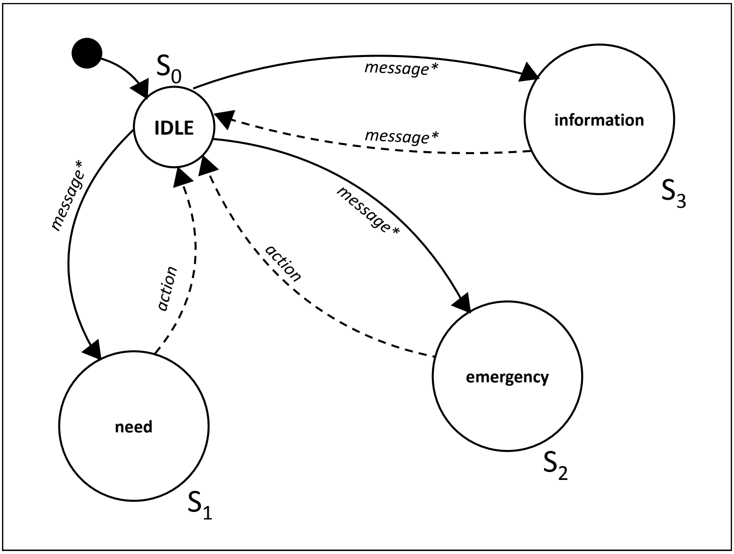


Figure 1.2: Finite State Machine modeling of communication protocol.

of defined states, and specifically, need (e.g., urgency to go to the toilet), emergency (e.g., having an epileptic shock), or information (i.e., interpersonal interaction or access to information resources). Figure 1.2 represents the three circumstances. In this case, we refer to the semantic component of messages (i.e., the intent), that allow others to interpret individuals state and to perform actions accordingly. Consequently, at a semantic level, messages are requests for actions defined by means of syntactic structures in the language of choice.

In our framework, languages are conceived as syntactic means for encoding intent. Moreover, as basic communication has the purpose of providing people having cognitive disabilities with a way to exchange functional messages, it requires the receptive and the expressive functions to use *transparent language codes*, that is, the *sign* and the *significant* (in semiotic terms) should have the least cognitive distance possible. In other words, basic communication aims at reducing the cognitive distance between the symbols and the subjects, the objects or the situations they refer to.

In basic communication, there is direct correspondence between semantics and one specific level of the language model (see Figure 1.3), without any further separation or additional specification. The syntactic layer can be represented by morphology, articulation, or lexical layer. Pragmatics play a fundamental role in disambiguating the meaning, so that the same articulation might be associated with different meanings, depending on the situation.

1.2.3 A hierarchical model of human language

The language component of our framework incorporates the basic structures that enable operating with different touch-based communication systems having heterogeneous features. Although there is an open debate on the model to be utilized for representing the human language, we employed a hierarchical structure. Basically, this is for simplicity in the description of the model, extensibility, and compatibility with the other components of the framework. In this paragraph, we introduce our model and we detail both its design and its implementation.

Actually, the human language inherently contains some form of hierarchical organization, as elements at one level (e.g., letters) are the foundation for the next level (e.g., words). Usually, layers are connected by means of causal or constructive relationships (e.g., letters are utilized to compose words). Also, there are different relationships that enable bidirectional connections between layers. Elements at a upper level constrain elements at the lower level, and vice versa: lower level elements are the necessary units of higher levels (e.g., words cannot be structured without letters); on the contrary, elements at higher levels determine the way in which lower level items have to be utilized in order for messages to be functional from an expressive point of view (e.g., words define the sequence in which letters have to be assembled in order to be significant). As another example, syntax rules over words, specifying how these can be combined in order for messages to be correct; simultaneously, syntax would have no meaning without the presence of words, which are the fundamental elements of sentences.

We modeled human language as a structure consisting of six nested layers, where each is a collection of homogeneous elements. Figure 1.3 shows a graphical representation of our language model. The five innermost layers (i.e., morphology, articulation, lexical, and syntax) incorporate the structural features of the language, whereas the two outermost layers (i.e., semantics and pragmatics) are more related to interpretation and meaning, and they include the functional desired outcome of any intentional communication. In our model, hierarchy is flexible, in the sense that the boundaries between levels can be adjusted depending on the communication intent and situation. Also, levels can be merged or removed depending on the complexity of the language. The only constraint is the presence of at least one structural layer and one functional layer. As the main objective of our model

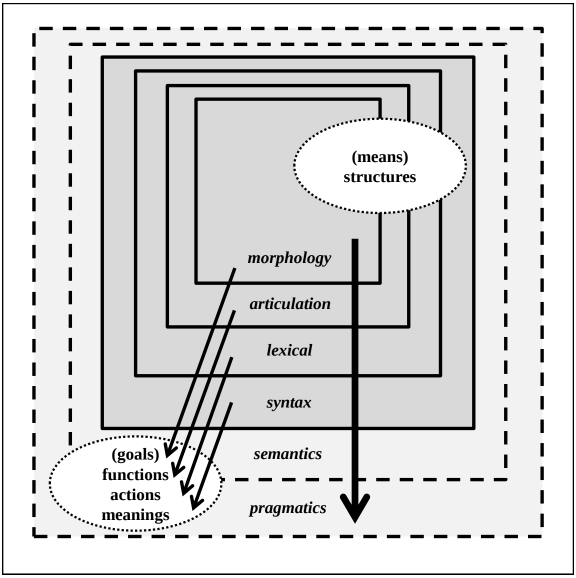


Figure 1.3: The hierarchical model of human language.

is to support functional communication (see previous section), we modeled language in order to primarily accomplish functional tasks. Therefore, we do not take into consideration more general-purpose semantics. Our proposed language hierarchy consists of the following layers:

1. *morphology*, which refers to atomic components of speech; in the case of spoken languages, this is the set of atomic sounds that compose the language, whereas in the case of gestural languages (such as fingerspelling), it is the set of basic configurations of the hands;

2. *articulation*, representing elementary combinations of morphological elements (e.g., letter and sound), such as complex gestures realized by sequential or simultaneous individual configurations;

3. *lexical*, including the set of individual words that are composed by multiple morphological symbols or articulations;

4. *syntax*, referring to the process by which words are combined together to form correct sentences that can be interpreted;

5. *semantics*, which refers to the functional outcome of intentional communication with direct links to the actions that have to be realized in order to accomplish the objective (e.g., messages, such as *I need water* or *I am thirsty* should activate the same action in the receiver, i.e., *bring water*, in order to move the sender to the state *I am ok*);

6. *pragmatics*, that is, the actual actions to be realized in order to satisfy the needs expressed by semantics.

The above categorization can be applied to spoken, visual and tactile languages, that is, it is independent from the communication channel being utilized. Also, it can be extended to encompass more layers (e.g., the discourse layer, which refers to large groups of sentences) in order to support more sophisticated applications. Moreover, the language model can be utilized in other scenarios and domains that are beyond the scope of this dissertation.

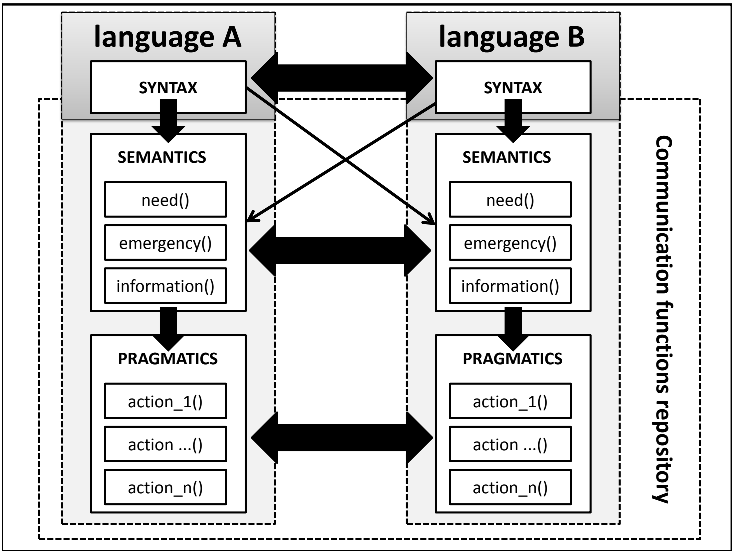


Figure 1.4: Interoperability of languages and repository of semantics and pragmatic features.

In our framework, different touch-based communication languages can be implemented by means of a meta-representation based on a mark-up language having an XML-like structure (see Figure 1.5). The objective of the meta-language is to provide a standard definition for the elements within the layers of the hierarchical model of human language (see Figure 1.3). To this end, the framework does not specify the implementation of syntactic and semantic features (though we detail some examples), which is left to the designers of assistive technology. Instead, the meta-language allows defining relationships between layers and it connects elements in the syntactic and in the semantic domains, so that higher-level syntactic elements are associated with items in the semantics and pragmatics layers. By doing so, our framework achieves interoperability. Figure 1.4 demonstrates this feature: syntax is a hard-coded feature of languages, in the sense that it is strictly related to the way in which different communication systems operate. Conversely, although they have some language-related components and they can be described within the specification of single communication systems, semantics and pragmatics are more independent from languages, and they can form a repository of reusable interaction components that can be referenced regardless of the language.

Languages can be defined using the tag **`lng`**, and layers can be identified by the tag **`lyr`**. The attribute **`name`** allows associating a text identifier, in addition to the integer identifier corresponding to the attribute **`id`**. Elements of the language are defined with the tag **`el`**, which can be used to add new items to the language. The attribute **`dom`** (domain) enables categorization. References to elements can be realized using the tag **`ref`**, and specifying the identifiers of the elements along the path to the referenced element, or using the unique identifier **`uID`**. The tag **`ref`** can be utilized either as unary, or it can reference to multiple uIDs included within the tag. This has global scope, whereas the visibility of **`id`** is within the innermost node. As in standard XML documents, the meta-language is divided into markup and content, which may be distinguished by the application of simple syntactic rules. Generally, strings that constitute markup either begin with the character **`<`** and end with a **`>`**. Strings of characters that are not markup are content. Content supports any type of strings (i.e., numeric, alphanumeric). The delimiters **`<![CDATA[ ]]>`** (which are classified as markup), employed for character data, enable the definition of complex data, which is classified as content as in the standard XML syntax. Complex data can contain definitions of functions in programming languages, or data files encoded in ASCII (e.g., pictures, 3d models). In order to avoid incorporating large data into the

XML representation of language, the tag **file** can be utilized to access to external resources. The attribute **type** represents the file type and the content of the external resource (e.g., image, text, 3D model, or other pieces of code). The attribute **setstate** connects the domain of syntax with the semantic layer. Specifically, it defines the intended meanings of an item in the lexical or in the syntax layers. Indeed, each syntactic element can be associated with many interpretations in the semantic domain. Therefore, disambiguation is required to choose the correct meaning depending on the context. The tag **doaction** connects the semantics layer to the pragmatics, by defining which action has to be activated depending on the intent of functional communication. The following code shows the high-level representation of the hierarchic structure of human language, divided into the syntactic and into the semantic components.

There is an open debate about the real organization of languages. However, we modeled the above components as necessarily organized into a hierarchical structure. In addition to a strict tree-like structure, in our representation items can be connected into a graph, thanks to the tag **ref**. This allows some degree of flexibility and robustness with respect to exceptions to the organization of the model.

In addition to a formalization of the language, the model requires a reasoning system that activates specific actions, an interpretation schema that enables the automatic translation of syntactic messages from one language another. Indeed, specific rules apply to each level. Therefore, the reasoning system and the interpretation schema manage two classes of constraints: syntactic or semantic. The former define rules for structuring words and sentences, which also introduce some regularity and provide some insight in the use of the language. The latter basically refer to:

- the *context* in which languages are employed, where implicit assumptions may add ambiguity or alter the significance of language cues;

- the *order* in which words are composed that may lead to multi-

```xml
<?xml version="1.0" encoding="UTF-8" ?>
<lng name="name-of-language">
    <lyr name="morphology" id="1">
      <el dom="letter" id="1">A</el>
    </lyr>
    <lyr name="articulation" id="2">
      <el dom="gram" id="3">wa</el>
    </lyr>
    <lyr name="lexical" id="3">
      <el dom="word" id="59" setstate="5">water</el>
      <el dom="object" id="63" setstate="5">
        <file type="picture">./images/water.png</file></el>
    </lyr>
    <lyr name="syntax" id="4">
      <el dom="sentence" id="26" setstate="5">I need
        <ref lyr="3" el="59" /></el>
    </lyr>
    <lyr name="semantics" id="5">
      <el dom="state" uID="1" doaction="2">set(user, thirsty)</el>
    </lyr>
    <lyr name="pragmatics" id="6">
      <el dom="action" uID="2">
        bring(water,user);...;checkstate(user);
      </el>
    </lyr>
</lng>
```

Figure 1.5: Example structure of the meta-language.

ple interpretations, though this primarily is a matter of syntax;

- the *reference* framework, in which missing information may lead to assumptions that add or remove significance.

The literature contains a variety of touch-based communication systems, and many of them include variations and adaptations that add branches and subtypes to the taxonomy. To this end, the definition of the language can be extended and detailed further. In the next paragraphs, we will detail the implementation of the most common communication systems based on touch, to show the applicability of our proposed framework to a variety of different languages.

For the purpose of this work, we focus on the most important systems being utilized by blind, deaf and deafblind people. Specifically, in this section we define the following taxonomy:

- *systems for basic communication and information* that utilize simple components for fulfilling elementary functions;
- *tactile codes* representing alphabets in a tactile form;
- *contact signing ad manually-coded languages* based on single-touch gestures and manipulation;
- *gestural languages*, which use dynamic configurations of the hands that can be perceived in close contact;
- *visual sign languages*, that is, complete languages having proper grammar and syntax.

For each of the aforementioned communication systems, we introduce an implementation of the language. Some of the systems discussed in our overview are extremely simple and they only allow limited or task-specific communication. Others, such as tactile languages, are suitable for interpersonal communication and they can be utilized by the blind to richly interact with the external world. Also, they provide individuals with a sophisticated way of exchanging messages in a bidirectional fashion. In this dissertation, we mainly focus on the latter, and we dedicate less attention to basic touch-based systems.

Although all touch-based languages are nonverbal by definition, from a functional point of view, the sense of touch supports both verbal and nonverbal communication, similarly to vision and audition. As a result, tactile languages can be subdivided into two main categories, i.e., alphabetic and symbolic. The former class utilizes or redefines ways to represent alphanumeric characters; also, this is based on adaptations of the communication method that allow to keep utilizing alphabets to form words, exactly as in common written or spoken languages. Among tactile languages, the most famous are the Braille system, and the Malossi or the Moon alphabets. Conversely, symbolic languages make use of higher-level items that are not directly mapped to words, but they rather refer to concepts, ideas and expressive emotions. Examples of symbolic languages are hand gestures, touch cues, and objects or shapes that are employed for expressing interest and emotional states. Indeed, alphabetic languages are rooted in syntax, whereas symbolic languages are more in the domain of semantics. Moreover, there are hybrid systems, such as visual sign languages, that integrate both symbols and alphabets in full languages having their own grammar and syntax.

For the purpose of this dissertation, we focus on verbal communication, which is based on alphabets, and we dedicate less attention to nonverbal touch-based communication. This is because research has shown that although the transmission rate of alphanumeric languages is much slower than the symbolic ones, communication methods based on alphabets have much higher accuracy with respect to symbolic languages [23]. As previously mentioned, symbolic and alphabetic language can be combined into one single language, in order to combine speed and accuracy. Specifically, alphabetic language can evolve into a more symbolic form (not, the vice versa). This is a property of all languages, which applies to touch-based communication systems as well. For example, the Morse code is a combination of such methods, because individuals start out by learning the alphabet; then, along with training they are able to perform simultaneous speech in addition to decoding Morse messages as sequences of symbolic representations in an audible format [28]. For instance, fingerspelling, a tactile language where the pressure and movement of one hand is received on the other hand is another example of a tactile language that has capabilities for both symbolic and alphabetic language

1.2.4 Exceptions: behavioral communication

Although the proposed framework introduces many elements that render it flexible and versatile, it has some limitations. Indeed, there are some forms of communication that cannot be represented by means of syntactic elements. Among the exceptions, there is behavioral communication. This is the most natural and basic form of functional communication. Also, it can be referred as *intensive interaction* or as *total communication*, because it is utilized with individuals who may be resistant to or disinterested in interacting with other people. It utilizes natural body movements, spontaneous gestures and facial expressions to convey messages. It is very personal and it is based on language codes that are extremely transparent only among close groups of individuals who know each other very well. As a consequence, its main limitation is in that only a few individuals are able to decode messages. Also, it allows expressing a few pieces of information and, consequently, its symbols can encode a limited set of needs, only. Usually, this is the first approach to be utilized for communicating with congenitally deafblind and multi-sensory-impaired people, or with children and adults who have severe learning difficulties, or autism. Thanks to its simplicity, behavioral communication is an approach that can be utilized simultaneously with other techniques for teaching pre-speech fundamentals of communication to people who are still at an early stage of communication development. [29] [34] [35] [39]. Despite being extremely simple from a purely-linguistic point of view, behavioral communication consists of a complex system of elements that include gestures, eye contact, touch cues, speech, and mouthing elements. Although it is mostly based on touch (especially when messages are exchanged with deafblind individuals), this type of communication depends on the personal relationship between the sender and the receiver, which is intangible. Thus, it is almost impossible to capture it into a description language that can be effectively reproduced using computer interfaces. Also, it is very personal and due to the inherent complexity of behavioral communication, it is extremely difficult to describe it in a language. This is also because it is based on spontaneous physical interaction, it has many features that cannot be encompassed in structured models. Consequently, it is beyond the purpose of this dissertation.

1.2.5 Object communication

Using objects in the environment as a representation of concepts is among the simplest communication methods, as it is based on manipulable objects, shapes perceivable by touch, and tactile textures embedded into some type of infrastructure. Depending on the specific type of objects being utilized for representing concepts, different types of formalizations are available. In general, object communication systems do not use alphabets, and they have only one syntactic layer. As a result, they realize direct association between the domain of syntax and the semantic layer. Thus, they can modeled as a function $f : O \longrightarrow M$ that allows the transition from the domain of tangible objects O to the set of functional intents M. Indeed, each code defines the function further, by specifying the characteristics of O. As a result, elements in object communication can be represented as follows, without any morphology or articulation components. The example shown in Figure can be adapted to encompass all the main types of resources employed in communication.

```xml
<?xml version="1.0" encoding="UTF-8" ?>
<lng name="Object communication">
    <lyr name="lexical">
      <el setstate="STATE_REFERENCE">
        <file type="OBJECT_REPRESENTATION">FILE_URL</file>
      </el>
    </lyr>
    <lyr name="semantics">
      ...
    </lyr>
    <lyr name="pragmatics" id="6">
      ...
    </lyr>
</lng>
```

Figure 1.6: Representation of object communication.

Representing concepts with objects

Among the most transparent basic communication systems, there is object communication. As its fundamental principle, it is based on items whose expressive function has to be extremely clear. To this end, object communication makes use of manipulable objects, each acting as a symbol that refers to concepts. They mainly are utilized to give information, make requests, and provide feedback. While some of the symbols used in the system are straightforward, conceptually concrete representations, such as parts of objects (e.g., a can of soda represents soda), others are utilized to identify concepts (e.g., a glass of water means *thirstiness*); also, there are more abstract symbols that refer to actions (two crossed paper clips represent *work*) or encode communication items (e.g., "*I want to go home see mom*"). In this regard, objects are employed to anticipate the activities or situations that are presented throughout the day (e.g., a small pillow is a signal for going to bed). Moreover, object cues or parts of objects can be associated with a particular individual; as an example, a teddy bear can mean *father*. Usually, educators, assistants and family have portable sets of manipulable objects that can be utilized in different situations. In order to optimize the language, symbols may have different interpretations depending on the situation, or on the way in which they are manipulated or presented. To be considered for a tactile symbol system, individuals should demonstrate some higher level cognitive abilities [38] with respect to those who can use behavioral communication only.

Indeed, for learning the numerous associations utilized in the system, individuals must be able to understand that symbols are arbitrary representations which do not always physically resemble the item they represent. To this end, meaningful object cues are considered with respect to the degree to which they can be associated with what they represent, by means of touch, only. Therefore, miniatures providing visual representations that cannot be seen by the blind may not be adequate to some individuals. Also, there are very small objects that provide limited tactile information and, thus, it may be more difficult for a child who has physical disabilities, such as cerebral palsy, to handle and explore them or to associate them with their meaning.

Several options can be utilized to represent objects in order to achieve interoperability. Depending on the application, objects can be simply referred to using words, or they can be described as three-dimensional models using a collection of points in 3D space, connected by various geometric entities such as triangles, lines, curved surfaces, etc. Being a collection of data (points and other information), 3D models can be created algorithmically, and they can be displayed using different types of technology. The lowest level representation for objects is the lexical level. This, in turn, can be directly associated with one or several elements in the domain of semantics. The advantage of using the propose framework to represent objects with 3d models is that this allows to build a set of standard items to be employed in communication. With the development of low-cost object printers, it will be possible to actually produce the objects that are most suitable for communication. Moreover, three-dimensional maps can be incorporated in the language, and they can be utilized to provide individuals with virtual representations of an environment, to help them achieve independent mobility [191], [192].

Using shape cues as a form of communication

Sometimes alternatives to object cues, such as shapes or textures, are employed if there is no logical object related to a specific activity, or in situations in which objects cannot be manipulated (e.g., in public spaces, in corridors, or at the entrance of rooms). To this end, clearly perceivable shapes are utilized within frames to provide the blind with language symbols or communication items. Shape cues, or tactile symbols, are concrete representations developed for individuals who are totally blind or function as if they were totally blind and who have a practical need for a graphic language system. Shape cues differ from *textured communication symbols* described by [40] as the former may be utilized to develop an object-based language, and therefore, they span across multiple syntactic layers in the language model. Conversely, textures are more similar to alert patterns, and therefore, they are in the domain of semantics. Consequently, they are less suitable for being utilized to structure sentences. Shape cues require the individual to have specific skills in communicative intent and symbolic development.

Indeed, labeling or recognizing tactile symbols never has a functional goal in itself (as an activity), but it may be a step in learning to use the symbols for more functional tasks (e.g., giving instructions or reporting on events). Shape cues can be mounted left-to-right or in a vertical sequence on strips on boards, or utilized in communication and educational books. Individuals can read the symbol as the identifier to next step in a routine, or they can point the shape cue associated with their need to communicate it to their assistant or peer in order to achieve their functional goal. As a result, shape cues are helpful in scheduling and organizing activities routines, even in longer time frames (e.g., different shape cues can be utilized on calendars in association with birthdays). Locations and materials can also be labeled with touch cues to help individuals with orientation or to identify their belongings. Also, symbols are employed to label shelves in kitchens, classrooms, dresser drawers, and lunch bags [41]. Shape cues and objects may not have a primary role in computer-based communication or in human-computer interaction. However, as they are tangible, they provide an insight to the communication system utilized by the deafblind. Moreover, they introduce a set of meanings that are part of individuals' vocabularies, which can be utilized for structuring a basic set of communication items.

As in the case of objects, shapes can be incorporated in our framework. Their low-level representation at the lexical level can be realized utilizing Scalable Vector Graphics (SVG), a widely-deployed royalty-free graphics format developed and maintained by the W3C SVG Working Group [195]. Several systems for assisting the blind currently use SVG as the primary system for translating visual content into tactile representation formats [183], [36]). Also, this representation is convenient for representing figures and symbols [193], [194], even if individuals are able to use more sophisticated forms of communication.

Textures and textured symbols

The purpose for using object communication is to provide people with vision impairments, or the deafblind, with an alternative form of communication. Usually, shape cues come in the form of labels or figures that can be attached to objects in the environment. Conversely, textures are replicable patterns forming touch cues that can be embedded into objects. As they are very simple and they are easy and immediate to identify, in general they have the purpose of conveying information, quickly. Textures (e.g., piece of carpet, blanket, wood, or plastic) can be utilized to represent activities, places, and people. Also, they can be employed as infrastructured means of information about the environment. In general, textures are employed to provide blind people with contextual guidance for achieving independent mobility. For instance, textures or tactile markings placed on pavement can indicate the presence of stairs, represent crossroads, or signal the route to the exit. Textured materials can be utilized as effective means of communication as well. For instance, sandpaper or bubble wrap are often used as abstract tangible symbols to promote communication with nonverbal children and adults who are blind or deafblind. One of the main purposes of textures is for schooling. Textured markings can be implemented on communication boards to give information, elicit requests, and provide choice making opportunities. Textures are based on materials that typically are selected based on the saliency of their tactile characteristics. Indeed, in order to effectively use them in communication, textures must have clearly perceivable patterns within frames that allow distinguishing the texture area [40].

In our model of object communication, textures are the least in complexity. They are defined as items in the morphological space, each directly linked to one element in the semantics layer. Let us implement textures in the form of height maps as defined in the domain of computer graphics [37]. Textures are represented as grayscale images in which pixels are a measure of surface indentation. The shade of gray that a pixel has determines the height of the terrain at that point, white being the highest, and black being the lowest. The size of textures may vary depending on their complexity. A texture $T_{S \times S}$ having size S can be formally defined as a square matrix of S^2 points P, each having a value ranging from 0 to 255. Each texture is directly linked with an element in semantics, in order to elicit an action. For instance, in textured pavements that support blind people in achieving independent mobility, different textures encode messages such as *stop*, or *walk straight*.

1.2.6 Tactile codes

Tactile codes are standardized representations of information by means of tactile symbols. There are many different tactile codes having diverse purposes. Several tactile codes are employed to provide the deaf and the deafblind with a tactile form for alphabets. Other types of codes are utilized for encoding different types of information. In general, tactile codes make use of dots and shapes to represent letters, situations, directions, routes, or the presence of any danger. In contrast with object communication and shapes, the general rule for tactile codes is that they are a standard set of symbols being utilized by a larger group of individuals. Although some are suitable for supporting communication, tactile codes are not usually designed to support simultaneous communication. Therefore, it is convenient to embed them into labels or tags on buildings (e.g., in proximity of stairs and elevators), on roads (e.g., coded pavement), or on the packaging of products. Some tactile codes have been designed by inventors who have become blind or deafblind in their life.

As tactile codes provide representations of alphabets, they can modeled as a function $f : A \longrightarrow T$ that allows the transition from the domain of the written alphabet A to the domain of a tactile code T. Indeed, each code defines the function further, by specifying the characteristics of T.

Braille

The Braille code is the most famous tactile writing system based on a code. It utilizes series of raised dots to form letters. Specifically, each symbol is represented using a cell consisting of six dots that can be raised or flat in order to obtain different configurations. Words are written as sequences of cells. These can be read by people who are blind (or whose sight is not sufficient for reading printed material) with the fingers, by simply passing the finger over the cells. Teachers, parents, and others who are not visually impaired ordinarily read Braille with their eyes.

However, Braille is not a language. Rather, it is a code by which languages (e.g., English) may be written and read, and thus, Braille readers first had to learn the alphabet, the grammar and the syntax of a language. It is generally assumed that the ability to read and understand Braille is dependent, in part, on a child's exploration or recognition of similarities and differences in the objects and materials provided to them. The relationships between variations in the features of objects and surfaces, similarly to tactile object exploration, have been hypothesized to be precursors of Braille readiness. As the Braille alphabet consists of 6 dots each assuming two values, it supports only a limited number of symbols to be represented (i.e., 64 configurations). Therefore, there are conventions for associating different meanings to the same configuration, and for switching between domains (e.g., music, or mathematics).

The Braille system includes an alphabet (A) based on a binary system that can be represented as a set of symbols

$$A = \{a_1, a_2, ..., a_n\} \text{ where } n = 64$$

where each element a_i in the alphabet A is represented by a combination of raised dots D on six possible fixed spatial positions. As a result, the Braille cell is represented by the following matrix:

$$A_i = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \\ d_{31} & d_{32} \end{bmatrix}$$

where

$$d_{ij} = \begin{cases} 0 & \text{if dot is not raised} \\ 1 & \text{if dot is raised} \end{cases}$$

This means that the value *0* encodes some information. Configurations can also be expressed as binary configurations, such as

$$a_i = \{d_{11}, d_{12}, d_{21}, d_{22}, d_{31}, d_{32}\}$$

As an example, the letter *e* corresponds to the configuration *100100* (though actually cells are read by columns). Words are composed by a sequence of symbols separated by the null symbol (having all flat dots), defined as

$$null = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Braille symbols may have multiple interpretations, and therefore, let us define I the set of interpretations

$$I = \{i_0, i_1, ..., i_m\}$$

such that

$$i_i(a_k) \neq i_j(a_k) \forall i, j | i \neq j$$

In regard to information coding, the Braille alphabet is better than

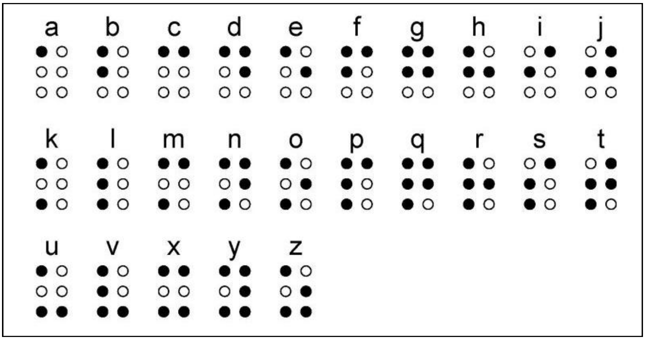


Figure 1.7: The Braille representation of the English alphabet.

the standard written alphabet, because it utilizes only two symbols to encode all the letters. However, from a practical point of view, it is harder to learn Braille because individuals should be able to get the differences between configurations based on small dots, which are difficult to pick at the beginning of the development of fine tactile skills. Figure 1.7 shows the representation of the Braille alphabet into our language model. Indeed, the formal representation of the language will not determine how the configuration of the actual Braille cell will be arranged, as this issue refers to the physical or virtual implementation of the interaction device (i.e., Braille cell displayed on dedicated display or on a standard computer monitor, respectively). This will require the device driver to convert the representation of the language into electrical signals to the physical device.

It is sufficient to implement its morphology, because all the other layers follow the rules of the chosen language localization. There are a few exceptions, such as domain switching. For instance, as ciphers are represented using the first ten letters of the alphabet, numbers consist of a sequence of letters, anticipated by the letter N. This is an example of a transformation rule between the morphology layer and the semantics layer. This is achieved by using a $listener$ is added to the element N in the morphology layer, so that, whenever the listener is triggered, a specific function will be activated. This, in turn, will operate in the domain of syntax in order to disambiguate between standard letters and numbers. The following code shows a meta-language representation of the Braille alphabet.

The following representation shows the complete definition of the Braille alphabet.

1.2.7 Contact signing and Manually-Coded Languages

In its broader sense, contact signing includes any type of language requiring physical contact between the sender and the receiver. However, as communication with deafblind people require all languages to use touch, in this dissertation, we will refer to contact signing as *single-touch contact signing*, in order to differentiate this category from that of gestural alphabets and languages. In general, all contact signing methods and manually coded languages include the possibility of sending and receiving messages. In order to receive messages, individuals passively expose a part of their body that will be utilized as a static surface for communication; conversely, when they want to transmit a message, senders manipulate the body part of the receiver in order to change its configuration. By definition, contact signing is *a sign language that has elements of both a natural sign language and an oral language* [42]. Conversely, single-touch signing methods and manually-coded languages are tactile alternatives to

```
<lyr name="morphology" id="1">
  <el dom="dot" uid="d1" name="11">11</el>
  <el dom="dot" uid="d2" name="11">12</el>
  <el dom="dot" uid="d3" name="11">21</el>
  <el dom="dot" uid="d4" name="11">22</el>
  <el dom="dot" uid="d5" name="11">31</el>
  <el dom="dot" uid="d6" name="11">32</el>
  <el dom="state" uid="s1" name="off">0</el>
  <el dom="state" uid="s2" name="on">1</el>
  <el dom="dotstate" uID="11"><ref>d1,s1</ref></el>
  <el dom="dotstate" uID="11R"><ref>d1,s2</ref></el>
  <el dom="dotstate" uID="12"><ref>d2,s1</ref></el>
  <el dom="dotstate" uID="12R"><ref>d2,s2</ref></el>
  <el dom="dotstate" uID="21"><ref>d3,s1</ref></el>
  <el dom="dotstate" uID="21R"><ref>d3,s2</ref></el>
  <el dom="dotstate" uID="22"><ref>d4,s1</ref></el>
  <el dom="dotstate" uID="22R"><ref>d4,s2</ref></el>
  <el dom="dotstate" uID="31"><ref>d5,s1</ref></el>
  <el dom="dotstate" uID="31R"><ref>d5,s2</ref></el>
  <el dom="dotstate" uID="32"><ref>d6,s1</ref></el>
  <el dom="dotstate" uID="32R"><ref>d6,s2</ref></el>
 </lyr>
<lyr name="articulation">
  <el dom="letter" name="A"><ref>11R,12,21,22,31,32</ref></el>
  <el dom="letter" name="B"><ref>11R,12,21R,22,31,32</ref></el>
  <el dom="letter" name="C"><ref>11R,12R,21,22,31,32</ref></el>
  <el dom="letter" name="D"><ref>11R,12R,21,22R,31,32</ref></el>
  <el dom="letter" name="E"><ref>11R,12,21,22R,31,32</ref></el>
  <el dom="letter" name="F"><ref>11R,12R,21R,22,31,32</ref></el>
  <el dom="letter" name="G"><ref>11R,12R,21R,22R,31,32</ref></el>
  <el dom="letter" name="H"><ref>11R,12,21R,22R,31,32</ref></el>
  <el dom="letter" name="I"><ref>11,12R,21R,22,31,32</ref></el>
  <el dom="letter" name="J"><ref>11,12R,21R,22R,31,32</ref></el>
  <el dom="letter" name="K"><ref>11R,12,21,22,31R,32</ref></el>
  <el dom="letter" name="L"><ref>11R,12,21R,22,31R,32</ref></el>
  <el dom="letter" name="M"><ref>11R,12R,21,22,31R,32</ref></el>
  <el dom="letter" name="N"><ref>11R,12R,21,22R,31R,32</ref></el>
  <el dom="letter" name="O"><ref>11R,12,21,22R,31R,32</ref></el>
  <el dom="letter" name="P"><ref>11R,12R,21R,22,31R,32</ref></el>
  <el dom="letter" name="Q"><ref>11R,12R,21R,22R,31R,32</ref></el>
  <el dom="letter" name="R"><ref>11R,12,21R,22R,31R,32</ref></el>
  <el dom="letter" name="S"><ref>11,12R,21R,22,31R,32</ref></el>
  <el dom="letter" name="T"><ref>11,12R,21R,22R,31R,32</ref></el>
  <el dom="letter" name="U"><ref>11R,12,21,22,31R,32R</ref></el>
  <el dom="letter" name="V"><ref>11R,12,21R,22,31R,32R</ref></el>
  <el dom="letter" name="W"><ref>11,12,21R,22R,31,32</ref></el>
  <el dom="letter" name="X"><ref>11R,12R,21,22,31R,32R</ref></el>
  <el dom="letter" name="Y"><ref>11R,12R,21,22R,31R,32R</ref></el>
  <el dom="letter" name="Z"><ref>11R,12,21,22R,31R,32R</ref></el>
</lyr>
```

Figure 1.8: Representation of the Braille alphabet.

the standard alphabet; the former utilizes the whole body, while in the latter messages are exchanged using the hands, only. The simplest single-touch contact signing methods realize elementary associations between body locations (syntax layer) and concepts (semantics layer), in order to achieve basic functional communication. However, the majority of them have the objective of representing the full alphabet of the original language in a tactile form, and to keep as much as possible the grammar and the syntax of the original language. This is a major difference with respect to other contact signing methods, which have evolved into complete and different languages having their own syntax and grammar.

On-body signing

On-body signing is the simplest form of contact signing. It has been developed based on tactile prompting, a well-studied system for initiating interaction with the deafblind [43] [44]. This communication system was designed as a methodology to teach language to students who are deafblind who are limited in the expressive function. On-body signing involves the sender pointing, tracing or generating configurations with the hand directly onto the face, hands, arms, torso or legs of the receiver. In this regard, body signing can be conceived as a sophisticated articulation of touch cues. However, differently from touch cues, body signs are based on a traditional manual signing system and thus, they are proper languages. This is the main advantage of on-body signing, as it provides a standardized communication method. Also, unlike touch clues, body signs can be presented in sentence form. Moreover, on-body signing can be utilized in any language, as all symbols have the body as a reference. Indeed, this type of communication represents a class of languages and methods [45]. For instance, signs can either be articulated in order to represent words and concepts, or they can be as simple as different spots on the skin that can represent individual letters.

On-body signing is based on a set of body locations B and on a set of touch modes T described as

$$B = \{b_1, b_2, ..., b_n\} \text{ where } n \text{ is limited}$$

$$T = \{t_1, t_2, ..., t_m\} \text{ where } m \ll n$$

The cardinality of T determines the base of the language. Intuitively, on-body signing languages can be unary, binary or they can have larger bases. Particularly, the relationship $m \ll n$ is extremely important as it enables some optimization to the language. Intuitively, less touch modes mean that individuals using the language might not be able to distinguish among different hand shapes, which implies some cognitive disability. In this case, more body locations are utilized, even if this affects the speed at which languages can be signed. Languages belonging to the family of on-body signing communication methods are structures $A = (B, T, l)$ where l is a function defined as

$$l : B \times T \longrightarrow A$$

As a result, symbols in on-body signing languages are sets whose elements are couples of values $a_i = (b_j, t_k)$ generated by the function l that can represent letters, words, concepts. Also, they can refer to people or activities. Not all touch modes might apply to every body locations, that is, function l is discontinuous and it can be undefined for a couple (b_j, t_k), so that the following may hold:

$$\exists i, k | i < n, k < m, b_j \in B, t_k \in T, f(b_j, t_k) \uparrow$$

Furthermore, each on-body signing languages may consist of sets of interpretations I, similar to that of the Braille system, as discussed previously.

The Malossi alphabet

The Malossi alphabet is named after his inventor, an Italian who became deafblind in his early life. The Malossi system defines an on-hand signing method and a tactile alphabet based on two types of stimuli: touch and pinch. Letters from A to O are distributed over the palm, on the 15 phalanxes from the thumb to the little finger, in a clockwise fashion. Each phalanx is associated with an area corresponding to a different letter that is activated when touched. Letters from P to Z (excluding the letter W, which is located close to the proximal phalanxes between the second and the third metacarpal bones) are distributed over the distal and the proximal phalanxes, and they are activated when the area is pinched. Two deafblind individ-

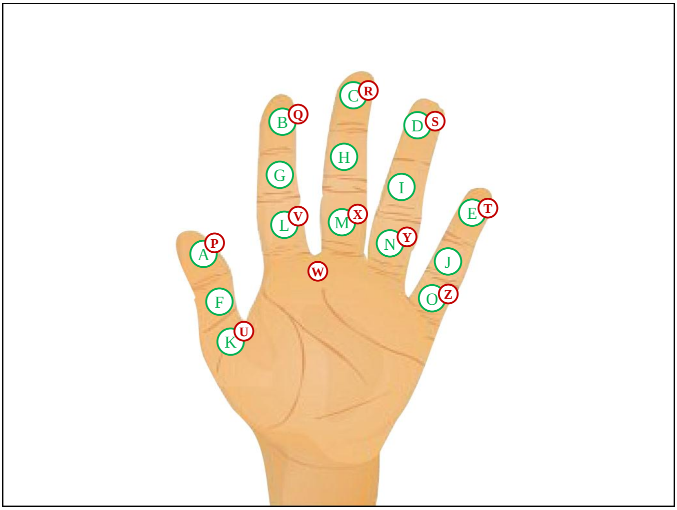


Figure 1.9: Configuration of the layout of letters on the palm in Malossi alphabet.

uals can communicate using Malossi method as follows: the hand (usually, the left one) becomes a typewriter for the receiver of the message. As a result, they can start *typing* messages on each other's hand, in turns: the sender writes words by subsequently touching and pinching in sequence different parts of the receiver's palm that correspond to the characters. Then, they can easily exchange their roles in order to achieve bidirectional communication. This method is often used by those who had learned to read and write before becoming deafblind. To this respect, the speed at which two deafblind people can communicate using the Malossi alphabet is impressive.

The Malossi alphabet is extremely intuitive and it is very suitable as a system for providing children with education to the Braille language. Also, it is a convenient substitute to the Braille system for people who go blind in later life, as they are unable to perceive the small dots utilized in Braille cells. This is also the reason why this alphabet is widely employed with people having cognitive impairments, who cannot learn more complex communication methods, such as alphabets involving shapes. Moreover, it provides the deafblind with an easy way to communicate with people who see and hear normally. In fact, many deafblind individuals achieve their mobility with the use of a white glove that shows the letters, so that people, without knowing the language, can immediately see the layout of the letters and use their hand as a keyboard.

As a result, the Malossi alphabet can be represented as a set of 16 body locations $B = \{b_1, b_2, ..., b_{16}\}$ mapped over the phalanxes as follows

$$B = \begin{Bmatrix} b_1 = p_{11} & b_2 = p_{12} & b_3 = p_{13} & b_4 = p_{14} & b_5 = p_{15} \\ b_6 = p_{21} & b_7 = p_{22} & b_8 = p_{23} & b_9 = p_{24} & b_{10} = p_{25} \\ b_{11} = p_{31} & b_{12} = p_{32} & b_{13} = p_{33} & b_{14} = p_{34} & b_{15} = p_{35} \end{Bmatrix}$$

$\cup \{b_{16}\}$

also, the Malossi alphabet includes a set of 2 touch modes
$T = \{t_1, t_2\}$ where

$$t_i = \begin{cases} touch \text{ or } 1 & \text{if } i = 1 \\ pinch \text{ or } 2 & \text{if } i = 2 \end{cases}$$

The resulting alphabet $A = \{a_1, a_2, ..., a_{26}\}$ is organized as follows

$$a_i = \begin{cases} (1, i) & \text{if } 0 \leq i \leq 15 \\ (2, i - 15) & \text{if } 16 \leq i \leq 20 \\ (2, i - 10) & \text{if } 21 \leq i \leq 26 \end{cases}$$

This representation is consistent with that of on-body signing languages. The following code shows the representation of the Malossi alphabet into markup meta-language.

Touch cues

Touch cues are an important communication strategy that is utilized with young children who are deafblind, as touch cues are especially suitable during the early stages of communication because of their simplicity. Usually, the meaning of touch cues is defined within a specific scope of interaction, and they are utilized and valid in small communities. Also, the meaning of a touch cue is derived from the specific context and situation, even though some of them might be somehow more *universal*. In order to be effective, the use of touch cues should be consistent, otherwise the recipient will not be able to decode the meaning of the message. This is especially true when different people use the same cue for representing a variety of messages. For instance, patting or tapping on the shoulder may express positive feedback, a request or directive, information, comfort, or reassurance. The structure of touch cues may be different depending on the community. For instance, there might be touch cues based on finger pressure, on hand touch, on manipulations of the hand, or on actions realized with arms. The grammar of touch cues is based on gestures involving a destination body location, specific movement, and a performing body part (usually the hand). Their representation is the same as that of contact-signing languages. Differently from manually-coded alphabets, touch cues may directly encode words. Moreover, as body locations and touch modes can be defined on an individual basis, each user model implements a different language model. The implementation of touch

```xml
<?xml version="1.0" encoding="UTF-8" ?>
<lng name="Malossi">
  <lyr name="morphology" id="1">
    <el dom="location" uid="L1">1</el>
    ...
    <el dom="location" uid="L16">16</el>
    <el dom="pressure" uid="pT" name="touch">0</el>
    <el dom="pressure" uid="pP" name="pinch">1</el>
  <lyr name="articulation">
    <el dom="letter" name="A"><ref>L1,pT</ref></el>
    <el dom="letter" name="B"><ref>L2,pT</ref></el>
    <el dom="letter" name="C"><ref>L3,pT</ref></el>
    <el dom="letter" name="D"><ref>L4,pT</ref></el>
    <el dom="letter" name="E"><ref>L5,pT</ref></el>
    <el dom="letter" name="F"><ref>L6,pT</ref></el>
    <el dom="letter" name="G"><ref>L7,pT</ref></el>
    <el dom="letter" name="H"><ref>L8,pT</ref></el>
    <el dom="letter" name="I"><ref>L9,pT</ref></el>
    <el dom="letter" name="J"><ref>L10,pT</ref></el>
    <el dom="letter" name="K"><ref>L11,pT</ref></el>
    <el dom="letter" name="L"><ref>L12,pT</ref></el>
    <el dom="letter" name="M"><ref>L13,pT</ref></el>
    <el dom="letter" name="N"><ref>L14,pT</ref></el>
    <el dom="letter" name="O"><ref>L15,pT</ref></el>
    <el dom="letter" name="P"><ref>L1,pP</ref></el>
    <el dom="letter" name="Q"><ref>L2,pP</ref></el>
    <el dom="letter" name="R"><ref>L3,pP</ref></el>
    <el dom="letter" name="S"><ref>L4,pP</ref></el>
    <el dom="letter" name="T"><ref>L5,pP</ref></el>
    <el dom="letter" name="U"><ref>L11,pP</ref></el>
    <el dom="letter" name="V"><ref>L12,pP</ref></el>
    <el dom="letter" name="W"><ref>L16,pP</ref></el>
    <el dom="letter" name="X"><ref>L13,pP</ref></el>
    <el dom="letter" name="Y"><ref>L14,pP</ref></el>
    <el dom="letter" name="Z"><ref>L15,pP</ref></el>
  </lyr>
</lng>
```

Figure 1.10: Representation of the Malossi alphabet.

cues is similar to Malossi. However, the main difference with respect to alphabetic on-body signing methods is that touch cues are more similar to object communication: there is direct association with meaning.

Tracing alphabets based on print-on-palm

Letters in standard alphabets can be reproduced in a tactile form using a variety of methods. Among the simplest systems, there is print-on-palm, which allows the sender to use one finger as a pen, and to write on the palm of the receiver as on a piece of paper. By doing this, letters can easily be traced as strokes, in sequence. In order to achieve bidirectional communication, subjects exchange the role of their hands, in turn.

Let us define tracing alphabets as a set of shapes S such that

$$S = \{s_1, s_2, ..., s_{26}\}$$

where each shape s_i is a combination of a sequence of strokes K that can be defined in two ways, that is, either using a matrix (low-level representation) or an action label (high-level representation). We will refer to the former for simplicity. Let K be a set of strokes such as:

$$K = \{k_1, k_2, ..., k_n\} \text{ where } n \ll 26$$

As a result, each of the elements in the set S can be expressed as a series of strokes from the set K. Indeed, in order to be recognizable, the following must hold:

$$\exists i, j | \forall k s_k^i \neq s_{k-1}^j \text{ where } 1 < k \leq 26, 1 < i \leq |s_k|, 1 < j \leq |s_{k-1}|$$

Similarly to on-body signing, tracing alphabets they require a body location B. However, this usually is one and fixed (the palm, in the majority of the cases). Therefore, let us assume $|B| = 1$. Each stroke is a sequence of pressure points that can be represented as a gesture (see next paragraph).

The block alphabet
The block alphabet is among the simplest communication systems utilized by the deafblind people who lost their sight in their later life (or after their education). As they already have been taught the alphabet, they can use it for communication by simply writing or reading it on the palm of the hand. Communication is realized by tracing with the forefinger the clear shape of capital letters on the palm. The whole area of the palm can be utilized to write letters, so that they will appear large and clear. Letters should generally be drawn from left to right and from top to bottom; they are written in sequence, one on the top of the other, with pauses at the end of each word. Letters M, N and W should be drawn as single strokes, keeping the finger on the palm. Numbers can also be drawn as figures.

Let us define the block alphabet as consisting of a set S including three basic strokes (i.e., slant, curve, flag), and a set of four directions D (i.e., up, down, left, right) that can be combined to form transversal directions (e.g., up right, or top left). Strokes and directions can be combined to generate the unique gestures shown in Figure 1.8.

Simplified alphabets: the Moon system
The Moon alphabet was invented by a doctor who lost his sight early in his life and, thus, needed a communication method based on the English alphabet. Consequently, the Moon alphabet aims at helping people who go blind in their later life, and thus, who are not able to read the small dots of the Braille system [27]. In order to achieve bidirectional communication, the Moon alphabet utilizes a set of embossed shapes to represent the alphabet. The Moon alphabet is especially designed to simplify the shapes of the alphabet and to avoid discontinuous paths or multiple strokes. Letters consist of single lines, angles, circles, and simple shapes [33]. As a result, they can be felt with a single touch of the hand. Some symbols are similar to the letters of the Latin alphabet, others are completely different. The Moon system can be implemented in our framework using a representation

```
<lng name="Block alphabet">
  <lyr name="morphology">
    <el dom="stroke" uID="F" name="flag">...</el>
    <el dom="stroke" uID="C" name="curve">...</el>
    <el dom="stroke" uID="S" name="slant">...</el>
    <el dom="direction" uID="L" name="left">...</el>
    <el dom="direction" uID="R" name="right">...</el>
    <el dom="direction" uID="U" name="left">...</el>
    <el dom="direction" uID="D" name="right">...</el>
  </lyr>
  <lyr name="articulation">
    <el dom="L" name="A"><ref>S,U,R</ref><ref>S,D,R</ref>...</el>
    <el dom="L" name="B"><ref>S,D</ref><ref>S,U</ref>...</el>
    <el dom="L" name="C"><ref>C,D,R</ref></el>
    <el dom="L" name="D"><ref>S,D</ref><ref>C,U.L</ref></el>
    <el dom="L" name="E"><ref>S,L</ref><ref>S,D</ref>...</el>
    <el dom="L" name="F"><ref>S,L</ref><ref>S,D</ref>...</el>
    <el dom="L" name="G"><ref>C,D,R</ref><ref>C,R,U</ref>...</el>
    <el dom="L" name="H"><ref>S,D</ref><ref>F,R,</ref>...</el>
    <el dom="L" name="I"><ref>S,D</ref></el>
    <el dom="L" name="J"><ref>S,D</ref><ref>C,D,R</ref></el>
    <el dom="L" name="K"><ref>S,D</ref><ref>S,U,R</ref>...</el>
    <el dom="L" name="L"><ref>S,D</ref><ref>S,R</ref></el>
    <el dom="L" name="M"><ref>S,U</ref><ref>S,D,R</ref>...</el>
    <el dom="L" name="N"><ref>S,U</ref><ref>S,D,R</ref>...</el>
    <el dom="L" name="O"><ref>C,D,R</ref><ref>C,U,L</ref></el>
    <el dom="L" name="P"><ref>S,U</ref><ref>C,D,L</ref></el>
    <el dom="L" name="Q"><ref>C,D,R</ref><ref>C,U,L</ref>...</el>
    <el dom="L" name="R"><ref>S,U</ref><ref>C,D,L</ref>...</el>
    <el dom="L" name="S"><ref>C,D,R</ref><ref>C,D,L</ref></el>
    <el dom="L" name="T"><ref>F,R</ref><ref>S,D</ref>...</el>
    <el dom="L" name="U"><ref>S,D</ref><ref>C,R,U</ref>...</el>
    <el dom="L" name="V"><ref>S,D,R</ref><ref>S,U,R</ref></el>
    <el dom="L" name="W"><ref>S,D,R</ref><ref>S,U,R</ref>...</el>
    <el dom="L" name="X"><ref>S,D,R</ref><ref>S,D,L</ref></el>
    <el dom="L" name="Y"><ref>S,D,R</ref><ref>S,D</ref>...</el>
    <el dom="L" name="Z"><ref>S,R</ref><ref>S,D,L</ref>...</el>
  </lyr>
</lng>
```

Figure 1.11: Representation of the block alphabet in the proposed meta-language.

Table 1.1: Stroke representation of the block alphabet.

letter	**stroke sequence**
A	slant up right, slant down right, flag left
B	slant down, slant up, curve down left, curve down left
C	curve down right
D	slant down, curve up left
E	slant left, slant down, slant right, flag left
F	slant left, slant down, flag right
G	curve down right, curve right up, flag left
H	slant down, flag right, slant up, slant down
I	slant down
L	slant down, slant right
M	slant up, slant down right, slant up right, slant down
N	slant up, slant down right, slant up
O	curve down right, curve up left
P	slant up, curve down left
Q	curve down right, curve up left, curve down left, flag right
R	slant up, curve down left, slant down right
S	curve down right, curve down left
T	flag right, slant down, slant up, flag left
U	slant down, curve right up, slant up
V	slant down right, slant up right
W	slant down right, slant up right, slant down right, slant up right
X	slant down right, slant down left
Y	slant down right, slant down, slant down left
Z	slant right, slant down left, slant right

similar to that of the block alphabet.

The Lorm deafblind alphabet

The Lorm alphabet was designed by a writer who lost both his sight and hearing in his childhood. As many other communication systems invented by deafblind people, the Lorm alphabet utilizes the hands to represent the letters in a tactile form. Communication occurs by touching, striking or squeezing parts of the hand and, specifically, the palm and the fingers. Differently from other communication systems based on alphabets, symbols are represented by dynamic gestures that occur on specific parts of the hand. As a result, although the Lorm alphabet is based on the English written alphabet, there is no correspondence in shape between symbols in the written alphabet and letters in the Lorm alphabet. The Lorm deafblind alphabet can be represented as follows.

The Lorm deafblind alphabet has a more complex representation, as it involves several types of touch modes, and even gestures. The Lorm alphabet defines seven touch modes in a way similar to other alphabets, four directions, and fourteen locations. These can be combined to form letters as shown in Table 1.2.

The Lorm alphabet is represented in our language as follows:

Cued speech

Cued speech is a phonemic-based system based on hand shape that makes the auditory aspects of spoken language accessible through visual means [30]. Cued Speech is unique among forms of Manually Code Language because it does not use signs in an attempt to substitute written alphabets. On the contrary, cued speech makes use of eight hand shapes (H) to represent consonant phonemes, four hand placements (HP) or four hand movements (HM) around the face to represent vowel phonemes. Such hand shapes do not have any

Table 1.2: Representation of the Lorm alphabet.

letter	gesture
A	touch tip of thumb
B	strike downwards along index
C	touch the middle point of the lowest palm
D	strike downwards along middle
E	touch the tip of index
F	squeeze the tips of index and middle
G	strike downwards ring
H	strike downwards little
I	touch the tip of middle
J	squeeze the tip of middle
K	touch with all tips together in the middle of the palm
L	strike downwards index, middle and ring
M	touch horizontal with three tips the higher palm
N	touch horizontal with two tips the higher palm
O	touch the tip of ring
P	strike upwards the outside of index
Q	strike upwards the outside of hand
R	drum with several tips in the middle of the palm
S	circle in the middle of the palm
T	strike downwards the outside of the thumb
U	touch the tip of little
V	touch with one tip the palm between thumb and index
W	touch with two tips the palm between thumb and index
X	strike horizontal the wrist
Y	strike horizontal all the fingers
Z	strike horizontal the center of the palm of hand

```xml
<lng name="Lorm alphabet">
  <lyr name="morphology">
    <el dom="touch" uID="T" name="touch">...</el>
    <el dom="touch" uID="S" name="strike">...</el>
    <el dom="touch" uID="Q" name="squeeze">...</el>
    <el dom="touch" uID="R" name="drum">...</el>
    <el dom="touch" uID="T2" name="2-tip-touch">...</el>
    <el dom="touch" uID="T3" name="3-tip-touch">...</el>
    <el dom="touch" uID="T5" name="5-tip-touch">...</el>
    <el dom="direction" uID="U" name="up">...</el>
    <el dom="direction" uID="D" name="down">...</el>
    <el dom="direction" uID="H" name="horizontal">...</el>
    <el dom="direction" uID="C" name="circle">...</el>
    <el dom="location" uID="1" name="thumb-tip">...</el>
    <el dom="location" uID="2" name="index-tip">...</el>
    <el dom="location" uID="3" name="middle-tip">...</el>
    <el dom="location" uID="4" name="ring-tip">...</el>
    <el dom="location" uID="5" name="little-tip">...</el>
    <el dom="location" uID="PT" name="palm-top">...</el>
    <el dom="location" uID="PM" name="palm-middle">...</el>
    <el dom="location" uID="PB" name="palm-bottom">...</el>
    <el dom="location" uID="W" name="wrist">...</el>
    <el dom="location" uID="F1" name="thumb-index">...</el>
  </lyr>
  <lyr name="articulation">
    <el dom="L" name="A"><ref>T,1</ref></el>
    <el dom="L" name="B"><ref>S,D,2</ref></el>
    <el dom="L" name="C"><ref>T,PB</ref></el>
    <el dom="L" name="D"><ref>S,D,3</ref></el>
    <el dom="L" name="E"><ref>T,2</ref></el>
    <el dom="L" name="F"><ref>Q,2,3</ref></el>
    <el dom="L" name="G"><ref>S,D,4</ref></el>
    <el dom="L" name="H"><ref>S,D,5</ref></el>
    <el dom="L" name="I"><ref>T,3</ref></el>
    <el dom="L" name="J"><ref>Q,3</ref></el>
    <el dom="L" name="K"><ref>T5,PT</ref></el>
    <el dom="L" name="L"><ref>S,T3,D,2,3,4</ref></el>
    <el dom="L" name="M"><ref>T3,H,PT</ref></el>
    <el dom="L" name="N"><ref>T2,H,PT</ref></el>
    <el dom="L" name="O"><ref>T,4</ref></el>
    <el dom="L" name="P"><ref>S,U,2</ref></el>
    <el dom="L" name="Q"><ref>S,U,5</ref></el>
    <el dom="L" name="R"><ref>R,PM</ref></el>
    <el dom="L" name="S"><ref>T,C,PM</ref></el>
    <el dom="L" name="T"><ref>S,D,1</ref></el>
    <el dom="L" name="U"><ref>T,5</ref></el>
    <el dom="L" name="V"><ref>T,F1</ref></el>
    <el dom="L" name="W"><ref>T2,U,F1</ref></el>
    <el dom="L" name="X"><ref>S,H,W</ref></el>
    <el dom="L" name="Y"><ref>S,H,1,2,3,4,5</ref></el>
    <el dom="L" name="Z"><ref>S,H,PM</ref></el>
  </lyr>
</lng>
```

Figure 1.12: Representation of the Lorm alphabet in the proposed meta-language.

equivalent to, neither are, derived from shapes of any sign languages. Cued speech is conceived to be utilized in combination with mouthing (i.e., simultaneously with speech), as the hand shape, hand placement, hand movement, and information on the mouth combine as unique feature bundles that represent phonemic values. Cues are not intended to be understood without mouthing. However, many deaf native cuers are able to understand the cues alone without the use of the mouth. Similarly, they tend to be able to perform well at deciphering the information on the mouth without the use of the hand (i.e., by lip reading, alone).

Cued speech can be represented by means of a set of phonemes P consisting of vowel phonemes and consonants such that

$$P = \{H_i + (HP_j + HM_k)$$

where

$$HP_j = \begin{cases} 1 & \text{if phoneme is D, P, or S} \\ 2 & \text{if phoneme is TH, C, V, or S} \\ 3 & \text{if phoneme is S, H, or RS} \\ 4 & \text{if phoneme is WH, B, or N} \\ 5 & \text{if phoneme is M, T, or FF} \\ 6 & \text{if phoneme is W, SH, or LL} \\ 7 & \text{if phoneme is TH, J, or JJ} \\ 8 & \text{if phoneme is Y, NG, or CH} \end{cases}$$

and $HM_k = (ip, ep)$ is a couple of values representing the initial and the final positions, respectively. Figure 1.13 shows a graphical representation of the alphabet. As there are four key positions (plus two derived positions, F for forward, and D for down), HP is defined as follows

$$HM_k = \begin{cases} (1,1) & \text{if phoneme is EI, or UR} \\ (2,2) & \text{if phoneme is A, UE, or E} \\ (3,3) & \text{if phoneme is OO, I, or A} \\ (4,4) & \text{if phoneme is consonant alone} \\ (4,F) & \text{if phoneme is OA, or O} \\ (4,D) & \text{if phoneme is U} \\ (2,3) & \text{if phoneme is OI, or AI} \\ (4,3) & \text{if phoneme is IGH, or OU} \end{cases}$$

As a result, the language can be represented as follows. As words are created by articulations of phonemes, the meta-language contains a definition of words as well. This is the main difference with respect to the systems analyzed previously. Gestures can be represented in a three-dimensional format by using 3D models and character animation, which allows encoding hand position as well.

```
<lng name="Touch cues">
  <lyr name="morphology">
    <el dom="configuration" uID="C1" name="D,P,S">...</el>
    <el dom="configuration" uID="C2" name="TH,C,V,S">...</el>
    <el dom="configuration" uID="C3" name="S,H,RS">...</el>
    <el dom="configuration" uID="C4" name="WH,B,N">...</el>
    <el dom="configuration" uID="C5" name="M,T,FF">...</el>
    <el dom="configuration" uID="C6" name="W,SH,LL">...</el>
    <el dom="configuration" uID="C7" name="TH,J,GG">...</el>
    <el dom="configuration" uID="C8" name="Y,NG,CH">...</el>
    <el dom="position" uID="P1" name="mouth">...</el>
    <el dom="position" uID="P2" name="chin">...</el>
    <el dom="position" uID="P3" name="throat">...</el>
    <el dom="position" uID="P4" name="side">...</el>
    <el dom="position" uID="P5" name="side-forward">...</el>
    <el dom="position" uID="P6" name="side-down">...</el>
  </lyr>
  <lyr name="articulation">
    <el dom="vowel" uID="V1" name="EI, UR"><ref>P1,P1</ref></el>
    <el dom="vowel" uID="V2" name="AL,UE,E"><ref>P2,P2</ref></el>
    <el dom="vowel" uID="V3" name="OO,I,A"><ref>P3,P3</ref></el>
    <el dom="vowel" uID="V4" name="CONS"><ref>P4,P4</ref></el>
    <el dom="vowel" uID="V5" name="OA,O"><ref>P4,P5</ref></el>
    <el dom="vowel" uID="V6" name="U"><ref>P4,P6</ref></el>
    <el dom="vowel" uID="V7" name="OI,AI"><ref>P2,P3</ref></el>
    <el dom="vowel" uID="V8" name="IGH,OU"><ref>P4,P3</ref></el>
```

```
  </lyr>
  <lyr name="lexical">
    <el dom="word" name="thanks"><ref>C7,V3</ref>...</el>
    <el dom="word" name="name"><ref>C4,V2</ref>...</el>
  </lyr>
</lng>
```

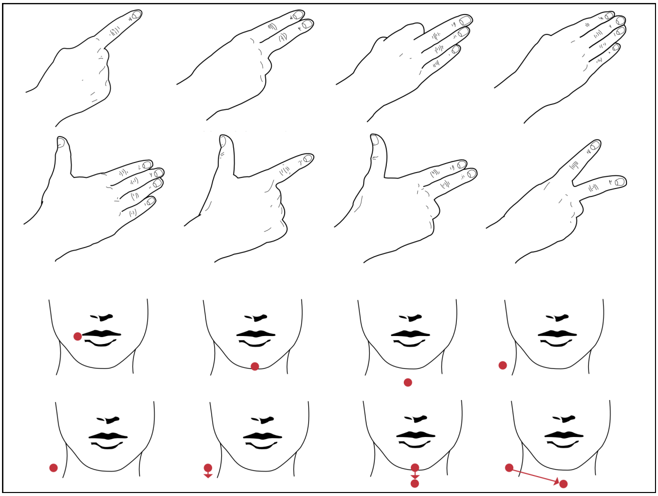


Figure 1.13: Elements of cued speech.

Fingerspelling and gestural alphabets

Fingerspelling belongs to the family of gestural languages, which includes visual sign languages as well. This category utilizes gestures to convey messages [23]. As a difference between fingerspelling and visual sign languages, the former is especially designed to be perceived in contact signing. Similarly to contact signing, gestural alphabets can be classified as follows:

- *passive touch languages*: receivers expose a part of their body that will be utilized as a static surface for communication;

- *active touch languages*: the sender manipulates the body part of the receiver in order to change its configuration;

- *visual sign languages*: there is no contact between the sender and the receiver, except in particular circumstances (i.e., deafblindness).

Sign languages are based on a combination of five parameters, that is, hand shape, hand orientation, location, hand motion, and facial expression [8]. Achieving communication by using a system of gestures is not an exclusively human way to interact: gestures are a basic form of communication in many animal species. However, utilizing complex gestural languages and alphabets for communication is extremely difficult, and it requires high cognitive abilities. When utilized by deafblind individuals, gestural alphabets are employed because they were deaf and lost their sight after having learned the language and, therefore, it is more convenient to keep using their language instead of forcing them to learn a new communication system. As a result, they can keep using their sign language with little adaptation by holding the hands of the conversational partner in order to feel their movements and to get information from them. Gestural alphabets are very easy to be utilized by sighted deaf people who have a great ability to receive information through their vision. Gestural alphabets use several other parts of the body in addition to the hands, to convey messages: for instance, the eyebrows, eyes and mouth, are also involved in language production. In general, these signals are visual, and they can be effectively captured by deaf people. Conversely, for those who are completely blind (other than being deaf), tactile sign languages are the only conversational form. In fact, visual sign languages mainly are employed for conversation, though they also are utilized to convey information in a one-directional fashion. As an example, some TV programs, such as the news, utilize sign languages. The grammar and the syntax of sign languages differ from that of written or spoken languages. Although at the syntactic level sign languages are not strict as spoken languages, usually sentences follow the order Object Subject Verb (OSV).

Fingerspelling and gestural alphabets, and particularly, visual sign languages can be represented using the same language as touch cues. However, as they involve the full body, they require complete character animation. Over the past decade several character modeling software have been developed to create and animate 3D human figures and to track the motion of real human body. Nowadays, there are several standard for modeling three dimensional human figures. For instance, the design tools realized during the V-sign project [24] can be utilized to model 3d hand gestures, as shown in Figure 1.14.

Figure 1.14: The hand modeling interface of V-sign.

Co-active signing

The name co-active signing represents the situation in which the sender moves and manipulates the hands and the arms of the receiver to form sign shapes, or fingerspelt words. As a result, in co-active signing the receiver passively realizes gestures guided by the sender of the message. This communication method typically is utilized to teach signs to deafblind children. Also, it is employed with people suffering from cognitive impairments. Consequently, this is not a bidirectional communication system, and its rules are defined by the language in which the sender actively signs. Passive touch languages can be represented within the framework in a way similar to active sign languages, because the communication system is similar. However, they add two functions: one confirms a particular message and it activates the action associated with it (positive response), the other skips the message (negative response).

Hand-over-hand

The hand-over-hand method is mainly utilized by deafblind people who were able to communicate using a visual signing alphabet. This is the case of deaf people who become blind in their later life. As they already know a signing language, the hand-over-hand method, also known as *hands-on signing* provides them with a communication system without requiring them to learn a brand new language from scratch. Thus, the sign language used in hands-on signing is often a slightly modified version of local sign languages. In hand-over-hand, the receiver's hands are placed lightly upon the back of the hands of the signer so that the receiver can read the signs through the sender's gestures and movement.

Tracking

Tracking enables blind and deafblind people to read messages by holding the wrists of the signer to get information from their movements. This communication method is suitable for receiving messages, only. Usually, it is employed when the receiver has a limited field of vision. This is because, giving the six degrees of freedom of the wrist, understanding movements by only sensing the signer's arms is extremely difficult.

1.2.8 Visual sign languages

All gestural languages consist of symbols that are based on configurations of the body (i.e., postures), hand gestures, and facial expressions for representing words and concepts. As they are mainly visual, gestural languages do not require the individuals to be in the same physical space. For instance, they can be utilized to sign TV shows, or the news. The majority of gestural languages are not *tactile*. Instead, they are *touchable*. Some gestural languages rely on touch, that is, are designed to be utilized in close contact. This is the case of contact sign languages, or contact sign. They are originated from contact between a deaf sign language and an oral language (or the written or manually coded form of an oral language). Signed languages are complete and complex communication systems that employ signs made by moving the hands combined with facial expressions and postures of the body to convey meaning.

Visual sign languages are largely utilized in the deaf communities, where different sign languages are used in different countries or regions (e.g., the American Sign Language Alphabet), or the British two-handed manual alphabet for sighted deaf people). This is because only a fraction of speech sounds can be seen on the lips and, thus, the deaf need a more significant and effective way to express and receive messages [26]. However, signed languages can be utilized by people who are blind and use contact to perceive movements, gestures, and postures, and to decode messages. Alternatively, some deafblind people with restricted peripheral vision may prefer the signer to sign in a very small space, usually at chest level. Also, signs located at waist level may require a little adaptation to keep them within the field of sight.

Several systems, such as WebSign, Vsigns and eSigns utilize the Web3d standards to generate 3D signing avatars that render written text. Web3d signing avatars are modeled using the specifications from the H-anim working group, which describe the methods for generating the skeleton and the models [25][47] [48] [**?**]. These can be directly included in our language description framework within the lexical layer, as follows, and they can be connected to a 3D engine system, such as Unity3D, to smooth key frames with inverse kinematics techniques. Also, as demonstrated previously, the framework supports the definition of both grammar and syntactic structures of the language, so that the basic hand shapes, gestures and position can be represented and utilized for learning purposes (i.e., to teach the language to novice users).

1.2.9 Hybrid contact alphabets

Although being purely based on tactile sensitivity, certain touch-based communication systems rely on visual or auditory components, such as movements, gestures, speech, or vibrations. As a result, they can be defined as hybrid, because they utilize tactile features of communications systems are not directly tactile. Together with visual sign languages, they are among the most complicated to formalize using a description language.

Mouthing

Mouthing [31] means realizing mouth movements during communication. This is an inherent feature of speech, as the mouth simultaneously changes its shape when speaking. The most common type of mouthing is the so-called *phonetic mouthing*, that is, the nonverbal articulation of words or segments of words [50]. Also, mouthing comes in the form of *iconic mouth gesture*, which is the formation of mouth shapes that represent signers' interpretation of a concept [51]. In general, mouthing occurs simultaneously and almost unintentionally with other forms of Manually-Coded Languages [32]: for instance, the hands and the mouth naturally integrate in sign language. Various types of mouthing and mouth gestures have been observed across many sign languages as a form of symbolic symbiosis ([51], [52]); for deaf individuals who are signing, mouth gestures perform a function similar to that of gestures, which tend to occur with speech in hearing individuals. To this end, mouthing can be seen as similar to speech. Thus, its formalization is beyond the scope of this dissertation.

Tadoma

Tadoma [9] was invented by a teacher in order to provide two deafblind children with means of communication. Tadoma involves a deafblind individual placing their hand on the face and neck of the speaker [20]. Specifically, the thumb is positioned over the lips, in order to lip-read using touch; the remaining fingers are placed along the speaker's face and neck, and they are utilized to feel motions of the jaw, facial expressions of the speaker, and vibrations. The latter are extremely important, as they allow distinguishing active speech from gestures. Although Tadoma is very difficult to learn, after some training it enables deafblind individuals to comprehend up to forty words a minute [53]. Indeed, this type of language can be utilized by people who can speak, otherwise it is not bidirectional. Tadoma can be considered as the receptive function of mouthing and, thus, we will not provide a formal description of this language, as in the case of mouthing (see previous paragraph).

Part II

Pervasive vibrotactile interaction for the blind and the deafblind

Chapter 2

Implementing hand-based communication using vibrotactile stimuli

2.1 Human tactile sensing and perception

Designing interfaces that have the purpose of supporting the deaf-blind in communication, using the sole sense of touch is a significant challenge. Indeed, interfaces for hand-based interaction require specific knowledge of the underlying dynamics of tactile perception. Although visual and auditory perception is well researched and understood, less is known about the sense of touch, in general. Thus, in in order to define the requirements in the design of assistive interfaces based on touch, and specifically, on vibrotactile stimuli, it is crucial to investigate the sensing mechanisms of the tactile channel.

In this section, we present an overview of the functioning of human perception of tactile stimuli, and we discuss the results of an experimental study on vibrotactile stimulation on the hand, which has set the basis for our research in the field of novel assistive devices for touch-based communication.

Types of tactile stimuli

As its primary function, the Somatic Sensory System (SSM) provides the Central Nervous System (CNS) with description about the environment and the external world. To this end, the human body incorporates several receptors for the transduction of mechanical solicitation on the skin into neuronal signals, which are responsible for the four different types of somatic sensibility:

- *discriminative touch*, which allows both perceiving movement across the skin and recognizing the size, shape, and texture of objects;

- *proprioception*, responsible for sensing current body position and for perceiving movement of the limbs and of the body;

- *nociception*, signaling tissue damage or chemical irritation, and providing individuals with the sensation of danger by means of pain or itch;

- *temperature sense*, which gives information about the warmth and cold of objects in the environment (and of the environment itself).

Neuronal transmission of stimuli

All somatic sensibilities share a common class of sensory neurons: the dorsal root ganglion neurons. Individual neurons in this class selectively respond to specific types of stimuli, because of the morphological configurations and the molecular characteristics of their peripheral terminals. The dorsal root ganglion has the main function of transmitting stimuli to the CNS. To this end, dorsal root ganglion neurons have two types of peripheral terminals: bare nerve ending and nerve ending

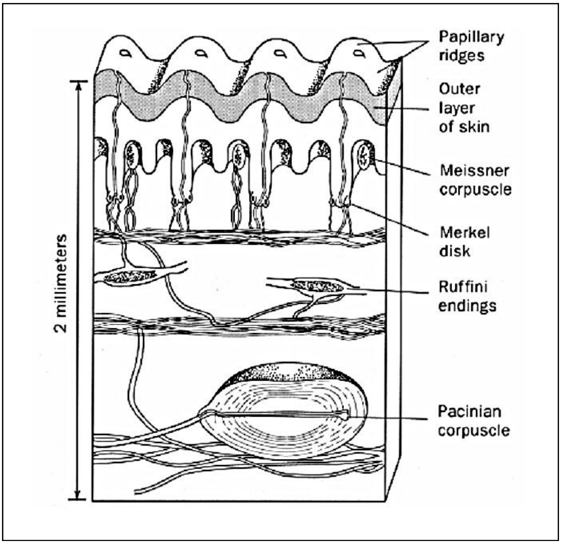


Figure 2.1: Different types of mechanoceptors.

encapsulated in a non-neural structure. The latter neurons mediate the somatic modalities typical of touch and proprioception, and they are responsible for sensing stimuli related to the perception of surfaces and objects. On the contrary, the former type of neurons mediates painful or thermal sensations. As mechanoreceptors and proprioceptors are innervated by dorsal root ganglion neurons with myelinated axons that conduct actions potentials rapidly and, therefore, stimuli are perceived very quickly. Conversely, thermal receptors and nociceptors have axons that are thinly myelinated (or unmyelinated); as a result, they conduct impulses more slowly. These types of neurons are associated with two types of somatic sensations: epicritic and protophatic sensations. The former involve fine aspects of touch, whereas the latter involve pain, sensation of temperature, itch, and tickle.

Epicritic sensations

For the purpose of this dissertation, we focus on epicritic sensations, which include the ability to:

- detect skin contact and localize the where it occurs (topognosis);
- distinguish vibration in frequency and amplitude;
- assess spatial detail (e.g., perceive textures or the distance between two points touched simultaneously);
- recognize the shape of objects (stereognosis).

Specifically, as the objective of this dissertation is interaction by means of vibrotactile technology, we focus on the neuronal ability of distinguishing skin displacement, which is the direct consequence of objects moving or vibrating in close contact with the skin. Also, we take into consideration the perception of the location where stimuli occur. Several studies demonstrated that sensitivity for vibrotactile stimulation depends on many different factors. For instance, the performance of perception through touch is associated with sex (see Figure 2.2). Moreover, variations in sensitivity occur between individuals, and they are affected by age. Furthermore, environmental conditions and stress temporarily alter the ability to perceive tactile sensations. Primarily, tactile sensitivity depends on body position and on the type of tissue: as glabrous skin has the largest concentration of mechanoceptors, the fingers, the palmar surface of the hand, the sole of the foot, and the lips also have the largest spatial resolution for tactile sensations. For the purpose of this dissertation, we examine tactile sensitivity on the hands. These are both the part of the body employed by the majority of touch-based languages and the areas where touch has the greatest performances. Specifically, spatial resolution is higher in young individuals, and it diminishes in the elderly.

Mechanoreceptors and tactile sensation

Four major types of mechanoreceptors are responsible for tactile sensitivity in glabrous skin. There are two principal mechanoreceptors in the superficial layers of the skin, and two corpuscles situated in the subcutaneous tissue. Among the former type of mechanoreceptors, there is the Meissner's corpuscle, a rapidly adapting receptor that is mechanically coupled to the edge of the papillary ridge. This confers fine mechanical sensitivity to the receptor. Also, the Merkel disk receptor is located in the superficial layers of the skin. This is a slowly adapting receptor that comes in the form of a small epithelial cell surrounding the nerve terminal. The Merkel disk incorporates a semi-rigid structure that transmits compressing strain from the skin to the sensory nerve ending. As a result, it is able to evoke sustained, slowly adapting responses.

Conversely, the two mechanoreceptors found in the deep subcutaneous tissue are the Pacinian corpuscle and the Ruffini ending. They are much larger and less numerous than Meissner corpuscles and Merkel disks. The Pacinian corpuscle responds to rapid indentation of the skin, but it is not able to perceive any information about steady pressure. Conversely, as it consists of a large capsule flexibly attached to the skin, the Pacinian corpuscle is able to sense vibration occurring several centimeters away. Ruffini endings are slowly adapting receptors linking the subcutaneous tissue in the skin to joints in the palm, or to the fingernails. These receptors are able to sense the amount of stretch of the skin and, therefore, they contribute to the perception of the shape of grasped objects.

Receptive fields and spatial resolution

Another fundamental property of mechanoreceptors is the receptive field, which is defined as the region of the skin from which a sensory neuron can be stimulated. As another measure of the sensitivity of mechanoreceptors, spatial resolution represents the extent to which humans can perceive two different points on the skin as distinct. In general, larger receptive fields are associated with smaller spatial resolution. The spatial resolution of the skin has been extensively tested, showing that information conveyed through the somesthetic system is extremely precise. Results of scientific experiments demonstrated that spatial resolution varies along the body, ranging from a few millimeters, in the fingers, to about four centimeters, in the trunk. This is mainly because receptive fields vary in size and structure depending on the layer in which receptors are located and, consequently, on the number of receptors that are fired upon stimulation. This was evaluated in several studies that investigated the spatial resolution of the skin in a static way; they demonstrated that spatial resolution in specific areas of the body is a function of the density of receptors. Single dorsal root ganglion cells in the superficial layers receive input from clusters of 10 or 25 Meissner's corpuscles or Merkel disk receptors. This corresponds to a receptive field having a diameter ranging from 2mm to 10mm, which is one order of magnitude greater than the field of an individual receptor. Conversely, nerve fibers in the deep layers of the skin are connected to a single Pacinian corpuscle or Ruffini ending. As a consequence, their receptive fields are larger, but they are not able to distinctively perceive borders and therefore, their spatial resolution is affected by noise.

Given their different characteristics, receptors in the superficial and deep layers of the skin play different roles: Meissner's corpuscles and Merkel disk receptors are able to finely detect spatial differences because they transmit information from a small area of skin. This feature allows humans to clearly perceive the single dots of a Braille cell. On the contrary, Pacinian corpuscles and Ruffini endings in the deep layers sense more global properties of objects. Also, they detect skin displacement from a wide area of the skin and they are responsible for sensing vibration.

Also, the speed at which information travels from the skin to the brain is extremely important: somesthetic information traverses the dorsal-lateral column path, which is among the fastest communication lines in the human body, as it is able to transmit information at a speed of over 100m/s.

2.1.1 Haptics and the hands

As discussed in the previous section, the sensitivity of the skin is not uniformly distributed across the body, and its largest values occur at the fingertip, because of the higher density of mechanoreceptors in this region. Specifically, the fingertips are the most densely innervated region of skin in the human body, consisting of approximately 300 mechanoreceptive nerve fibers per square centimeter. The number of mechanoreceptive fibers is reduced to 120 in proximal phalanges, and to 50 in the palm [7]. Tables 2.1.1 and 2.1.1show the characteristics of tactile sensitivity in the hands. Here, the rapidly adapting Meissner's corpuscles (MC) the slowly adapting Merkel disk receptors (MD) are the most numerous, preferentially distributed on the distal half of the fingertip. Also, Pacinian corpuscles (PC) and Ruffini endings (RE) are distributed more uniformly on the hand, but they are much less common and, therefore, their response has a different weight. Cutaneous receptive fields in the hands, similarly to those in higher-order visual cells, may encode complex spatial information. Single neural units (such as Meissner's corpuscles and Merkel disk receptors) may receive information from areas of the skin as small as 1 mm in diameter, they could have receptive areas as large as a

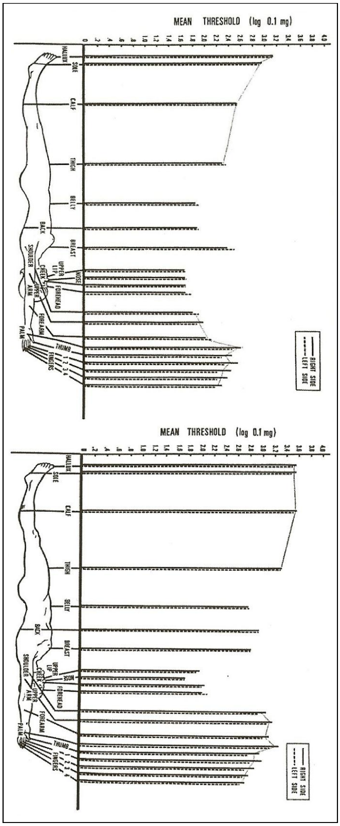


Figure 2.2: Tactile sensitivity in female individuals. Figure taken from [6].

finger (i.e., Pacinian corpuscoles), or they may even be directionally sensitive channels, such as in the case of Ruffini endings. This was measured using static pressure [89], that is, continuous pressure without any skin displacement.

Table 2.1: Characteristics of mechanoreceptors found in human fingertip skin (1).

	MD	**MC**
RF size	$1mm^2$	$0.82mm^2$
Aff. denz.	$100cm^2$	$150cm^2$
Diverg. (RF area)	4-16 ($5mm^2$)	4-16 ($5mm^2$)
Convergence	1:1	2-7
Adekv. Ing.	Strain energy density	Slip, load force
Function	Form, texture	Grip control

Table 2.2: Characteristics of mechanoreceptors found in human fingertip skin (2).

	PC	**RE**
RF size	diffuse	diffuse
Aff. denz.	$350/ujj$	Unknown (low)
Diverg. (RF area)	1:1	1:1
Convergence	1:1	1:1
Adekv. Ing.	High-freq vibration	Skin stretch
Function Distant events	Hand shape	

2.2 Perceiving vibrotactile stimuli

Our intention is to exploit mechanoceptors' performances in recognizing skin displacement for designing innovative haptic devices incorporating vibrotactile stimulation. Usually, such devices are already employed as an alternative communication system for the blind or the deafblind. However, in our research we make extensive use of vibrotactile actuators as means for simulating touch and for implementing technological supports that enhance current touch-based communication systems.

Activation thresholds

Action potentials represent the activation of neurons, and they are responsible for the perception of all stimuli, including vibration. Particularly, this is the sensation produced by sinusoidal oscillation of objects placed against the skin, where mechanoreceptors respond to cyclic waves by pulsations of action potentials each representing one cycle of the sinusoidal curve of the original stimulus. Individual mechanoreceptors have their own sensitivity thresholds to vibration, in the sense that their action potentials may respond to stimuli having different frequencies and amplitudes. Merkel disk receptors are most responsive to extremely low frequencies, such as those ranging from 5 to 15Hz. Conversely, Meissner's corpuscles show better response to midrange stimuli in the interval from 20 to 50Hz. The Pacinian corpuscles are activated with high frequencies, and specifically by vibrations in the range between 60Hz and 400Hz. At 250Hz, they detect vibrations as small as 1 μm. On the contrary, at 30Hz they require stimuli with much larger amplitudes.

The receptor thresholds determine the ability to sense vibration: humans are most sensitive to frequencies of 200-250Hz. Both lower and higher frequencies must have proportionately larger amplitude vibrations in order to be perceived. Although greater vibration amplitudes increase the probability of being sensed, they have an impact on larger areas of the skin and, therefore, they affect spatial resolution. The intensity of vibration is signaled by the total number of sensory nerve fibers that are activated (i.e., that are transmitting action potentials) rather than by the frequency of firing, which represents the vibratory frequency. As for tactile stimuli conveyed by static pressure, receptors involved in the detection of vibration are not uniformly located on the skin. Moreover, concerning spatial resolution of vibrations, [123, 18] showed that in the lateral back near the scapula, it is as small as 11mm (showing greater sensitivity than that for static stimulation, measured as 40mm [19]). A study by Cholewiak [89] utilized a frequency of stimulation from 100Hz to 250Hz to demonstrate that spatial resolution in a normal population is 25 mm. Indeed, as in the case of static pressure, sensitivity for vibrotactile stimulation depends on the age of the subjects [89]. Moreover, vibration performs very well in heterogeneous tissue: although tactile perception is greater in glabrous skin, psychophysical experiments have also evaluated subjects' abilities to discriminate the frequency and amplitude of vibrotactile stimulations on hairy skin [11]. In these studies, stimulations were distinguished by applying different pulses of one frequency (or amplitude) followed by short pause and then another stimulus [16].

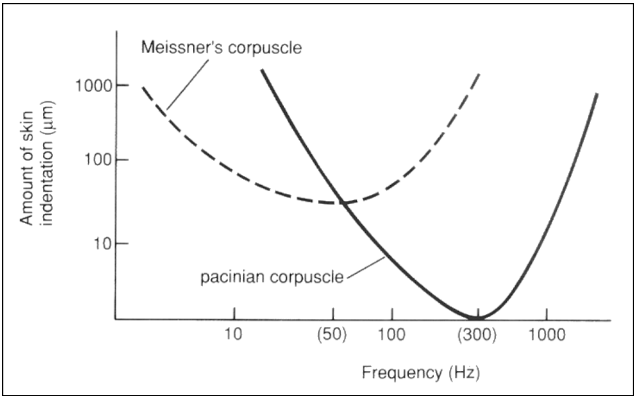


Figure 2.3: Thresholds for detecting vibration in the Pacinian corpuscle and in the Meissner's corpuscle.

2.2.1 Features of vibrotactile stimuli

Although vibrotactile stimulation is based on the displacement of the skin, vibrotactile sensations are relatively uncommon, if compared to sensing pressure or temperature. In general, vibrotactile stimulation is not found in nature. Conversely, it was studied to generate a tactile stimulation particularly suitable for signaling the presence of some danger. However, vibrotactile sensations were introduced only recently, and they were associated to alerts when pagers were introduced in the market.

Given the variety and the characteristics of mechanoreceptors, several features of vibrotactile stimuli can be utilized in order to convey information via the sense of touch. Vibrations and sounds share many features. Usually, vibrations are associated with the production of sound, because no sound could be generated without any vibrations. Tactile features include the following:

- *frequency*, the main spectral component of the sinusoidal stimulus;
- *intensity*, which represents the strenght of the stimulus measured as force applied or displacement being produced on the skin;
- *timbre*, i.e., the harmonic content in the spectral component of the stimulation waveform;
- *duration*, which measures the length of the stimulus;
- *spatial location*, representing the area of the body being stimulated.

In addition to physical characteristics, there are features that can be perceived by an individual, even if they do not rely on single properties of the receptors. The following type of features requires to be interpreted at a higher cognitive level:

- *rhythm*, the sequence of stimulation and pauses, with specific durations, that compose the current message (i.e. a triplet of peeps, a Morse coded S.O.S., etc.);
- *tempo*, the fastness, due to longer or shorter duration of the whole message, given a fixed rhythm;
- *flutter*, an amplitude modulation of the stimulation carrier frequency, that can either be perceived increasing and decreasing intensity (if modulation is slower than 5Hz) or be perceived as "roughness" (if modulation is faster than 10Hz);

All the above features render vibrotactile stimulation extremely versatile for being utilized as a support for communication systems. Moreover, differently from other types of stimuli (e.g., electric shock), as vibrotactile output is based on little displacement caused by low-intensity mechanical force, it is non-invasive and it does not result in any painful sensation.

2.2.2 Evaluation of the spatial resolution of vibrotactile stimuli on the hand

Several physiological studies showed that different receptors for the transduction of the mechanical solicitation to the skin into neuronal signals are available in humans [6] [89]. Small vibration motors have been available on the market since the 1960's. Initially, they were developed for massaging products. Nevertheless, as tactile and vibrotactile actuators were uncommon on the market, they were very expensive; moreover, their physical characteristics were not adequate for implementing them into human-computer interfaces. As a consequence, haptic devices were still in the conceptual design stage, until fifteen years ago. Their first utilization in interaction contexts was in the 80's, when they were incorporated into pagers and into force-feedback joypads.
However, development took a new turn in the 90's, when mobile phones started penetrating the market. With consumers requiring the

vibracall function on their devices, vibration motors started being a native feature. In the recent years, thanks to smartphones becoming large-scale products, vibrotactile output has become inexpensive. Accordingly, the demand of alternative tools for haptic feedback increased, so that new devices have been developed and distributed on the market. Currently, vibrotactile actuators come into very different forms and at low price.

A large set of miniaturized precision devices allow creating pervasive, inexpensive feedback and output systems based on vibrotactile stimulation. Moreover, it is expected that the increasing interest in vibrotactile actuators will lead to further improvements and cost optimization. Recently, touch is more systematically introduced in interfaces for providing users with a variety of novel applications. After two decades of mobile phones, on the one hand have designers unleashed their creativity in the use of vibrotactile stimulation; on the other hand, users are proficient in associating vibration with alerts, and they are able to configure and use different vibration patterns for individual types of events. Nowadays, vibrator motors are the main actuators for implementing haptic feedback into tools having work, education and entertainment purposes: miniature vibrating actuators are incorporated into a variety of products, from entertainment peripherals to medical devices for rehabilitation and surgery, from GPS navigation to control devices in industrial applications. Also, a variety of innovative applications are being studies: as an example, vibration patterns have been proposed to convey speech-type information [14].

Although vibration is most commonly used to provide feedback with respect to events, multiple vibrotactile stimulators can be placed at various locations on the skin to convey messages using different patterns of activation, or generating sense of motion or direction [13, 15]. However, as pacinian corpuscles (which are responsible for vibrotactile perception) have large receptive fields, actuators must be placed several centimeters apart to allow subjects to discriminate between them. Typically, two methods are utilized for generating vibrotactile stimulation in portable devices:

- an *elliptic element* provides a rotational motor with an unbalanced inertia that creates a vibration stimulus varying in both frequency and amplitude depending on the modulation of input voltage to the motor; this type of actuators is incorporated in pagers, cell phones, and smartphones;

- a *linear actuator*, such as a voice-coil or piezoelectric actuator, can be utilized to send arbitrary waveforms to the actuator in order to generate modulations in amplitude, frequency, waveform type and a number of other properties of the stimulus, which can be specified independently.

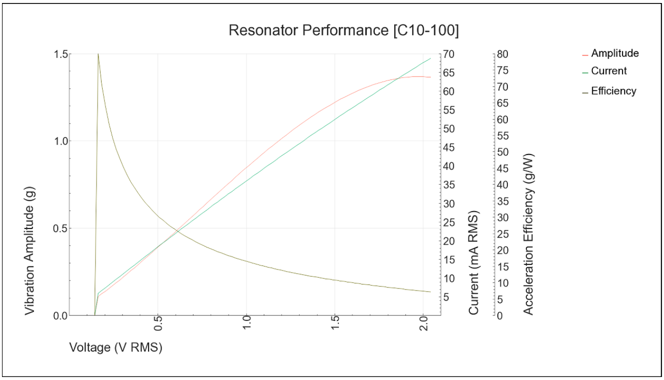


Figure 2.4: Average performance of the Linear Resonant Actuators evaluated for the use in our stimulation device.

Stimulation device

In order to realize our evaluation, we built a stimulation device based on vibrotactile actuators and specifically designed for this experiment. The experimental equipment consists in an array of 54 vibrotactile

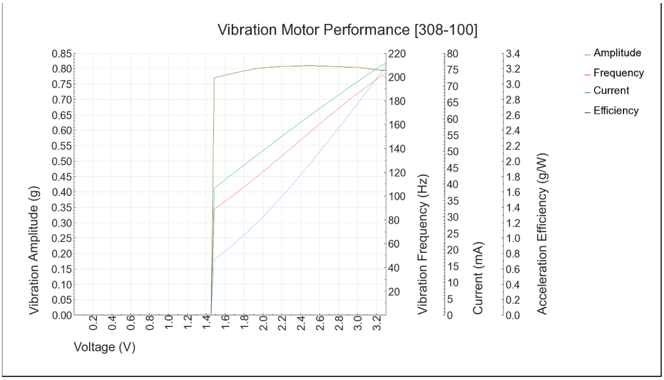


Figure 2.5: Average performance of the Eccentric Rotating Mass Actuators utilized in our stimulation device.

actuators incorporated into a hand-shaped pad, so that subjects could layer the palm of the hand over the surface of the pad. Figure 2.6 shows the configuration of the device and the positioning of actuators. Specifically, six arrays of actuators (i.e., A, B, C, D, E, P) were developed, each consisting of 9 miniaturized vibrating motors. To this end, we evaluated several models of both Linear Resonant Actuators (LRAs) and Eccentric Rotating Mass Actuators (ERMs) from Precision Microdrives. The former perform better in precision haptics and have great versatility. However, for the purpose of this experiment, we implemented the latter, whose amplitudes are proportional with respect to frequency. Also, they have better efficiency. Figure 2.4 and 2.5 show the performance sheet of two actuators among those considered. ERM vibration motors are the same utilized in pager motors. They incorporate a DC motor with an elliptic mass attached to the shaft. Their offset creates a non-symmetric rotation resulting in a net centrifugal force, which causes a displacement of the motor. Particularly, we employed a coin vibration motor, which is a shaftless unit that encapsulates the elliptic mass in a metal enclosure so that there are no external moving parts.

The actuators have a diameter of 8mm and they are 3.4 mm long. Thus, they are perfectly suitable for being applied on the hand. Their activation voltage ranges from 1.5V to 3.3V, and their operating current is 100mA (they drain more current with respect to LREs). Most importantly, they have amplitude linearly increasing with vibration frequency, and ranging from 0.20g to 0.80g. This, in turn, ranges from 90Hz to 200Hz. This is consistent with the literature about vibrotactile perception, and with studies that set the perceivable frequencies in a range between 100Hz and 250Hz. Vibrotactile actuators were distributed in a matrix, as shown in Figure 2.6, at a distance ranging from 3 mm to 1 cm, depending on the area. A control board based on four Arduino Mega 2560 was employed to drive motors at different amplitudes using Pulse Wave Modulation (PWM). This is because the drive signal needs to alternate the direction of current and hence the magnetic field to make the permanent magnet oscillate back and forth with the spring. The moving mass is connected to the magnet, and it is the moving of the mass back and forth that generates the vibration. The pad was attached to the hand in order to facilitate perception and to avoid the displacement of actuators.

Objectives

Although research has shown the potential of tactile displays as means for providing information, there are several factors that must be taken into consideration in order to maximize the benefits of tactile cueing. The proper body location and tactile cue type must be carefully identified and adjusted to users in order to match their specific characteristics. This is due to the varying requirements of the tasks and the environments in which users must operate. In order to evaluate the feasibility of designing novel interfaces implementing touch-based communication systems, we assessed the spatial resolution of vibrotactile stimuli on the hand. To this end, we conducted a study in which we employed the two aforementioned types of miniaturized vibrotactile actuators. Several studies on the performance of vibra-

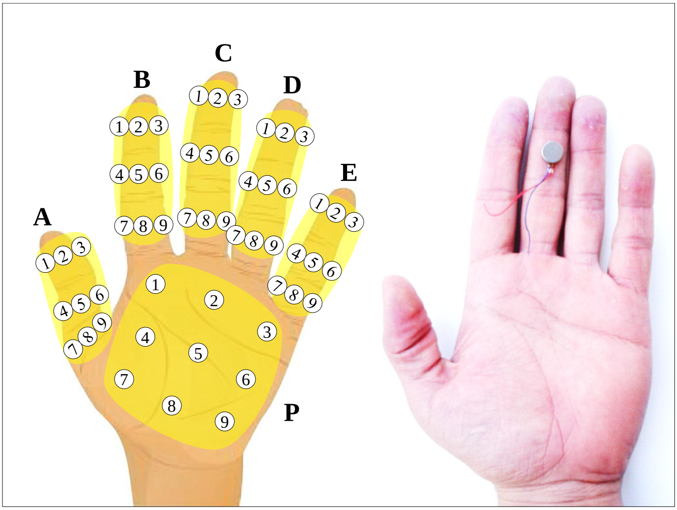


Figure 2.6: Configuration of the actuators in the stimulation device and actual dimension of the vibrotactile actuator.

tion tactile feedback have been published in the literature, in the last decades. However, none of these studies took into consideration the spatial resolution when multiple vibrotactile output has to simultaneously be conveyed on the palm of the hand.

The majority of the studies published in the literature focus on the torso [75, 127, 79, 131, 86, 132, 87, 136, 88, 138, 90, 139, 92, 142, 93, 146, 94, 149, 96, 153, 99, 157, 97, 158, 97, 161, 109, 172, 110, 168, 111, 170, 114, 178, 115, 116, 76, 169, 78, 171, 91, 172, 105, 109, 117, 122, 123, 125, 126, 135, 137, 143, 144, 148, 168]. Also, there are a number of publications especially dedicated to the upper limbs [83, 82, 84, 85, 95, 101, 102, 123, 128, 129, 152, 159, 77, 81, 123, 144, 147]. Conversely, in our experiment, we particularly focus on the hand. This is because the majority of communication systems especially designed for the blind and the deafblind are based on the hands alone, because of their sensitivity (see Section 1.1) and their ability to easily support bidirectional communication.

The objective of our experiment is to identify the feasibility of using vibrotactile stimuli as a viable output system for touch-based communication languages. To this end, we investigated the type of vibrotactile stimuli that can be delivered to subjects in sequence. Specifically, we utilize the Two-Area Discrimination Threshold (TADT) as an alternative measure to evaluate tactile sensitivity in different areas of the palm of the hand. Also, we aimed at identifying the minimum vibration intensity to be delivered in order for subjects to perceive the stimulus (i.e., sensitivity threshold). The ultimate goal of this study is to identify specific areas of the hands in which it is possible to implement vibrotactile stimuli for encoding messages that can be correctly received by the subject.

Limitations of the two-point discrimination threshold method

In general, the two-point discrimination threshold (TPDT) is employed as a measure of the topognosis of mechanoreceptors in different parts of the skin. This represents how far apart two pressure points must be in order to be perceived as two distinct areas on the skin [16]. Usually, the TPDT is employed to define the density of a tactile display in regard to the part of the body in which it will be mounted. From studies in the literature, it was calculated that tactile displays should integrate actuators at a distance of 2.54mm interspacing and produce an effective skin indentation of 1mm at 1Hz (see Figure 2.3, Meissner curve) or produce 10μm of skin indentation at 100Hz (see Figure 2.3, Pacini curve), in order to correctly stimulate the fingertips. Although vibrotactile stimulation has been studied extensively, physiological studies about perception focused on evaluating the TPDT in experimental conditions, using points of contact having a diameter smaller than that of actuators. Unfortunately, current vibrotactile actuators based on miniaturized technology that can be utilized for pervasive interaction span across an area that is bigger than the TPDT. In our experiments, we utilized a different method of measuring the TPDT. Specifically, we employed the Two-Area Discrimination Threshold (TADT). This basically is a measure of the area affected by and of the propagation area of the stimulus.

Experimental task

The experiment consisted in one task. Subjects were presented with different sets of stimuli each having randomly chosen frequency ranging from individuals' sensitivity thresholds (measured as varying from 100Hz to 130Hz, depending on the subject) to 200Hz. Stimuli were fired in sequence, in randomly chosen locations among the 54 implemented in the stimulation device. Subjects were asked to identify the area and the intensity of the perceived stimulus. The experiment was divided into 4 runs consisting of 54 trials each. For the purpose of this dissertation, we ran the experiment on the left hand. As tactile sensitivity is demonstrated to be similar in the hands [19], data are expected to be a little different in the right hand but in line with our results. Moreover, using the calibration routine, our results can substantially be replicated by only scaling the Minimum Perceived Threshold (MPT).

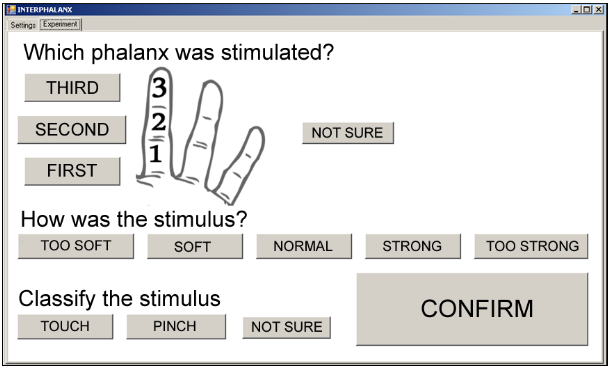


Figure 2.7: Software interface utilized in the experimental study.

Experimental setup and protocol

At the beginning of the experiment subjects received a short document describing the task in clear and informal words. Then, their hands were attached to the stimulation device. We prevented subjects from seeing their hand, so that they could not visualize the area being stimulated. Also, we provided participants with an interface (i.e., a PC equipped with mouse) that allowed them to provide an answer to the following items: subjects had to identify the area in which they perceived the stimulus among the 54 possible locations over the palm (as shown by Figure 2.6), by clicking on a visual representation of the palm. Also, subjects had to indicate a perceived intensity on a Likert scale ranging from 0 (no perception of stimulus) to 9, using a slider or by entering a value. Figure 2.7 shows the software utilized to guide participants in the experiment.
Subjects were allowed to rest for 2 minutes after each run. In order to limit the duration of the experiment, for each stimulation, we set a timeout of 5 seconds to give their answer. We included two buttons for situations in which participants were not sure about the location or the intensity of the stimulus.

Evaluation of the sensitivity threshold

In order to assess individuals' sensitivity thresholds, before the experiment, we did a preliminary evaluation of the minimum perceivable frequency. To this end, we defined two test sequences each consisting of 5 vibration stimuli in the range from 80Hz to 200Hz; set A implemented increasing frequencies and intensities, whereas set B consisted of values having decreasing frequencies and intensities and specifically:

- f_1^A = $\sim$80Hz (0.20g), f_2^A = $\sim$100Hz (0.35g), f_3^A = $\sim$130Hz (0.50g), f_4^A = $\sim$160Hz (0.60g), and f_5^A = $\sim$200Hz (0.75g).
- f_1^B = $\sim$200Hz (0.75g), f_2^B = $\sim$170Hz (0.65g), f_3^B = $\sim$140Hz (0.55g), f_4^B = $\sim$110Hz (0.40g), and f_5^B = $\sim$80Hz (0.20g).

The stimulus duration was 250 milliseconds, and the inter-stimulus time was 500 milliseconds. Subjects were asked to press a button as soon as they felt the stimulation. The stimulation protocol is described by Figure 2.8: we randomly fired all actuators from 1 to 54; for each actuator, we fired sequence A and sequence B, one after another. Specifically, we fired all the items in sequence A from 1 until the subject pressed the button (e.g., on item j), which interrupted the counter on sequence A; then, we switched to set B and we resumed firing the items from index j, until the subject stopped pressing the button (e.g., on item k), which allowed switching to the next area. The resulting sensitivity threshold for area i would be the average between the value of item i in sequence A and the value of item k in sequence B, thus increasing the threshold of 5Hz with respect to the sensitivity recorded when firing sequence A. Results are shown in Figure 2.9. We utilized two types of stimulation patterns: one based on the same pattern replicated over all the areas, and one based on different stimuli for individual sets of actuators. Specifically, we utilized one vibration to identify the central area of fingers (i.e., actuators 2, 5, and 8), two short vibrations followed by a long stimulus for the left side of fingers (i.e., actuators 1, 4, and 7), and three short vibrations for the right side of fingers (i.e., actuators 3, 6, and 9).

```
for i randomly chosen until all 54 areas are consumed
    for j in sequence A from 1 to 5
        fire actuator i with amplitude j
        if button pressed
            for k from current j to 5
            fire actuator i with amplitude k
            if button pressed
                increment k by one
                continue
            else end
        else
                increment j by one
                continue
    set threshold for current area i = average(current j, current k)
    increment i by one
    continue
end
```

Figure 2.8: Routine for the evaluation of the Minimum Perceived Threshold.

Participants

35 volunteer participants were involved in the study. They were 18 female and 17 male. All had a normal sight, hearing and tactile sensitivity (we did not measure the different acuities). Subjects ranged in age from 23 to 41 years with an average of 32. All use computers on a daily basis (1.5-8 hours usage per day). All were novice for the system. Subjects participated on a voluntary basis and they were not paid or rewarded. All subjects were right-handed as assessed by the Edinburgh inventory [55]. All subjects were prepared to the experiment by a technician who gave them instructions about the test and the experimental tasks.

Results and discussion

During the preparatory task, all subjects were able to recognize the stimulation in every location of the hand, though they had different sensitivity thresholds. Data regarding the Minimum Perceivable Threshold (MPT) show that all subjects have sensitivity ranging from $\sim$110Hz ($\sim$0.43g) to $\sim$136Hz ($\sim$0.52g), with a center value of $\sim$121 $\pm$7.8Hz, that is, $\sim$0.46g. Data show that tactile sensitivity is unaltered with respect to age. However, the age of subjects (32 $\pm$5.4) is such that no particular difference was expected, as all subjects reported normal tactile sensitivity. Also, data show that the areas of the hand have similar sensitivity, in average ranging from $\sim$117Hz to $\sim$127Hz, with a center value of $\sim$121Hz $\pm$3, and no significant difference between the areas. This shows that the threshold measurement protocol is effective in estimating individuals' sensitivity on the palm of the hand. Values are a little higher than those reported in the literature. However, this could be due to the structure of the stimulation device. Figure 2.9 shows the average Minimum Perceivable Thresholds in the different areas of the hand.

During the experimental task, we recorded the Actual Stimulus (AS) and the Perceived Stimulus (PS); intuitively, the former is the frequency at which the stimulus was delivered, whereas the latter

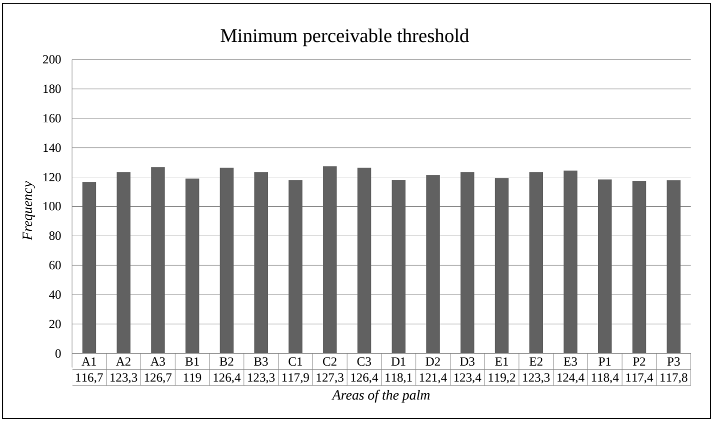


Figure 2.9: Minimum Perceived Threshold experienced by participants.

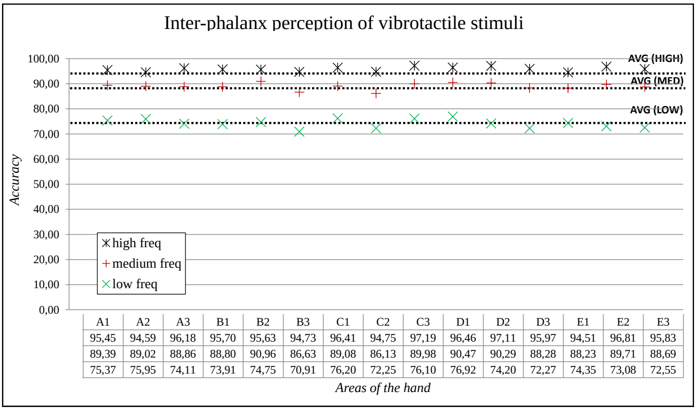


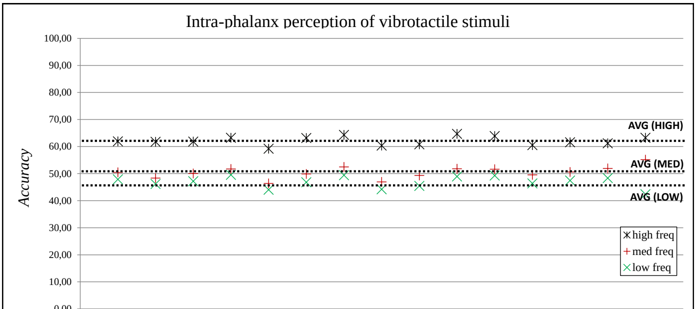
Figure 2.10: Performances in the inter-phalanx perception of vibrotactile stimuli.

represents the intensity perceived by the user. Also, we measured the Actual Stimulus Location (ASL) and the Perceived Stimulus Location (PSL), which represent the area where the stimulus occurred and the area where it was perceived, respectively. Moreover, we measured the Response Time (RT) as an additional metric of accuracy, which is calculated as the distance between PSL and ASL: we assigned 1, 2 or 3 points for a correct detection of the finger, of the phalanx, and of the intra-phalanx area, respectively. Also, we added the accuracy in detecting intensity by multiplying the difference (in intensity) between AS and PS, weighted by 0.5, and normalized to 100.

As the Minimum Perceivable Thresholds are in a short range of frequencies and intensities, it is possible to identify a standard minimum threshold under which no subject is able to perceive the stimulus, and to utilize that as a baseline for the stimulation protocol. On the contrary, in the experimental task, we employed individual thresholds, in order to better evaluate the perception of stimuli. However, in order to standardize the measurements utilized in the study, we calculated the Normalized Perceivable Ranges (NPR) as the frequencies ranging from individuals' MPTs to the maximum frequency value (i.e., 200Hz). The spectrum for the NPR was calculated as large as $\sim$78.5 $\pm$7.8Hz. Then, we divided stimuli into 9 frequency and intensity ranges, and we defined three groups (i.e., low, medium, and high), each spanning across a range of $\sim$25Hz ($\sim$0.12g). These were utilized to evaluate the results independently from individuals' specific MPTs. Data from the experimental task show that all the subjects were able to identify the location of vibrotactile stimuli at an inter-phalanx level, achieving performance values of 95.82%, 88.97%, and 74.19% (on average) for high, medium, and low frequencies, respectively. Results are shown in Figure 2.10. All subjects performed extremely well in recognizing the location of the stimulus at frequencies ranging from $\sim$170Hz to $\sim$200Hz. Results show that, although performances deteriorate at lower frequencies, they remain above 70%, which is acceptable, especially considering that subjects were not trained on tactile feedback.

However, when we applied the same pattern to every location, participants were unsuccessful in detecting the intra-phalanx stimulus location, showing accuracy values below 70% at higher frequencies, and below 50% at medium and low frequencies and intensities. Such results, shown in Figure 2.11, are independent from the subject and regardless of the location of the stimulus. This may be caused by the size of the actuator, and by the fact that the displacement occurring over a large area propagates in the surrounding areas (i.e., vibration at lower frequencies have a larger propagation area). Consequently, using the same vibration pattern, the TADT is as large as the interphalanx distance, that is, from 0.5cm to 1cm, on average.

Conversely, when we applied different vibrotactile patterns to



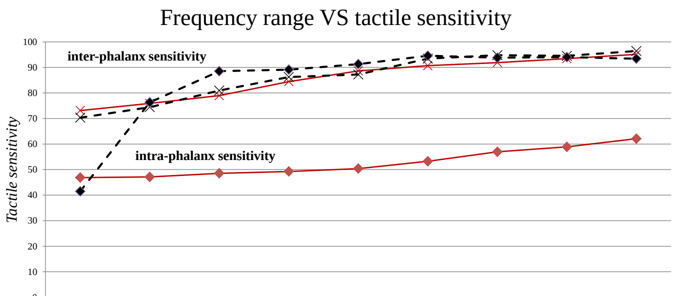
	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3
high freq	61,92	61,75	61,80	63,23	59,20	63,13	64,30	60,33	60,80	64,66	63,88	60,51	61,57	61,17	63,23
med freq	50,44	48,32	50,03	51,70	46,37	49,87	52,43	46,90	49,30	51,79	51,62	49,49	50,58	51,89	55,12
low freq	47,83	46,14	47,15	49,49	44,01	46,79	49,40	44,20	45,41	48,90	49,24	46,36	47,40	48,30	42,34

Figure 2.11: Performances in the intra-phalanx perception of vibrotactile stimuli.

different areas of the hands, results show better performances in terms of TATD: subjects were able to distinguish the precise location within the same phalanx by decoding the specific vibrotactile pattern associated with the left, central or right area of fingers. This leads to

TADT smaller than 0.4cm. Figure 2.12 shows a comparison of the performances in recognizing inter- and intra-phalanx stimuli over a sequence of nine trials. All subjects immediately show better sensitivity to different patterns.

The purpose of the experiment was to evaluate the feasibility



1	2	3	4	5	6	7	8	9
73,12	75,91	78,95	84,43	88,64	90,68	91,87	93,44	95,12
46,87	47,12	48,53	49,27	50,39	53,26	56,95	58,89	62,10
70,31	74,42	80,94	86,23	87,21	93,44	94,78	94,51	96,42
41,49	76,32	88,51	89,12	91,30	94,55	93,79	94,02	93,42

Figure 2.12: Characteristics of vibrotactile actuators utilized in the stimulation device.

of implementing clusters of vibrotactile actuators to provide assistive interfaces with means for delivering distinct output to the users. Results from the preliminary task show that miniaturized vibrotactile actuators are suitable for delivering stimuli at frequencies in the range between 100Hz and 200Hz. However, the design of the enclosure of the actuators may alter the perception of vibrotactile stimuli, and affect individuals' performance in terms of sensitivity. Also, experimental data from the preliminary task show that individuals have a Minimum Perceivable Threshold that is almost the same over all the areas on the skin of the palm of the hands. This allows standardizing the output frequencies and intensities, and it eases the design of assistive interfaces based on vibrotactile stimuli, because it is sufficient to identify the MPT to rescale all the available frequencies and intensities for stimuli. Consequently, the routine for calculating the MTP is suitable for calibrating devices that utilize vibrotactile actuators for generating output.

At the beginning of our experiment, we obtained contrasting results: subjects show different performances that are significantly correlated with the location of the actuators. Specifically, data show that the system:

- underperforms (and in some circumstances, it fails) in delivering distinguishable vibrations with respect to intra-phalanx stimuli;
- leads to significantly better performances in delivering inter-phalanx stimuli;

However, by introducing different vibration patterns associated with the areas of the phalanx, it is possible to convey clusters of distinguishable stimuli that can be easily interpreted as distinct. Tactile perception varies depending on several factors including stress and environmental conditions (e.g., presence of humidity), which we did not take into consideration.

From the results of the experiment, we can conclude that vibrotactile stimulation can support the implementation of touch-based languages that require many signals to be conveyed in the same area. Specifically, it is possible to include several actuators on the same phalanx, by differentiating the vibrotactile pattern of actuators.

Chapter 3

Incorporating two-dimensional spatial interaction based on bimodal tactile feedback

3.1 Limitations of current interfaces

The most utilized paradigm for representing output messages in software is the visual Graphical User Interface (GUI). Nowadays, it is a worldwide standard for desktop, mobile, and home technology. Specifically, Windows-Icon-Menu-Pointing-devices (WIMP) interfaces enable desktop users to achieve great flexibility in running and controlling multiple actions and tasks by means of a keyboard and a pointing device, such as a mouse, or simply using touch. This requires the manipulation of a motion- or touch-enabled device that allows pointing a specific part of GUI. Also, visual GUIs are employed in touch-enabled devices, such as smartphones, where little tactile feedback is utilized for alerting the user on specific situations. However, as blind and deafblind people are not able to see visual displays and interfaces, they are not able to use any pointing devices.

Apart from a few exceptions (see Section 4.1), visually-impaired people and individuals suffering from multi-sensory impairments are still provided with first-generation user interfaces providing linear feedback and allowing text-based interaction, only. This is because the majority of the technology for blind and deafblind people outputs information in a one-dimensional fashion, that is, as sequences of text, despite the evolution of visual user interfaces, which allow exploring data in two or three dimensions. Consequently, sensory impaired people are not able to get access to the majority of the features of visual interfaces, and primarily, to benefit from the spatial organization of content.

Remarkably, blind and deafblind people generally have no difficulty in using standard input peripherals, such as the keyboard or the mouse. Also, they are able to interact with devices providing adequate representations of bidimensional information. Particularly, output systems represent the main barrier and, simultaneously, the main area of improvement. Although systems explored the possibility of using touch for representing some elements of GUIs, such as icons, there is no complete system that enables full control of a the visual interface of current software. In this section, we introduce a device for enabling blind and deafblind people to autonomously interact with visual GUIs, and to control the WIMP interface of standard software applications. Specifically, we discuss the design and the implementation of bimodal tactile feedback based on simultaneous vibrotactile output and static pressure, and we evaluate the applicability of double feedback modality in Human-Computer Interfaces. Moreover, we evaluate the representation of elements of visual GUIs into tactile form using touch-based actuators working with vibrotactile stimuli and with continuous pressure.

3.2 A device for two-dimensional bimodal tactile interaction

Usually, blind and deafblind people have extremely well-developed abilities in spatial organization, and they are trained to use their environment navigation capabilities, because they are able to move independently. Results from neuropsychological experiments showed that deafblind individuals took significantly lesser time to feel and remember objects when presented in tactile form [60]. Furthermore, results from this study also showed superior performance in tactile memory for the location of objects. Therefore, by adding mouse-like interaction, in addition to getting access to current software by means of standard GUIs, users could benefit from spatial organization of digital content. This would also help them optimize content navigation thanks to two-dimensional spatial organization. However, displaying the position of the cursor using alternative sensory modalities is extremely difficult. In this regard, sensory substitution is employed to cope with impairments to one communication channel. Simultaneously, audio feedback is known to further improve the performance of haptic devices [57]. Nevertheless, current systems based on audition or touch, do not take into consideration or they are not able to represent spatial information in a way similar or comparable to visual display. Multimodal feedback based on audition is employed to signal particular events, or to replace text with speech. Although it is useful for tasks having a short duration (e.g., identifying obstacles in close proximity), the prolonged use of auditory feedback as a support for spatial navigation can be tedious.

Haptic feedback is known to significantly improve human-computer interaction. Findings from several studies [56] show that visual feedback can be ameliorated, and in certain cases even replaced, by tactile stimuli. Vibrotactile devices delivering variable pressure on the skin have been employed as an alternative sensitive channel for blind or deaf individuals [58] [59]. Also, studies demonstrated the advantages of vibrotactile stimulation in the context of Human-Computer

Interaction: especially in circumstances of sensory or cognitive impairments, vibrotactile output can improve the performance of users in interacting with a device in spatial navigation tasks. Moreover, the tactile channel is extremely convenient, as it guarantees privacy, and it is more robust in noisy environments [62]. However, vibrations are not able to encode sophisticated information, because of the simplicity of their features. Moreover, due to the size of current actuators, vibrotactile stimuli have a Two-Area Discrimination Threshold larger than the Two-Point Discrimination threshold experienced with static pressure, as demonstrated in Section 2.1.

In general, multimodal feedback is known to be effective in Human-Computer Interaction. Specifically, touch has been experimented in combination with other sensory modalities (Geldard, 1967) to reinforce perception and communication:

- research has demonstrated that, when tactile and auditory feedback are combined, (Tan, 1996) the ability in speech recognition increases dramatically (Reed 1995, Tan 1997); this especially is the case of devices for enabling deafblind use Tadoma as their communication method (Aeur, et.al, 1999);
- touch has been experimented in combination with smell to reinforce memory, mood perception and to engage users in the recall of emotional states (Aggleton, 1998) Ehrlichman (1998);
- several studies focused on combining touch and vision, showing better reflexes to stimuli and faster perception (Roy, 1997).

Most of the publications in the literature regard multimodality simply as combining two different senses (i.e., inter-sensory multimodality). Although it has been utilized in the last two decades as an effective way to allow communication channels to work together and enrich user experience, less is known about intra-sensory multimodality, that is, exploiting different components of tactile stimuli for providing users with multiple types of information combined together.

This is a natural feature of audition, in which speech can be simultaneously combined with other types of signals without introducing noise. Therefore, auditory feedback has been explored as an alternative modality to render tone-based spatial information about the movement of a cursor on a standard computer display and, concurrently, it has been employed for providing users with textual information (e.g., speech). A widely employed solution in this sense is to split information over two channels, i.e., to combine haptic continuous feedback with sounds associated to discrete events [57]. However, this solution would not be suitable for deafblind users and is more prone to errors when ambient acoustic noise is present.

3.2.1 Tactile bimodality

According to the human physiology of touch, described in Section 2.1, the human skin contains several different classes of mechanoreceptors, each capable of sensing specific tactile features. Particularly, some receptors are very sensitive to vibration, while others are stimulated by static pressure, only. This feature of the human sense of touch can be exploited for designing output modalities. Moreover, as demonstrated in Section 2.1, mechanoreceptors have great performances in discriminating stimuli over two adjacent fingers. Our proposed solution implements instead a bimodal tactile feedback through haptic channel splitting, and it combines two types of actuators to deliver vibration and static pressure. Specifically, due to their specific features, vibrotactile stimuli can be associated with continuous motion, and they can be utilized to encode the movement of an object along one or two axes. However, different types of stimuli have to be employed for representing other components of GUIs such as text, icons, and menus.

There are different types of mechanoreceptors that respond to multiple levels of pressure [67]: rapidly adapting receptors react to an immediate stimulus, while slowly adapting receptors respond to continuously applied pressure. Thanks to this feature of human touch, blind people are able to read Braille displays. These use different configurations of static pressure to represent symbols, as described in Section 1.1. Other receptors enable people to sense vibration, as discussed in Section 2.1. Thus, different types of mechanoreceptors can be stimulated depending on the type of operation. Particularly, continuous information, such as motion, can be represented by exploiting the ability to sense skin displacement. Conversely, discrete symbols can be displayed by applying different levels of pressure. Unfortunately, there have been no studies on tactile multimodality.

Several Braille-based devices could be suitable for this solution: in particular, there are mouse-like computer accessories having a character code member which enables visually impaired users to read text on a computer screen in Braille format [68]. Especially, the tactile communication system proposed in [69] is a low-cost input/output peripheral, shaped like a mouse, which consists of a haptic device having the purpose of both a Braille display and a sensor combined in a unique tactile information system. Input is acquired by sensing the pressure of a finger with a grid of 64 electrodes, while output is based on the use of low-voltage electrical current as a stimulus: mechanoreceptors' axons within nervous cells underneath the fingertip are excited with anodic or cathode current in order to generate different sensations on the user's skin. Nonetheless, there are many challenges that need to be solved in order to achieve practical usability. First of all, the sensibility of this device to the current is different among individuals and it is subject to skin impedance changes that also depend on the environment and vary along time too. Moreover, such devices offer haptic feedback but they do not provide any spatial information about the cursor position. Hence, there is no feedback received by users when navigating over the screen apart from the movement of their own hand. As a result, visually impaired users are able to recognize the direction in which they are moving the mouse, but they are not aware of the exact location of the pointer on the screen. To solve these problems, our implementation is therefore aimed at inserting the feedback for spatial information, which also needs to be properly elicited through a tactile channel.

Differently from other systems on the market, which simply use tactile feedback to convey basic warnings or event notifications, our design strategy aimed at fully exploiting the potential of the tactile channel. We defined a bimodal tactile interaction and designed a more expressive feedback environment based on several types of information. For the execution of continuous control operations, such as tasks in which the user navigates over the screen, tactile feedback provides immediate spatial information, allowing blind and deafblind individuals to modulate their control depending on their purpose: vibrotactile actuators give them real-time feedback about the trajectory of their movement, and they are able to adjust it. In addition, static pressure can create the appropriate feedback for discrete control operations (i.e., for reading a text or a symbol on the screen) without affecting or interfering with the information about continuous control.

As a result, our system provides different tactile feedback using vibrotactile actuators delivering continuous pressure, and one refreshing Braille tactile actuator that generates discrete stimuli. Bimodal tactile feedback can be employed so that the different actuators can be fired in parallel (i.e., for the notification of an event, when the application alerts the user and requires him to read a text which is not in the cursor position) without any interference. As a consequence, we rely on the sense of touch as a common information source for several types of non-collapsing messages.

3.2.2 Interaction design

Usually, interaction based on tactile output is sequential, and structured into text-based implementations. Conversely, our device implements two tactile modalities that enable delivering two types of information: textual and spatial, in a bidirectional fashion.
The system consists of a hardware device driven by a software component that has the purpose of translating the visual content of the

screen into a bidimensional (and bimodal) tactile representation. Particularly, the device driver of the system enables to capture and display the GUIs of standard WIMP applications. As a result, the device does not simply read the content of the screen. On the contrary, it analyzes the content of the screen and it determines the portions corresponding to different windows, or to the specific pieces of the layout. As a result, similarly to a screen reader, the system can focus on a specific area of the screen, such as a menu, or the text next to a cursor. Most importantly, with our system, users have fine control over the discrete units of the screen, and they can navigate over visual GUIs using touch to distinguish window title bars, menus, status lines. Then, users can either use the buttons on the device to send simple commands, or they can type text on a standard keyboard to compose messages. This is a fundamental advance with respect to sequential, speech-based interfaces primarily used by people who are blind. By achieving control over information organized into a spatial form, the blind and deafblind can form mind maps of content, and they can associate pieces of data with areas of the screen.

As many current versions of screen readers, the software of the system is designed to intercept information on the screen and manage it in the so-called off-screen model (OSM). This essentially is a memory consisting of a database that contains the information displayed on the screen, such as text, graphics and interaction controls. By doing so, the device accesses the information in the OSM and renders using the Braille cell or the vibrotactile actuators, depending on the data being displayed. Several operating systems support the OSM by exposing objects in the user interface so that assistive technologies can access and display them using alternatives to visual displays. For instance, the Microsoft Active Accessibility contains programming language enhancements and standards that can be utilized to access the content of the screen in applications, such as Word, and Excel. Moreover, additional information can be obtained by accessing the Document Object Model available in web pages and in several applications.

Consequently, users can zoom into an area of the screen to focus on specific content, or to filter out information that is not crucial to them. With the proposed device, it is not necessary to write dedicated applications that are very specific to the needs of single users. On the contrary, it is sufficient to develop new screen filters to accommodate visual features that cannot be captured by the standard driver. Furthermore, in addition to getting access to standard software, several other applications can be developed *ad hoc*, with a specific focus on needs for assistive technology, and particularly designed with accessibility in mind.

Moreover, our system supports the integration of three sensory modalities (i.e., visual, auditory, and tactile) to simultaneously provide users with information perceivable using the senses of sight, hearing, and touch. Consequently, although it is especially designed for the deafblind, the proposed system guarantees an improved usability for any type of user, both blind and sighted.

By building features on top of the operating system and current software applications, our approach benefits from software reuse, and it focuses on rendering existing resources accessible.

Hardware architecture and design

The system architecture was designed according to a modular approach that is especially suitable for interactive devices. The system consists of three independent components, namely the *physical*, the *control* and the *communication* layers. They are logically conceived as layers, and connected to one another by means of interfaces for data exchange (see Figure 3.1). The former has the purpose of exchanging input and output from and to the user. On the one hand, it directly interacts with the user, on the other hand, it sends and receives data to and from the control layer. This, in turn, is responsible for managing input and output messages, and for managing the operation of the device. Furthermore, it exchanges data with the communication layer, which is responsible for transmitting data over the network, or to the PC, depending on the implementation. The communication layer can be connected to a computer or to a network server. In our prototype, all the layers are assembled into different printed circuit boards (PCBs), though they can be arranged to fit into a single or double layer PCB.

The hardware enclosure of the system consists of a small plastic case having a shape similar to that of a mouse. Therefore, it can be controlled by the user with one hand, only. The components of the physical layer are assembled close to the external surface of the enclosure, because they are the elements that sense the environment and exchange messages with the user. The optical sensor is located at the bottom of the device. This is because, similarly to a mouse, the movement sensor has to be in contact with the surface where it is positioned. Moreover, the device is equipped with pairs of vibrotactile actuators that are located on both the left and the right sides, so that users can touch them with the distal and the intermediate phalanges of their thumb and middle finger. Two sensors are located immediately above the vibrotactile actuators, in order to be in touch with the distal area of fingers. They are located one on the left and one on the right, so users can easily press them with the thumb and with the fourth finger, respectively. The Braille cell is placed on the top of the peripheral and it is in contact with the distal phalanx of the second finger. The control board is located within the device, and it is not visible, similarly to the communication layer. The peripheral can be connected to a computer via USB and it can be controlled as a serial port. Alternatively, it can exchange data on a wireless connection (i.e., Bluetooth). The inner structure of the communication layer may vary depending on the implementation of the communication layer. The device was designed to be portable and to be manipulated with one hand: its total size is about 12cm (length) $\times$ 8cm (width) $\times$ 8cm (height).

The most expensive part of the device is the piezoelectric Braille cell, not only due to its market price, but also because as there are only a few manufacturers, it is extremely difficult to find distributors. Nevertheless, Braille cells have a unitary cost of about 35 U.S.$. Other components are relatively less expensive, and easier to source. The overall cost for a complete device (complete prototype) can be estimated below 80 U.S.$ (Bill Of Material). As a result, the proposed device introduces new features with respect to state-of-the-art devices, and it is cost-effective compared to other solutions on the market (e.g., Braille displays). Specifically, the price ratio is about 1:15. Moreover, as all the sensors and the actuators (except for the Braille cell) can be gathered from spare hardware and non-functioning devices (i.e., a computer mouse and mobile phones), and given the simplicity of the hardware design, it can be released as open source and it can easily be built as a do-it-yourself project. This allows creating communities of developers and raise new design models (see Section 4.1).

For instance, as vibrotactile actuators have larger drain with respect to other components, sources of improvement may consist in power saving techniques to reduce energy consumption, especially in battery-powered and in wireless models. Similarly to a computer mouse, the device can implement standby modes during which the laser or the LED blink instead of being continuously active. Moreover, several power saving routines can be introduced in order to reduce battery consumption and save energy; for instance, the device (or some of the components of the device) can go into sleeping state when inactive. This function would also increase the life of the optical sensor.

Physical layer

The physical layer of the system consists of four separate peripherals that have very different purposes and, thus, utilize four different types of sensors and actuators. Although they are embedded into a unique layer, the input and the output modules can work independently. The former consists of two main elements: the navigator and the selector.

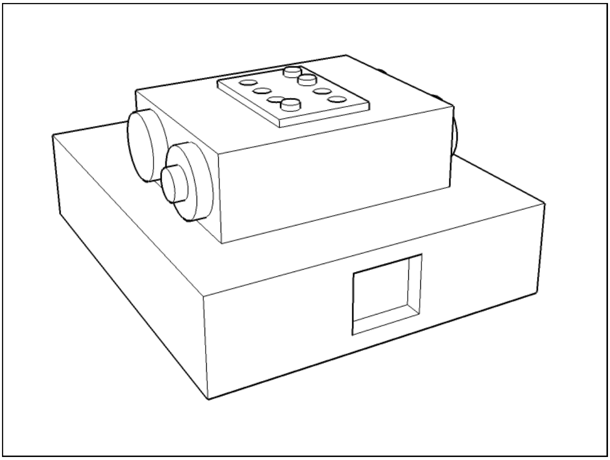


Figure 3.1: Architecture and design of the hardware prototype.

The former allows sending messages that encode continuous information about the coordinates over two dimensions of the device moving on a surface. This is captured by means of a two-axial motion sensor. On the contrary, the selector consists of buttons that allow sending simple discrete commands.

The output subsystem consists of two components, also: one provides vibrotactile feedback about the structural content of the screen when navigating over two dimensions. This basically represents graphical information about the structure of the content of a visual display. Conversely, the latter output subcomponent has the purpose of displaying textual information. Specifically, it provides a representation of the content of the part of the screen being currently observed. Figure 3.1 describes the architecture of the physical layer and it details its modularity.
Moreover, the physical layer contains the circuits connecting the all the components of the device that are required for exchanging data

with the other layers.

Navigator

The navigator is based on motion sensors that can reveal the position of the device. Specifically, it can be implemented using optomechanical components that are capable of detecting two-dimensional motion relative to their underlying surface. In our prototype, the navigator consists of an optical sensor (similar to the component embedded into computer mouse) whose purpose is to acquire continuous movements over a flat surface and to determine the distance between their starting and ending positions within a certain time frame. This can be realized with light-emitting diodes (or with infrared diodes) in combination with photodiodes. The former illuminates the surface, the latter acquire light changes, which are then processed and translated into movements on the two axes using basic vision processing algorithms. One of the advantages of this type of sensors is that they are surface independent: especially their last generations are suitable for being utilized over a variety of different materials. In our prototype, we employed a common 3mm red Light Emitting Diode (LED) and a standard metal-oxide semiconductor (CMOS) sensor. The light bouncing on the surface is capture by the CMOS and processed with a Digital Signal Processor (DSP) algorithm embedded into the electronics of the device. The navigator provides the control layer of the system with the exact position of the device, so that the control layer can process motion into coordinates defined in terms of pairs (x, y). These define motion with respect to a reference position. Among its routines, the software driver of the system has the purpose of processing the spatial information sent by the navigator, and to translate it into the movement of a pointer over the computer screen, exactly as in the case of a mouse cursor.

Selector

Basically, the selector consists of buttons located in a position that makes reaching them very easy. In order to improve the ergonomics of the device, we designed the buttons so that they can be activated with the thumb and the middle finger. This is a very convenient position, especially when the user manipulates the device. The purpose of the buttons is to send basic commands (as sequences of button-click actions) that depend on the number of buttons incorporated within the device, and by the interaction situation. In our prototype, we employed low-profile tactile switches having a size of 0.5cm $\times$ 0.5cm $\times$ 0.3cm This type of components provides excellent tactile feedback, thanks to their mechanical sensitive release to an actuation force of about 1.35 ± 0.50N. Also, they are well known for their high reliability and long-lasting life (usually, from 200.000 to 1 million expected cycles). Moreover, they are extremely cheap (about 0.15 U.S.$ each). In our prototype, we implemented two buttons, which are sufficient to achieve full control of several tasks. However, extra switches can be added to provide users with more control features.

Navigation feedback

The provider of navigation feedback is realized by means of four vibrotactile motors. These components act as transducers that convert electrical signals into tactile stimuli in the form of vibrations. The vibration motors implemented in our prototype are Eccentric Rotating Mass Actuators (ERM) from Precision Microdrives, similar to the actuators embedded in mobile phones and pagers to provide the vibracall feature in addition to or as a replacement of the ringing tone. As they incorporate a DC motor with an elliptic mass attached to the shaft, their offset creates a non-symmetric rotation resulting in a net centrifugal force and causing a displacement of the motor. Particularly, we employed exactly the same motor utilized in Section 2.1, that is, a coin vibration motor. This is for convenience. However, given the size and the structure of the device, there is no need of having motors that are based on a shaftless unit that encapsulates the elliptic mass in an enclosure. Also, motors having external moving parts can be utilized and enclosed into the external surface of the device. The actuators included in our prototype have a diameter of 8mm and they are 3.4 mm long. Thus, they are perfectly suitable for being applied on the hand. Their activation voltage ranges from 1.5V to 3.3V, and their operating current is 100mA (they drain more current with respect to LREs). They have amplitude linearly increasing with vibration frequency, and ranging from 0.20g, at 90Hz to 0.80g, at 200Hz. This is consistent with the literature about vibrotactile perception, and with studies that set the perceivable frequencies in a range between 100Hz and 250Hz (see Section 2.1). Vibrotactile actuators were assembled in a 2×2 matrix, as shown in Figure 3.2. Their distance was set consistently with studies in the literature and with the findings of the experiment discussed in Section 2.1: different vibrotactile patterns allow improving the Two-Area Discrimination Threshold and distinguishing the position of the actuator. A control board based on Arduino was employed to drive motors at different amplitudes using Pulse Wave Modulation (PWM) as described previously.

Content information

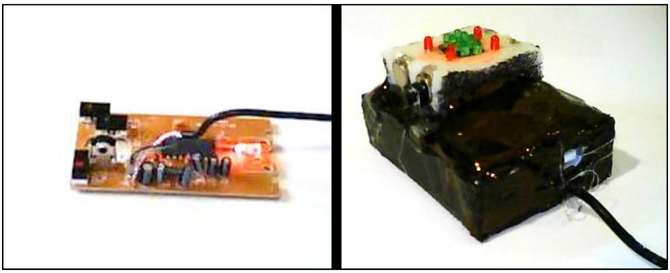


Figure 3.2: Implementation of the prototype.

The architecture of the physical layer, as detailed in Figure 3.3, contains several elements that deserve more emphasis. The provider of positional information consists of one lightweight and small-size Braille display cell so that when the user navigates over a standard display, information about the content of the screen in each area is provided in real-time using the Braille alphabet to encode visual text into tactile form. This is realized using a piezoelectric unit capable of representing one Braille character. Piezoelectric Braille cells have been developed to provide visually impaired people with means for reading digital documents in Braille. Users of Braille displays read by passing the fingers over several cells assembled in a row Of 20 or 40 actuators. Nevertheless, as it is refreshable, the configuration of each Braille cell can change over time. Consequently, a single Braille cell can represent multiple characters by modifying its configuration to show them in sequence. Each piezoelectric unit consists of six or eight actuators arranged in a rectangular array of 2×4 dots. The height of each point with respect to the cell surface is controlled by a bimorph that is stimulated with electrical signals to bend up or down. As a result, the actuators extend (rise) or contract (lower) to represent Braille characters. Several countries defined different standards for the horizontal and vertical distance between the dots, for the diameter of points, for the elevation of the piezoelectric actuator with respect to the surface of the cell and for other characteristics. We implemented an International Building Standard [46] compliant cell (2.5mm for horizontal and vertical dot-to-dot distance, with a dot diameter of 1.5mm - 1.6mm and a dot height ranging from 0.6mm to 0.9mm). As well as this kind of components relies on direct electrical control, it provides fast feedback to the user (the Braille cell has an activation time of $\sim$0.01ms and a lowering time of $\sim$0.15 seconds). The stiffness of the actuators is approximately 5N. Regarding the capabilities of the piezoelectric Braille cells in terms of information representation, as well as each cell consists of 8 dots, it is possible to encode up to 256 symbols, which is a number sufficiently high for encoding non-letter symbols, also.

Control layer

This layer consists of the processing unit (microprocessor) that manages the device operation. Its purpose is to translate physical stimuli (i.e., movement of the device over the surface and pressure of buttons) from the user into digital data to the computer and, vice versa, it converts binary data transmitted from the computer into output (vibration, and Braille information) tangible to the user. When the user

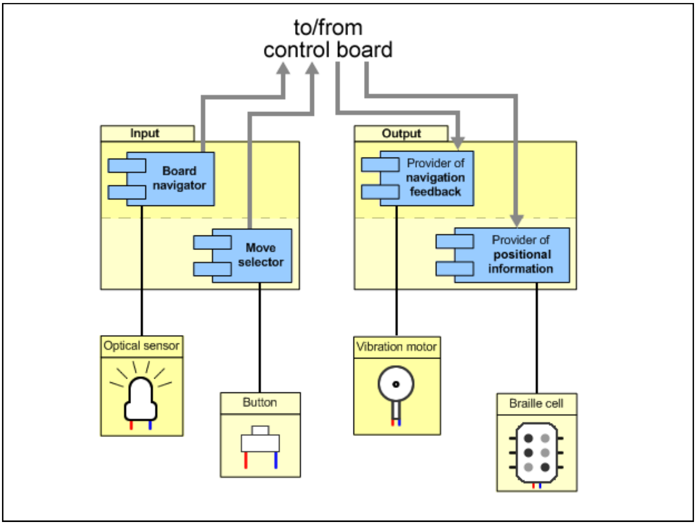


Figure 3.3: Architecture of the physical layer.

moves the device on a surface to navigate over a 2D display or when some content is selected by pressing the buttons, the microcontroller receives sequences of electrical inputs from the sensors located in the physical layer, converts them into logical messages and sends them to the communication layer; conversely, when data are received from the upper layer (i.e., the communication layer), the control layer converts them into tactile stimuli by triggering actuators (i.e., firing vibrotactile motors or changing the configuration of the Braille cell to display a symbol). In our prototype, we implemented both the control and communication layers using an open source cross-platform hardware tool for rapid prototype development, the Arduino Nano control board. This includes a 16 MHz ATmega168 microcontroller with 1Kbyte SRAM, 14 digital input/output pins and 6 analog inputs. Also, it supports Pulse Wave Modulation (PWM) on 6 output pins. Moreover, it has small form factor (1.85mm $\times$ 4.31mm) and it operates at 5V, powered by the on-board mini-USB connector. The firmware is programmed within the Processing environment in a C- or Java-like language.

The navigator acquires input about the spatial location of the device at a sampling frequency of 256Hz. The microcontroller processes the sampled CMOS signals incoming on pins from 23 to 26, and it converts them into pairs of bytes representing the actual coordinates of the device, which are then sent to the communication layer by raising an event containing the message $pos(x, y)$. This message is sent at a frequency according to the sampling rate and to the bandwidth of the connection. Also, each button-click raises a different event that is sent to the device driver via the communication layer. Different sequences of clicks generate command configurations that are interpreted by the device driver. For instance, buttons can be utilized in the same way as in a mouse, that is, button A (on the left side) is equivalent to left click, and it can start a selection or confirm an operation; conversely, button B (on the right side) can activate the contextual menu, if present, or cancel an operation.

The microcontroller in the control layer receives and executes commands from the transport layer via serial communication. Each incoming message consists of 2 bytes: the first one contains the command and the other one contains the parameter. Thus, up to 255 commands can be implemented. For example, we can trigger the provider of navigation feedback, the provider of content information, or to generate arbitrary time delays. The provider of navigation feedback is triggered by vibrating one or more motors with a given intensity. This is done by a digitally-generated analogue 8-bit PWM output (on pins 3, 5, 6, and 9): voltage amplitudes are represented by integers with four possible levels (zero, low, medium, high). As the prototype incorporates 4 motors, this information can be encoded with a byte (2 bits per each motor). Commands for the provider of content information command have the purpose of changing the configuration of the Braille cell by rising or lowering one or more piezoelectric actuators. The parameter of the command represents the state of each of the dots (0 for low, 1 for high) starting from the first row and the first column. This can be used to display characters using the standard Braille system described in Section 1.1.

Communication layer

This module consists of the electronic components that allow the device to transfer data from and to the computer and to interact with the network. The system is designed to support several types of wired or wireless connections. The control system natively implements a standard serial RS-232 port. Also, we added Universal Serial Bus (USB) support, which provides power supply to the device. Several wireless solutions based on Radio Frequency signals, such as Bluetooth and ZigBee can be used with an additional battery. Thanks to the modular approach of the design, changing the network interface does not require any special modification to the architecture of the device.

Control software

The device is controlled by a software driver enabling serial communication between the computer and the communication layer of the hardware. The device appears as a Human Interaction Device (HID) to the computer, and the input system mimics the behavior of a standard mouse. By doing this, a single peripheral is capable of interacting simultaneously with multiple software applications. Also, the system software can directly support dedicated applications over the Internet by establishing a local User Datagram Protocol (UDP) connection that allows exchanging streams of data and share messages with other systems in a client-server fashion.

3.3 Application scenario: enabling blind people to play chess

Our system is designed to be general purpose and to support interaction with multiple applications in a WIMP fashion. Nevertheless, in order to experiment the efficacy of our design, we focused on a very specific albeit entertaining task: playing board games, and particularly, chess. Indeed, this type of games are perfectly suited for sensory-impaired people because they challenge them in engaging activities based on reasoning, thus, they require players to concentrate, and they stimulate critical thinking and problem solving skills. Moreover, they involve players in a variety of different interaction situations. Given the importance of this type of activity, blind chess has been developed as a chess game in which sighted opponents play blindfolded; this has the purpose of helping people strengthen their ability concentrate.

We focused on chess because it is the most sophisticated among board games and, therefore, it is suitable for evaluating the cognitive load in highly-demanding tasks in terms of working memory, attention, and reasoning [63]. Also, it has several variants with many different rules and conditions of play. Moreover, as it involves handling time and turns (players have a limited period to make their move) and space (the chessboard is an ideal representation of an environment that contains obstacles having different characteristics); furthermore, it requires the player to spend an incredible effort in decision-making, and in both perceptual and cognitive tasks; moreover, it can be played with other opponents and, thus, it has a social component as well, though individuals can play against a computer. Additionally, it is not based on a specific language, and it has the same rules all over the world. Consequently, it is a fun way for keeping users busy, and to help them socialize, in person or via the Internet. In this section discusses a multipurpose system for board games that allows blind and deafblind people playing chess or other board games over a network. In particular, we describe a prototype of a special interactive haptic device to play online board games receiving feedback about the game on a dual tactile feedback.

Benefits and barriers of board games for blind people

The interest in chess among blind people has increased in many countries during years, and chess tournaments are hold by dedicated organizations such as the International Braille Chess Association [72]. However, blind people have no dedicated online chess association, likely due to the difficulty of using commonly adopted interfaces for online games. As a result, although IBCA has been recognized as a part of IBSA (International Blind Sportsmen Association), teams from IBCA have taken part in chess Olympiads only four times since 1994.

Several solutions have been developed to enable blind people to play chess, and they are based on software and on tools for in person play. The latter are utilized with almost the same rules as conventional chess. However, as playing chess involves visualizing the board for acquiring information during the gameplay and for organizing the next move and the strategy, when blind people play chess on a standard board, they explore it with their hands in order to understand its current configuration. This is the only between sighted and blind players: the latter require much more time because they need to sense the board with their hands from time to time. This limits the opportunities of socializing by playing chess: for a blind player it is difficult to find an opponent who would accept to play with someone who always needs to have his hands over the board. The system was designed so that the blind player is able to manipulate a tangible representation of the chessboard at any time, without interfering with the activity of any other user. Nevertheless, the ability to play a game, especially chess, depends on the availability of an interesting opponent, but for blind and deafblind people, this is not an easy problem to solve. In this regard, even if advances in technology could help them, there is an important issue that is still missing in current computer applications: all the available software is designed only for sighted people.

Particularly, computer networks have significantly influenced the diffusion of online games, and they aggregate players internationally. Unfortunately, usual interfaces for board games are based on the visual channel. For example, they require players to check their moves on a video display and to use standard pointing devices to interact with the board. Hence, they are not suitable for the people who have visual impairments. Dedicated chess software have been developed to be controlled with the keyboard alone, to avoid using the mouse. However, reducing functionalities is not the correct approach to visual impairment and, in general, to assistive technology, as discussed previously.

3.3.1 Current technology enabling the blind play board games

Usually, blind people play chess or any other similar game thanks to special boards where cells have distinctive patterns so they can be recognized by touching them. Pieces are designed to be easily distinguishable at touch, and in addition they can be steadily stuck in

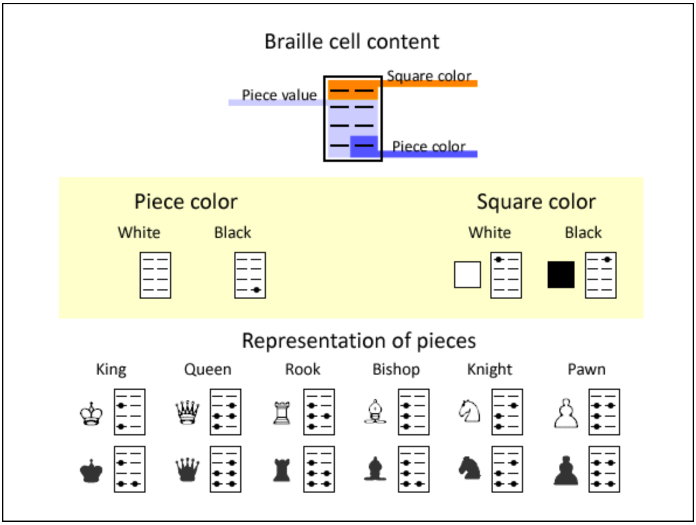


Figure 3.4: Configuration of the Braille cell.

the center of a square to avoid that touching them alters the game configuration. Such a checker and chess set costs about 30$ [71]. Additional improvements [70] involve magnets under the pieces and a rigid metallic sheet beneath the playing surface, which enhances the stability of the game configuration when a blind individual "reads" the board by touching it. However, these special boards are not easily interfaced with computer systems. Conversely, the available software interfaces for remote games are designed only for sighted people, so that players interact using a mouse and a standard screen. Therefore, blind people should be provided with some extra tool providing a non-visual representation of the board. One possibility is to replace the screen with a tactile interface controlled by an electromechanical device, providing information about the actual configuration of the board and being capable to refresh it at each turn. Even though this could be implemented with an ad hoc electro-mechanical board, such a solution would not be efficient in terms of cost and complexity.

3.3.2 Interpreting standard games using novel devices

As mentioned earlier in this section, rendering current software accessible to the blind does not necessarily involve rewriting applications so that they can be utilized with the keyboard alone. This approach is extremely inefficient, as it leads to an increasing fragmentation of tools each proposing a fix to a specific situation. Instead, innovative hardware and software systems should be able to translate current applications into a form that is accessible to users depending on their conditions. By doing this, it is possible to reuse current software, and to focus on the accessibility on their features, alone.

Differently from other systems that represent data in a sequential fashion using auditory feedback, information is presented on the tactile channel: thus, visually impaired players are able to freely navigate over the board and to access information about the squares as if they were touching real pieces. Moreover, it supports different directions of movement over the board to obtain a mouse-like interaction during the game. As the device utilizes bimodal tactile feedback, it is able to provide users with spatial awareness. Consequently, blind players can identify the placement of pieces over the board. Simultaneously, this renders homogeneous the game dynamics for multiple types of users, sighted, blind, and deafblind. We believe that filling the gap in the availability of board games over the network for visually impaired people represents an original and significant step forward towards inclusion of sensory-impaired people. This particular approach to the design of assistive technology enables different types of players: sighted, blind and deafblind. As a result, although different players are able to play with the same piece of software, they receive different feedback depending on their condition; accordingly, the system will signal opponents' moves using different channels for feedback. For instance, blind players will receive tactile and auditory feedback whenever they move the device over the board, and they will get a stronger signal when they move the cursor outside of the border, whereas the sighted player will have visual feedback regarding the validity of their moves and the game status, only. As this is independent from the structure of the software, because it is realized by the wrapper, whenever players start a new game, feedback is automatically set to fit their particular needs, being transparent to the user.

Operating the game with the device

In our implementation, actuators inform the user about the different types of information such as game status (the configuration of the board and the status of the game), time (elapsed and remaining), events, and system responses, by exploiting the features of mechanoreceptor to deliver the appropriate feedback strategy. The blind user can select the starting position of a move by clicking button A (start-square selection button) of the device. Then, the piece can be released on the final position by clicking once button B (end-square selection button). Alternatively, users can click button A again to choose another piece from a (non-empty) square of the board. By simultaneously clicking both buttons, the navigator is reset to the default position (center of the chessboard). Indeed this interaction mode can be employed for playing other board games, such as standard or non-standard types of checkers (e.g., Shogi, which is played on a 9×9 chessboard).

Our technology simulates existing Braille chessboards, where tactile information allows recognizing checkers and pieces. Particularly, pieces can be represented using different configurations of the Braille cell. Figure 3.4 reports an example for chess, using the international code of Braille chess. The last row of the Braille cell is used to represent the color of the piece, whereas the dots in the first row display the color of the square. In our experiment, we employed a suboptimal configuration of Braille dots in terms of information coding. This is because our primary objective was providing non-trained subjects with means to easily decode information represented in Braille.

3.3.3 Evaluation of bimodal and bidimensional tactile feedback and output

Playing chess is a sophisticated task, comparable in terms of complexity to interacting with a WIMP system. Consequently, it is suitable for evaluating the dynamics of user experience that occur when playing using an innovative device. Also, as chess is a widespread game, it is eases the explanation of the experimental tasks. In this study, our objective was to evaluate the efficacy of the device as an interface for providing the blind and the deafblind with means of utilizing interfaces based on the WIMP paradigm. To this end, we designed an experiment that exploits the game dynamics of chess to evaluate the ability of participants to navigate into a bidimensional environment, to recognize objects, and to consistently manipulate them. Indeed, the experiment simultaneously evaluates the feasibility of delivering concurrent tactile output based on two different types of stimuli.

Objectives

In order to evaluate the design of the system, the effectiveness of the feedback strategy, and the feasibility of using the proposed device for enabling interaction in WIMP interfaces, we conducted a controlled experiment focusing on the navigator, on the move selector, and on the provider of navigation feedback. Our aim was to evaluate the following hypotheses:

1. users are able to recognize the vibrotactile pattern or the Braille configuration associated with the current cell;
2. users are able to identify the position of the current cell within the chessboard by sensing transition between cells having different vibrotactile patterns;
3. the actual configuration of the environment is physically perceivable and the user is able to navigate over the board without any cognitive overload;
4. any manipulation that occurs is physically perceivable by the user at any time;
5. the effects that any manipulations have on the environment are clearly perceivable by the user.

Experimental tasks

Subjects were asked to complete three tasks: task I focused on points 1 and 2, Task II was related to point 3, and Task III regarded points 4 and 5. The experimental tasks were designed for the chess scenario, as our objective was to simultaneously evaluate the use of bimodal and bidimensional feedback in a tangible application.

Task I - Position recognition

This task required participants to use both the ability to recognize tactile and vibrotactile patterns, and that of accurately navigating over the board. To this end, the task was divided into two heterogeneous subtasks. In subtask 1, subjects were asked to recognize the color of the current square S (i.e., $black$ or $white$), by distinguishing the vibrotactile pattern associated with it or by sensing the configuration of the Braille actuator. Squares are represented using different vibration frequencies and amplitudes. Specifically, white squares are represented by a frequency of 120Hz (corresponding to an intensity of 0.45g), and black squares have higher vibration intensity and frequency (0.60g and 160Hz, respectively). In the second subtask, subjects were asked to explore the board and to identify their initial position (the location of the starting square) by opportunistically navigating across the board using the least number of moves. Subtask 1 and 2 were realized in sequence as they are similar in regard to reporting (see Experimental protocol). The starting position S of the user within the board was randomly chosen at the beginning of each trial. The experiment was divided into 3 runs consisting of 10 trials each. The board was not populated with any pieces: on the one hand, this facilitates navigating; on the other hand, it makes it more difficult to recognize the position of the initial cell as there are no reference points relative to the standard starting configuration of the chess board. The trial timeout was set to 5 seconds. Subjects were allowed to rest for 2 minutes after each group of runs. The inter-trial interval was 2 seconds.

Task II - Piece recognition

This task required subjects' ability in recognizing the configuration of the Braille display. To this end, Task II was divided into two subtasks. In subtask 1, subjects were required to identify the nearest piece with respect to the current position. At the beginning of each trial, the configuration of the board changed, and subjects were randomly positioned on an initial cell S within the board. Thus, they had to finely explore the surrounding cells to identify the nearest occupied square D (destination square). Then, in subtask 2, subjects were required to identify the piece occupying the destination square. The experiment was divided into 3 runs consisting of 10 trials each. The color and the value of the piece were chosen at random at each trial. The trial timeout was set to 5 seconds. Subjects were allowed to rest for 2 minutes after each group of runs. The inter-trial interval was 2 seconds. The inter-run interval was 30 seconds. The average distance was about 3 squares long. To simulate a real gameplay situation, the chessboard was occupied by other pieces as it would be in a standard game. The chessboard configuration was generated so that the starting square S was always empty.

Task III - Guided move

The objective of this task was to evaluate the performance of the device in supporting people to play chess. This is a sophisticated operation for the blind, as they have to simultaneously manage multiple types of information, that is, position within the board, configuration of the board, and next move. As each of these actions has some degree of complexity, the aim of Task III was to evaluate the feasibility of using our device in playing chess, and to assess the cognitive overhead to the user. Thus, participants were involved in a real gameplay situation in which they had to realize complex interaction with the board and with the pieces. They were required to programmatically move a piece from one square to another according to the standard move configurations of chess. Figure 3.5 shows the experimental setup.

At the beginning of each trial, the cursor position was set at the center of the board (S) and the move was announced with a message indicating in sequence: the initial position (I), the content of the square C, and the final position (F) of the move (e.g., H1, white rook, H8). Participants were asked to move the device until they reached the starting square I (e.g., H1) and, if the square contained the piece C mentioned at the beginning of the task (e.g., white rook), they were required to pick it by pressing the left button, and to drag and drop it to the defined location F using the right button (e.g., H8) if empty (legal move). They were asked to discard the move (by clicking both buttons of the device) if the start square was empty (illegal move A) or occupied by a piece different from what announced in C (illegal move B), or if the end square was occupied by a piece having the same color as that in S (illegal move C). The color and the value of the piece, as well as the start and the end squares, were chosen at random at each trial. The trial timeout was set with respect to the distance between the start and the end location (1 second per square plus 2 seconds from the beginning of the trial). As a result, for the longest path, involving a movement over 28 squares, the timeout was set as 28 seconds. Subjects were allowed to rest for 2 minutes after each group of runs. The experiment was divided into 3 groups of 3 runs each. Runs consisted of 5 trials (task executions). The inter-trial interval was 2 seconds. The inter-run interval was 30 seconds. The average path was 4.5 squares long. To simulate a real gameplay situation, the chessboard was occupied by other pieces as it would be in a standard game. The chessboard configuration was generated so that the requested move is always consistent, and it was refreshed at the beginning of each trial.

Experimental setup

The system device was the only interface to the user. As Task III is extremely complex for a non-Braille reader, the provider of positional information was substituted by auditory feedback rendered by audio speakers, and consisting in messages spelling the position of the square as well as its content (e.g., "A4, black rook"). Subjects were seated in front of a computer equipped with the gaming software, and they were blindfolded. The experiment was supervised by a technician. Experimental data from the device were logged on the same computer where the gaming software was. We did not extensively evaluate the provider of positional information because we could not get access to Braille-trained users, such as blind or deafblind people. As a replacement, appropriate feedback about the content of the square was provided. The total duration of the experiment was about 60 minutes, including training. At the end, participants received a questionnaire. This had the purpose of measuring participants' perception of the Tasks, which allowed us to qualitatively evaluate cognitive overload, in addition to quantitative data recorded during the experiment. Also, this allowed us to assess if the system was able to engage subjects and provide them with an entertainment game experience.

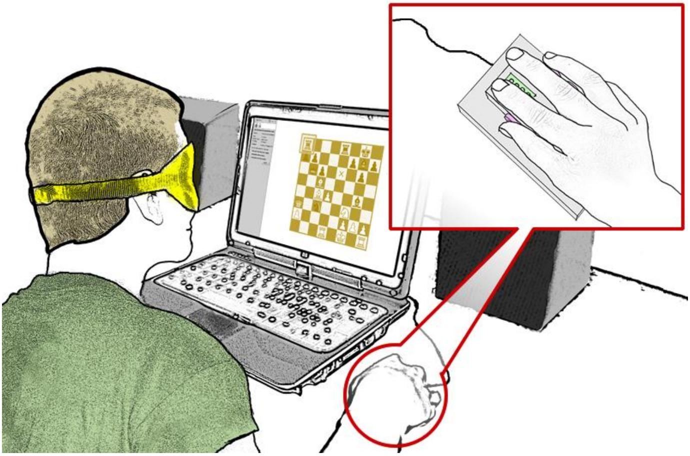


Figure 3.5: Experimental setup.

Participants

We recruited 14 volunteer participants, 6 female (S2, S3, S5, S9, S11, and S12) and 8 male. All had a normal sight, hearing and tactile sensitivity (we did not measure the different acuities). All subjects were right-handed as assessed by the Edinburgh inventory [55]. Subjects ranged in age from 15 to 61 years with an average of 31. All use computers on a daily basis (1.5-8 hours usage per day). All were novice for the system; 10 of them are able to play chess, the others (S2, S7, S8, and S13) have no experience of the logic of the game. Subjects were not paid; they were recruited from another experimental study, which was already rewarded.

Results and discussion

In Task I and II, we analyzed the Success-to-Failure ratio (SF), the Time required to complete the Move (TM), and the Path Accuracy (PA). The former is the average number of correct moves with respect to the incorrect ones. WTM is the interval between the beginning of the trial and the accomplishment of the move. We intend PA as inversely proportional to the deviation from the minimum length of the path. Figure 3.6 show the accuracy of experimental subjects. In the beginning of the task (trials from 1 to 10), we utilized different intensities to encode the color of squares. Then, we modified the pattern to include rhythm: we associated prolonged vibration at low intensity and frequency (0.45g and 120Hz, respectively) to white squares and short vibration sequences at 150Hz (0.65g) each lasting 100 millisecond, to black squares.

As the main variables analyzed in Task III, we took into consideration the Success-to-Failure ratio (SF), the Weighted Time required to complete the Move (WTM), the Path Accuracy (PA) and the Move Attention (MA). The former is the average number of correct moves with respect to the incorrect ones. WTM is the interval between the beginning of the trial and the accomplishment of the move. We intend PA as inversely proportional to the deviation from the minimum length of the path. MA refers to the ability to detect an illegal move and to discard it before the timeout. S = Sex, C = Chess player (Y for yes and N for no), SF = average Success to Failure, WTM = average Weighted Time required to complete the Move (for a 5 square long move), MA = average Move Attention, PA = average Path Accuracy.

The Success-to-Fail ratio, having an average of $86.14\% \pm 5.52\%$ indicates that all subjects were able to understand the task and to accomplish before the timeout.

Subjects were able to recognize when they were asked to per-

Table 3.1: Performances of experimental subjects in tasks I and II.

Subject	**Pattern recog.**	**Place recog.**	**Path acc.**	**Path acc.**
S_1	100.00	100.00	46.14	97.87
S_2	86.67	83.33	71.75	93.56
S_3	100.00	80.00	72.78	90.72
S_4	76.67	93.33	95.35	95.58
S_5	86.67	83.33	67.81	87.76
S_6	86.67	90.00	58.20	93.91
S_7	66.67	80.00	94.95	99.54
S_8	100.00	100.00	59.34	91.31
S_9	76.67	76.67	46.57	80.31
S_{10}	86.67	73.33	72.25	96.14
S_{11}	90.00	83.33	67.01	86.40
S_{12}	73.33	73.33	81.12	95.04
S_{13}	96.67	83.33	45.44	100.00
S_{14}	100.00	100.00	62.50	99.83

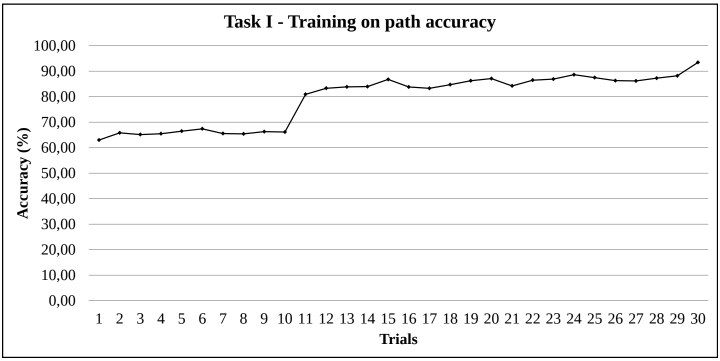


Figure 3.6: Subjects' performances over time.

form an illegal move, and they reported it quickly. As a result, they achieved performance in terms of Move Attention always higher than 94%, with an average MA of 96.1% $\pm$1.01%. This also means that they were able to recognize the content of the squares and that tactile feedback about navigational information does not prevent the user to focus on cognitive tasks. Users were not precise during the movement across the chessboard, resulting in lower Path Accuracy performance with an average value of 80.03% $\pm$3.86%. However, path accuracy was determined with respect to an ideal, straight path, which players rarely follow in real chess. Subject spent an average of 7780 milliseconds to complete a 5 squares long move. However, this value is subject to a training effect which persists with time. Although there is no difference in PA, MA and SF between the runs, there is a decreasing trend in the WTM. The difference is more significant between the

Table 3.2: Performances of experimental subjects in Task III.

Subject	Age	S	C	SF(%)	WTM (msec)	MA (%)	PA (%)
S1	25	M	Y	94	7135	96.60	82.03
S2	15	F	N	86	7338	94.92	77.58
S3	54	F	Y	84	8272	96.12	82.74
S4	61	M	Y	72	8960	95.91	85.1
S5	23	F	Y	84	7592	94.80	82.15
S6	26	M	Y	94	6985	97.91	85.55
S7	30	M	N	84	7516	95.61	76.57
S8	33	M	N	86	8479	97.81	83.94
S9	42	F	Y	82	7642	95.80	74.21
S10	18	M	Y	88	6828	95.99	77.41
S11	21	F	Y	90	6472	97.03	82.19
S12	35	F	Y	90	8129	96.62	80.06
S13	38	M	N	84	8809	94.74	75.26
S14	43	M	Y	88	8757	95.55	75.57

first and the third group of runs (p=0.07). Also, the evolution of the curve between the trials of the same group of runs indicates that users become more responsive when they are longer exposed to the system. Our findings suggest that the ability to play chess provides the users with an advantage which is relatively small, confirmed by a very low correlation factor. Conversely, the results show a significant inter-group difference with respect to age. Participants below 30 achieved better performance, while higher values of WTM were found for older subjects. This indicates that age may have an influence on the duration of training required, confirmed by a negative correlation factor of -0.64. The difference between the groups may be due to the shorter learning curve of younger subjects, who are more familiar with tactile stimulation. Although subjects' questionnaires reported that the task

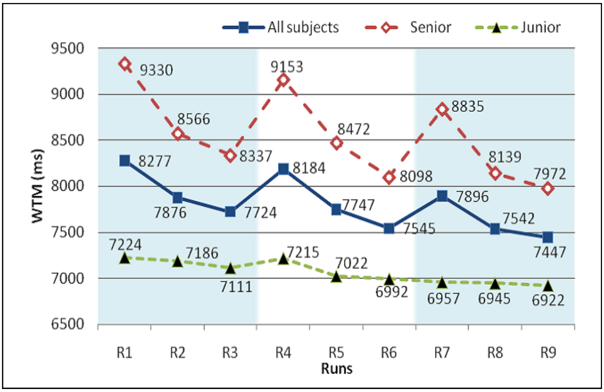


Figure 3.7: Trend of the Weighted Time to Complete a Move over time.

was challenging, data show no attenuation of performances due to habituation to prolonged tactile stimuli, or fatigue in using the device. Strong negative correlation (-0.78) was found between the subjects age' the time they required to accomplish the task. We developed a practical and low-cost system architecture which enables remote board game playing over a network for visually impaired people. Our solution is cost attractive and easy to implement. Moreover, it can be combined with other feedback techniques and is simple to use even for non-impaired people. We also discussed several feasibility issues showing that the practical implementation of the proposed solution is easy and cheap.

Chapter 4

dbGlove: a wearable device for pervasive interaction

4.1 A wearable interactive glove based on the Malossi alphabet

As explained in Section 1.1 the Malossi alphabet enables individuals to achieve touch-based communication thanks to a form of on-body signing based on a tactile code in which phalanxes represent letters. As each of the distal and the proximal phalanxes is associated with two letters, two pressure cues are employed to discriminate between touched letters and pinched letters. Individuals communicate in turns: the sender utilizes the left palm of the receiver as a typewriter, in order to transmit a message. By switching their roles, individuals can achieve full-duplex interaction. As the Malossi alphabet is extremely easy to learn and understand, it is among the preferred education methods for the deafblind. Usually, children who are deafblind born receive the Malossi alphabet as one of the simplest form of alphabetization. Also, it is taught to people who become deafblind later in their life. Moreover, people who learn the Malossi alphabet continue using it for interpersonal communication, in addition to the Braille system, which is mainly employed for reading books and for accessing information available in digital formats.

Attempts in implementing the Malossi alphabet by means of technological devices have been made since 1970. However, there is poor documentation about prior research, as research was abandoned due to the inadequateness of technology, which could not support this application. In 2004, we started envisioning a device that would reproduce interaction with the Malossi method using miniaturized sensors and actuators. The main difference between our proposed system and the research going on in the last decades is in that our device incorporates electromechanical components into a wearable interface. Instead, the state of the art technology utilized complex external systems with moving elements that were supposed to capture and deliver touch and pinch cues. However, the resulting interfaces were not natural at all, and they were abandoned after a short adoption time, due to their low acceptability, and to their poor usability. Conversely, we aimed at realizing a natural interface that could be appropriate for accompanying users in their everyday tasks (e.g., use public transportation, or move independently in a care center).

Specifically, our objective is to provide the deafblind with means for achieving some form of interaction with information and with others, especially when assistants and interpreters are not available. As caregivers are a scarce and expensive resource, the aim of our research was to help deafblind people in being independent from a human assistant in communicating and in accessing information. This can be realized with static interfaces. However, as many sensory-impaired people move and live independently, our objective was to develop a wearable device that could be utilized all day long, regardless of the interaction context.

As a result, we designed a glove that support the blind and the deafblind in achieving autonomous, pc-mediated communication and access to information. The Malossi method exploits the palm of the hand as a communication device by dividing phalanxes into keys. These, in turn, are associated to letters, as in a normal computer keyboard shaped as a hand. There are two types of keystroke: pressure and pinch. The former basically reproduce standard interaction with a keyboard. On the other hand, an interactive device can encode messages in the Malossi alphabet by associating them to stimuli that simulate touch and pinch cues on the palm of the hand. This has no equivalent in standard computer peripherals: input actions that have similar features to multi-touch tablets have no output counterpart.

In our early research, we adopted a tinkering approach to the design of the device, and we developed an initial prototype consisting of a PVC surface incorporating buttons. Although this strategy led to an effective system for acquiring input, it was inadequate for providing the deafblind with messages. Moreover, as the deafblind are able to use other input systems, but they have no dedicated output device, our solution did not fit the real need of this category of users. As an input only device, our device could support some tasks, and it could be employed for training assistants and relatives of deafblind people in the use of the Malossi alphabet. However, it was not suitable for providing the deafblind with the desired level of interaction. Nevertheless, the major challenge in completely implementing the Malossi method into an interactive device enabling bidirectional communication is output. We evaluated several systems that are suitable for conveying tactile stimuli, and specifically pinch cues, including motor-driven restraining strings, electric shocks, piezoelectric actuators, and artificial muscle fibers. Unfortunately, the majority of the technology is inappropriate, expensive, or it has physical features that do not fit characteristics of the Malossi alphabet in terms of interaction.

Research on vibrotactile perception showed that vibration can stimulate in a way that can induce a large set of sensations ranging from soft displacement to painful cues, depending on the waveform, and on its intensity and frequency. Although we evaluated the possibility of incorporating vibrotactile actuators, in the last decade, they were the most cumbersome part of a mobile phone: almost the same size as the antenna. Conversely, as discussed in Section 2.1, recently, their form factor is much lower. New miniaturized motors, similar to those employed in the device described in Section 3.1 can be utilized to provide individuals with sophisticated feedback. As a result, we designed an output system that exploits the features of vibrotactile stimuli for simulating touch and pinch cues that are able to provide the receiver with means for decoding the letter associated with the stimulus.

In this section, we describe the design and development of dbGLOVE, an interactive glove based on the Malossi alphabet. dbGLOVE provides blind and deafblind people with bidirectional interaction with the computer and computer-mediated communication with others. The deafblind can wear the device on the left hand, and they can type messages on their own palm, as on a keyboard. We incorporated the array of sensors and actuators that compose the input and the output subsystem into a pad that can be worn on the palm of left hand as if it was a glove, and connected to a computer. By doing this, the deafblind can type on their own hand, instead of that of the receiver. Input is acquired and processed as a command to the PC (e.g., *open application*), or as a message to be displayed to another individual (e.g., *I want to eat*). Also, dbGLOVE includes a tactile monitor. So, the deafblind can receive messages in the form of tactile stimulations, as if someone was typing on their palm. Responses can be received by the user in the form of vibrotactile stimulation at different intensity and frequency that simulate touch and pinch cues, as if someone was typing on their hand. As a result, the device is able to provide the user with bidirectional communication.

Moreover, the system can be attached to a smartphone mounted on the wrist in order to activate a set of functionalities, such as Internet connectivity, GPS-assisted navigation, text-to-speech translation for non-Malossi speakers. By doing this, the device is wearable, portable, and it enables pervasive interaction in a variety of scenarios. For instance, the deafblind can type their request using the device, and it can be displayed on the screen of the smartphone, so that a sighted non-Malossi speaker is able to read the message; also, the reply can be acquired using speech recognition algorithms, and translated into a tactile form that can be received by the deafblind. In addition, users can be assisted in using public transportation and in moving in the environment thanks to tactile stimuli presenting the output of directions given by a GPS navigator. Moreover, dbGLOVE can provide deafblind people with means for social inclusion, reading documents, sending e-mail, web browsing, chatting. Among the advantages with respect to the state of the art, dbGLOVE is easier to learn and cheaper than Braille displays.

Evaluation of germane cognitive load

In order to evaluate the feasibility of a system based on touch or pinch cues in different areas of the hand representing alphabetic characters, we analyzed the frequency of letters in the Italian and English languages. According to our preliminary assessment, the most frequent letters are located in the areas shown in Figure , which represents the probabilities over the different phalanxes.

Table 4.5 shows that the areas of the hand are significantly unbalanced, with the distal and proximal phalanxes having average probability (Italian 8.45%, English 8.02%) compared to the intermediate phalanxes (Italian 2.57%, English 3.30%). As a consequence, distal and proximal phalanxes would receive a larger number of stimulations with respect to the intermediate phalanxes (see Figure 4.1).

Table 4.3 shows the frequency (F) for each of the areas where combined letters are, calculated as $P(l_1)UP(l_2)$. The distance shows the differential in probability between two letters in the same area, i.e., $|P(l_1) - P(l_2)|$. The average distances are 0.60 and 0.58 for Italian and English, respectively. Consequently, error probabilities can be calculated as $1/D$, are 0.40 and 0.42, showing that the Malossi configuration for English is slightly less performing as that of Italian. However, the weighted error probability (WEP), calculated as $F(P_i) * EP(P_i)$ shows values that are almost similar in both languages (English is 0.004 worse).

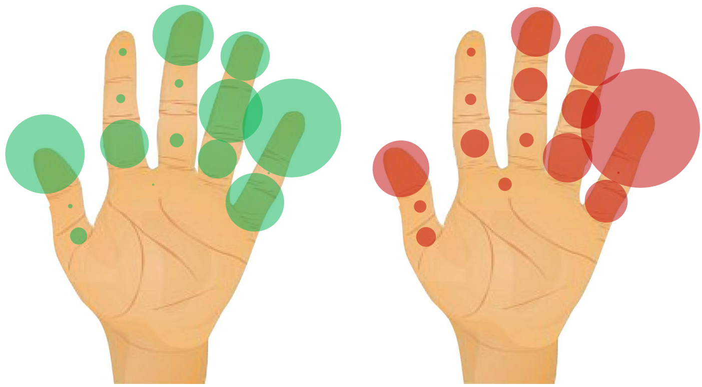


Figure 4.1: Correspondence between error probabilities in the areas of the hand.

4.1.1 Hardware and software design

The system architecture was designed in order to be consistent with the modular approach for interactive devices similar to that described in Section 3.1. It consists of the *physical*, the *control* and the *communication* layers. They are three independent logical layers, connected to one another by means of interfaces for data exchange. The physical layer has the purpose of sending messages using vibrotactile actuators that simulate touch and pinch cues on different areas

Table 4.1: Most frequent letters in the Italian and English alphabets.

letter	**Italian**	**English**
a	11.740%	8.167%
b	0.920%	1.492%
c	4.500%	2.782%
d	3.730%	4.253%
e	11.790%	12.702%
f	0.950%	2.228%
g	1.640%	2.015%
h	1.540%	6.094%
i	11.280%	6.966%
j	0.000%	0.153%
k	0.000%	0.747%
l	6.510%	4.025%
m	2.510%	2.406%
n	6.880%	6.749%
o	9.830%	7.507%
p	3.050%	1.929%
q	0.510%	0.095%
r	6.370%	5.987%
s	4.980%	6.327%
t	5.620%	9.056%
u	3.010%	2.758%
v	2.100%	1.037%
w	0.000%	2.365%
x	0.000%	0.150%
y	0.000%	1.974%
z	0.490%	0.074%

Table 4.2: Relative probability of letters per areas.

letter	**Italian**	**English**
$P_{11}(a+p)$	14.790	10.096
$P_{21}(b+q)$	1.430	1.587
$P_{31}(c+r)$	10.870	8.769
$P_{41}(d+s)$	8.710	10.580
$P_{51}(e+t)$	17.410	21.758
$P_{12}(f)$	0.950	2.228
$P_{22}(g)$	1.640	2.015
$P_{32}(h)$	1.540	6.094
$P_{42}(i)$	11.280	6.966
$P_{52}(j)$	0.000	0.153
$P_{52}(k+u)$	3.010	3.505
$P_{52}(l+v)$	8.610	5.062
$P_{52}(m+x)$	2.510	2.556
$P_{52}(n+y)$	6.880	8.723
$P_{52}(o+z)$	10.320	7.581
$P_0(w)$	0.000	2.365

Table 4.3: Relative probability of letters per areas (values in percentages).

letter	**Italian**	**English**	
$P_{11}(a) = 79.38$	$P_{11}(p) = 20.62$	$P_{11}(a) = 80.89$	$P_{11}(p) = 19.11$
$P_1(b) = 64.34$	$P_{11}(q) = 35.66$	$P_1(b) = 94.01$	$P_{11}(q) = 5.99$
$P_{11}(c) = 41.40$	$P_{11}(r) = 58.60$	$P_{11}(c) = 31.73$	$P_{11}(r) = 68.27$
$P_{11}(d) = 42.82$	$P_{11}(s) = 57.18$	$P_{11}(d) = 40.20$	$P_{11}(s) = 59.80$
$P_{11}(e) = 67.72$	$P_{11}(t) = 32.28$	$P_{11}(e) = 58.38$	$P_{11}(t) = 41.62$
$P_{11}(k) = 0.00$	$P_{11}(u) = 100.00$	$P_{11}(k) = 21.31$	$P_{11}(u) = 78.69$
$P_{11}(l) = 75.61$	$P_{11}(v) = 24.39$	$P_{11}(l) = 79.51$	$P_{11}(v) = 20.49$
$P_{11}(m) = 100.00$	$P_{11}(x) = 0.00$	$P_{11}(m) = 94.13$	$P_{11}(x) = 5.87$
$P_{11}(n) = 100.00$	$P_{11}(y) = 0.00$	$P_{11}(n) = 77.37$	$P_{11}(y) = 22.63$
$P_{11}(o) = 95.25$	$P_{11}(z) = 4.75$	$P_{11}(o) = 99.02$	$P_{11}(z) = 0.98$

Table 4.4: Error probabilities.

P	F^{IT}	F^{EN}	D^{IT}	D^{EN}	EP^{IT}	EP^{EN}
$P_{11}(a,p)$	0.15	0.10	0.59	0.62	0.41	0.38
$P_{11}(b,q)$	0.01	0.02	0.29	0.88	0.71	0.12
$P_{11}(c,r)$	0.11	0.09	0.17	0.37	0.83	0.63
$P_{11}(d,s)$	0.09	0.11	0.14	0.20	0.86	0.80
$P_{11}(e,t)$	0.17	0.22	0.35	0.17	0.65	0.83
$P_{11}(k,u)$	0.03	0.04	1.00	0.57	0.00	0.43
$P_{11}(l,v)$	0.09	0.05	0.51	0.59	0.49	0.41
$P_{11}(m,x)$	0.03	0.03	1.00	0.88	0.00	0.12
$P_{11}(n,y)$	0.07	0.09	1.00	0.55	0.00	0.45
$P_{11}(o,z)$	0.10	0.08	0.91	0.98	0.09	0.02

Table 4.5: Weighted error probabilities.

P	WEP^{IT}	WEP^{EN}
$P_{11}(a,p)$	0.06	0.04
$P_{11}(b,q)$	0.01	0.00
$P_{11}(c,r)$	0.09	0.06
$P_{11}(d,s)$	0.07	0.09
$P_{11}(e,t)$	0.11	0.18
$P_{11}(k,u)$	0.00	0.01
$P_{11}(l,v)$	0.04	0.02
$P_{11}(m,x)$	0.00	0.00
$P_{11}(n,y)$	0.00	0.04
$P_{11}(o,z)$	0.01	0.00

of the palm of the hand, in order to implement the output function; also, it receives messages from the user, who presses sensible areas equipped with touch sensors. Moreover, the physical layer can incorporate other types of sensors that allow acquiring input from the user in addition to touch (e.g., force sensing resistors). The physical layer directly interacts with the user, and it exchanges messages to and from the user with the control layer. This, in turn, is responsible for managing the input and output functions, and for governing the operation of the device. The control layer exchanges data with the communication layer, which has the only purpose of transmitting information over the network. The communication layer directly communicates with a computer, or with a smartphone. All the layers are physically assembled into one printed circuit board.

The physical layer is enclosed within a pad consisting of a material made of a mixture of plastics and textiles. The former render the device highly resistant and durable, while the latter have the purpose of increasing skin transpiration, and it renders wearing the device more comfortable. The pad is shaped in a way that enables to autonomously wear the device using elastic straps or bendable plastic wings. During the prototyping phase, several pad models were designed and experimented in order to define a model that can be utilized by the deafblind. Vibrotactile actuators are in the lower layer of the pad, so that they are in close contact with user's skin. They are embedded into cavities within the pad, so that they can be independently fired without causing the entire device to propagate vibrations. Touch sensors are assembled in the upper layer of the pad, so that they can easily pressed and pinched. Particular attention was dedicated to ensuring adequate distance between sensors, so that each of them can be touched without interfering with others. Sensors and actuators are located on top of one another, so that they are placed in the same areas. Moreover, by doing this, actuators provide a base for sensors.

The control and the communication layers are located in a wristband that is connected to the physical layer. As they incorporate bigger components, such as the battery, and connectors, this is the most convenient position to avoid cumbersome elements on the glove. The device was designed to fit the palm of the left hand of users: its size varies accordingly to that of users' hands. Future work will describe how the pad is customized to accommodate different hand shapes and sizes. The device is designed to be connected to a smartphone that plays the role of an application platform. In addition to control the operation of the device, the features of the smartphone can be utilized to add more sensing capabilities with respect to those of the physical layer.

The control and the communication layers are the most expensive part of the device, as they consist of units for data transmission and device control. Conversely, the pad is designed to be replaced after some time. All the components are relatively inexpensive and easier to find on the market. The overall cost for a complete device (complete prototype) can be estimated as 140 U.S.$ (Bill Of Material). This leads to a consumer price of about 300 U.S.$. In addition to introducing a novel approach with respect to state-of-the-art devices, our device has a price ratio of about 1:10, compared to the least expensive Braille displays on the market. Similarly to the device described in Section 3.1, all the specifications have been released to the open source community, and several users already contributed to the project by submitting new design models, as described in Section 3.1. Also, as sensors and actuators can be found on the market, and given the simplicity of the hardware design, the device can easily be built in a do-it-yourself fashion.

Physical layer

The physical layer of the device consists of two subcomponents: the input and the output system. They operate independently, to enable concurrency between input and output. This is crucial for interaction, because users should be alerted on events occurring while they are typing some input on the device. Moreover, the physical layer contains the circuits connecting the all the components of the device that are required for exchanging data with the other layers.

Letter sensors
The input component consists of a set of sensors based on capacitive technology, or on electromechanical components, depending on the implementation. The number of sensors may vary depending on how the device is implemented. The general design consists of 16 active areas each incorporating one or two sensors. In our prototype, we utilized 26 sensors for representing letters, plus 4 sensors for additional commands and features. However, these can be reduced to 16 by introducing some processing based on algorithms for smart input. In our prototype, we employed low-profile tactile switches for implementing letter sensors. We utilized components similar to those employed in the device described in Section 3.1: 26 micro-tactile switches having a size of 0.5cm $\times$ 0.5cm $\times$ 0.3cm were introduced. In addition to input sensors providing mechanical tactile feedback, in our experiments we utilized capacitive touch sensors. Our prototype incorporates 4 additional switches for special menu functions. However, extra switches can be added to provide users with more control features.

Compatibility with Braille
In order to render the device compatible with Braille displays, sensitive areas can include embossed dots representing letters in the Braille alphabet. They can be realized in conductive or plastic material, depending on the technology employed for input. As a result, this would help Braille-trained individuals in learning to use dbGLOVE, and vice versa, it will render our device a training tool for learning Braille.

Force sensors and other input
In addition to sensors for detecting simple input, such as key presses, other types of components can be incorporated in the device to add features and capabilities. For instance, flexion sensors can be implemented to modulate output so that vibrotactile pattern can reproduce

the shape of objects, as discussed later. From an architectural point of view, each input functionality represents a sub-layer of the input component. This renders the device extremely versatile and customizable depending on the application scenario, and on users' needs.

Vibrotactile actuators

Moreover, the physical layer contains actuators for delivering vibrotactile stimuli. The device incorporates 16 vibrotactile actuators. In our prototype, we incorporated the same Eccentric Rotating Mass Actuators (ERMs) from Precision Microdrives, as those we employed for the experimental study in 2.1, because of their great performance and efficiency.

The actuators have a diameter of 8mm and they are 3.4 mm long. Thus, they are perfectly suitable for being applied into arrays to be placed on the palm of the hand, as demonstrated before. Their activation voltage ranges from 1.5V to 3.3V (the operation voltage of the device), and their operating current is 100mA. Due to their current drain, we implemented a 2000mAh LiPo battery, which is able to provide enough power for their operation. Their amplitude is linearly increasing with vibration frequency, and ranging from 0.20g to 0.80g. This, in turn, ranges from 90Hz to 200Hz. As we already ran experiments on vibrotactile feedback using this type of actuators, we were more familiar with implementing them in our prototype. However, they can be replaced by other types of vibration actuators, without changing the architecture of the system. Also, the calibration routine discussed in Section 2.1 can be applied to other types of vibration motors as well. They were positioned one per phalanx, at a minimum distance of 0.5 cm from one another. This is consistent with the literature about vibrotactile perception, and with the studies detailed previously in this dissertation.

Control layer

This layer consists of the processing unit (microprocessor) that is responsible for governing the device operation. Its purpose is to convert physical stimuli (i.e., pressure at different intensities in areas of the hand) from the user into digital data to the computer. Also it converts binary sequences transmitted from the computer into tangible output (vibration stimuli simulating touch and pinch cues) to the user. When the user touches the sensitive areas of the device by pressing capacitive or switch buttons, the microcontroller receives sequences of electrical inputs and it converts them into keystrokes that are sent to the communication layer; conversely, when data are received from the upper layer (i.e., the communication layer), the control layer converts triggers the actuators associated with the character encoded in the message, by firing vibrotactile motors, simultaneously or in sequence). In our prototype, we implemented both the control and communication layers using an open source cross-platform hardware tool for rapid prototype development, the Arduino Mega control board. This includes a 16MHz ATmega1280 microcontroller with 8Kbyte SRAM, 54 input/output pins, 14 of which supporting Pulse Wave Modulation (PWM) output. Due to its form factor, we incorporated it into the wristband. This is connected to the physical layer using a set of wires to the input and output layers. The firmware is programmed within the Processing environment in a C- or Java-like language.

Depending on the transport layer, the microcontroller in the control layer receives and executes commands via serial USB or Bluetooth communication. As the control layer does not support concurrency, each message has to be structured so that parallel processes (i.e., firing two actuators) can be realized with one function. To this end, the control layer receives four commands in sequence: first, the begin-of sequence (BOS) message contains an action initialization command, and it represents the action to be realized by the device (e.g., fire actuators). Subsequently, two separate option commands

(O) allow specifying the duration and the intensity of the stimuli. Duration is represented as multiples of 100ms. The duration of each firing can be set up to 6400ms. Intensity (or frequency) is represented by multiples of 2Hz ranging from 120Hz to 248Hz. Then, the following messages contain the actuators IDs, in sequence. As soon as they are received, they are stored in an array. The third command specifies the end of the sequence. The end-of-sequence (EOS) command starts the action defined by BOS. Sequences of messages allow defining different vibration patterns and tactile icons. Diverse frequencies and intensities in stimuli are obtained by using the PWM output that allows firing actuators at voltage amplitudes represented by integers corresponding to frequencies.

Communication layer

This module consists of the electronic components that allow the device to transfer data and to interact with the computer, or with a smartphone. dbGLOVE is designed to support wired or wireless connection protocols, depending on the connection type: a USB and a Bluetooth module allow the device to achieve both types of connection, although the latter requires the device to be equipped with an additional battery.

Firmware and software

The firmware of the device consists of an invariant part containing the core functions that drive the vibration motors and that is responsible for the acquisition of input controls. Moreover, there is a part governing the communication layer that consists of two interchangeable functions that connect the device to a smartphone or to a PC. The connection functions incorporate the Bluetooth and the serial stack, so that it is easy to interface dbGLOVE with other devices. Our system includes a software driver whose ultimate purpose is to allow the user to control the Operating System and to gain access to standard applications such as Internet browsers, word processors, instant messaging tools and many other programs. In addition, the device software should be able to parse the content of the messages which are sent with the device: they may contain a command for the Operating System (e.g., "*open a file*") or an input message for an application containing a sentence that the user wants to communicate (i.e. "I need some water") into a chat. The software architecture, which is not complete yet, is being designed to be also an extensible framework which contains the main elements to realize multimodal input and output. In fact, one of the most important elements we had to take into account is that even if dbGLOVE allows deafblind people to be autonomous in the interaction, there is usually an assistant with them, especially if they have other disabilities. Nevertheless, in our prototype, we implemented simple ad hoc applications that enable basic communication (i.e., chat) and device configuration, both local and remote.

Tablet training Application

As discussed in the previous sections, it is fundamental both for the deafblind and for their family and friends to be able to use a communication system. This is crucial for achieving interpersonal interaction without necessarily using technological aids. To this end, we developed an application that basically reproduces the interaction method of dbGLOVE on a multi-touch enabled device, that is, a tablet. This is a tool for training professionals, families and friends in the use of the Malossi alphabet, without requiring them to actually possess dbGLOVE. The mobile application is available on smartphones and tablets mounting an Android operating system. It is very simple, and it consists of three views, only. The main view contains a figure with the language reference; this allows users to review the Malossi alphabet and the communication method, and it supports learning the language using a basic tutorial. The second and the third views contain two quizzes that enable playing with the input and with the output functions, respectively. In the input testing view, the system suggests a word that the user has to type as quickly as possible by touching and pinching the palm shown on the display. In the output testing view, the application shows the picture of the palm of the hand. Areas blink in sequence in two different colors to distinguish touch from pinch. The objective of the user is to recognize the word being communicated and to correctly spell it. Also, there is the possibility of using the device for taking notes using the input view and setting the mode to *free input mode*.

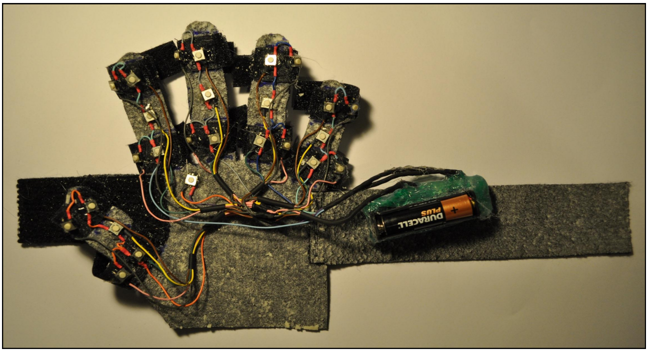


Figure 4.2: Initial prototype of dbGLOVE (input system only).

4.2 Performance evaluation of an interactive glove for the deafblind

dbGLOVE is the result of several years of research that is still ongoing. During the last eight years, we conducted several experiments: Some have been simple attempts to advance our system, others were more structured evaluations. In this dissertation, we only report the studies we realized using experimental protocols, though the discussion of the results may include findings that are derived from the everyday design and development experience, and go beyond data acquired in scientific experiments.

In order to evaluate the applicability of dbGLOVE as a natural

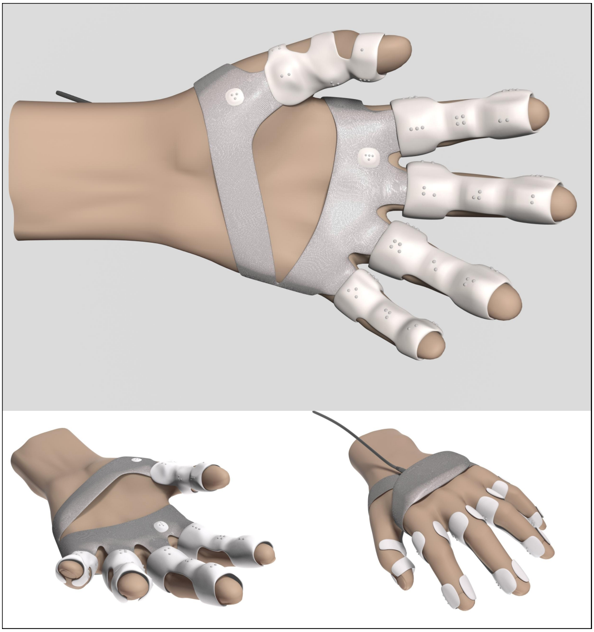


Figure 4.3: Final design of dbGLOVE.

interface, we realized several experiments that focused on improving specific aspects of the performances of the proposed device. They are discussed in the next sections. Particularly, at the initial stages, we evaluated the input and output capabilities of dbGLOVE as a feasible bidirectional communication system. Subsequently, we compared the learning curve of the device to standard computer peripherals, to estimate the training required for a proficient use of the device. Indeed, most of our work focused on the output feature. The majority of the deafblind population can use standard or dedicated input systems, but they have difficulties in finding tactile displays that specifically accommodate their needs. Consequently, providing the deafblind with an alternative and effective output modality is among the most challenging tasks. Actually, as mentioned earlier, not only is the output system challenging in terms of user evaluation, it also is the most sophisticated component of our device. In this regard, we evaluated interference between output and feedback using vibrotactile actuators, and the difference between mechanical and vibrotactile feedback as a response to input.

4.2.1 Study I - Validating dbGLOVE as an input/output device

In the early stage of the development of our device, the goal of our experiments was basic. We designed output features on top of the findings about vibrotactile feedback discussed in Section 2.1. The objective of our research was to design an effective wearable communication system based on vibrotactile output and consisting of arrays of miniaturized vibrotactile motors functioning as actuators. This involves two tasks: distinguishing different vibrotactile stimuli, and associating their location to letters of the alphabet. In this section, we discuss the findings of an experimental study in which we evaluated the input and output features of dbGLOVE from a functional point of view. Particularly, our purpose was evaluating the feasibility of using vibrotactile actuators to simulate pressure and touch cues and to reproduce the communication system implemented by the Malossi method. In addition, we assessed input as well, as recognizing the layout of the device is fundamental to effectively use dbGLOVE.

Objectives

In order for dbGLOVE to support the receptive and the expressive function as a natural interface, Malossi-trained users have to be able to straightforwardly utilize the Malossi method in a bidirectional fashion, as soon as they are provided with the device. To this end, we evaluated if dbGLOVE:

1. the configuration of the device, and the layout switches can be utilized as an input device based on the Malossi method;

2. actuators are effective in generating output by simulating touch and pinch cues that can be associated to letters in the alphabet;

3. the system is effective in supporting communication in situations of deprived vision.

Experimental tasks

We designed three experimental tasks, each focusing on a single item in the objectives. As discussed earlier, the design of the device implements the input and the output functions as two distinct modules. Consequently, we could separately evaluate them. Before the experiment, the experiment technician explained the Malossi alphabet to subjects, and we evaluated subjects' ability in associating tactile stimuli in different areas of the palm to letters in the Malossi alphabet. Subsequently, after sufficient training in the use of the Malossi method, subjects were asked to complete the three tasks.

Task I - guided input

In task I, we evaluated the performance of the device with respect to the input function. Participants were presented with sequences of words on a visual display, and they were asked to type them using dbGLOVE. The objective was typing as many words as possible in a limited time, and to simultaneously minimize the number of typos. The experiment was divided into 3 runs each lasting 120 seconds. They could see both the display and the glove.

Task II - output
In task II, we evaluated the performance of dbGLOVE in sending tactile stimuli to the user. Participants were presented with sequences of letters represented into a vibrotactile form by dbGLOVE. The different areas of the hand associated with the letters were stimulated with vibrotactile cues simulating touch and pinch cues, and participants were asked to speak the character back to the technician. The objective of the subject was identifying as many letters as possible. We executed three runs each consisting of 40 trials having two seconds inter-trial interval. Subjects were allowed two minutes to rest after each run. The trial timeout was set to 5 seconds.

Task III - blindfolded input and output
Task III included two subtasks similar to Task I and Task II except in that subjects were blindfolded. Particularly, in subtask I, subjects were presented with words reproduced by a text-to-speech system, and they were asked to type them back using dbGLOVE. Conversely, in subtask II, subjects' hand was stimulated with vibrotactile representation of words, and participants were asked to speak them to the technician.

Experimental setup and protocol

At the beginning of the experiment, participants were provided with detailed information about dbGLOVE, and they were allowed half hour training with the experiment technician. Also, they were provided with a tablet running an application (discussed later) for learning the Malossi alphabet. After the training session, participants were provided with dbGLOVE and they were allowed another five minutes of training with the device. During the experimental tasks, we acquired variables for evaluating the accuracy in the use of the device.

Specifically, in Task I, we measured the number of Characters Per Minute (CPM), the number of Words Per Minute (WPM), as well as the correctly written characters and the wrong characters. They are standard measurements of the proficiency in the use of input system. Also, we logged the time users spent in typing each letter, in order to evaluate the letters that require more effort.

In regard to Task II, we did not employ words. Instead, we utilized sequences of characters, as this is an easier way to measure subjects' ability in recognizing vibrotactile stimuli in the different areas of the hand, and to associate touch and pinch cues to letters of the alphabet. Moreover, they were only required to speak the letter to the technician, who recorded the answer as correct or wrong. This was to avoid subjects to actually type the letter on a keyboard, which implies some delay that would have affected the experimental result. Saying the correct letter allowed subjects to advance in the task, whereas the wrong answer allowed repeating the vibration for the last letter, and attempt to answer again. As the trial duration was set to five seconds, we considered as wrong all the letters that subjects could not recognize before the timeout. The device incorporates the calibration routine described in Figure 2.8 (see Section 2.1), which was executed before the experiment. Therefore, both the frequency and the intensity of the stimuli were calibrated to accommodate individuals' thresholds. The stimulus for touch cues had duration of 400 milliseconds at low frequency, whereas pinch cues were displayed by firing twice the actuator at high frequency.

The experimental protocol of Task III was identical to that of Task I and II, except in that in subtask I words were presented using speakers, because subjects were blindfolded. Also, we recorded the same variables as in Task I and II.

Participants

64 volunteer participants were involved in the study. They were 26 female and 38 male. All had normal sight, hearing. Their tactile sensitivity was not measured, though we utilized the calibration routine, which allowed us to acquire their Minimum Perceived Thresholds. Subjects ranged in age from 19 to 53 with an average of 29. All use computers on a daily basis (1.5-8 hours usage per day). All were novice for the system, but several of them had prior experience with vibrotactile feedback, as they were previously involved in other experiments. Moreover, prior to the experiment, they received extensive training in the use of the Malossi alphabet, and they were provided with the tablet application so that they could improve their proficiency. Subjects participated on a voluntary basis and they were not paid or rewarded. All subjects were right-handed as assessed by the Edinburgh inventory [55]. All subjects were prepared to the experiment by a technician who gave them instructions about the test and the experimental tasks.

Results and discussion

All subjects were able to understand the functioning of the system, and they had a positive reaction to the device, even though it was a prototype. Our result evaluation focused on values of KPM. Although Words Per Minute is the standard in reporting typing speed, evaluating keystroke per minute gives a more detailed picture of the typing speed regardless of the length of the words.

In Task I, subjects were asked to type words using dbGLOVE and a standard keyboard. Our objective was to compare individuals' performances in terms of speed and accuracy to evaluate the possibility of comparing the speed of our device with that of a standard keyboard. Figure 4.4 shows the result. There are 4 outliers that do not significantly affect data. Using dbGLOVE, participants achieved an average speed of 141.34 ± 91.38 keystrokes per minute. Conversely, using a traditional input device, they were able to type almost twice as fast, as the average KPM rate was 224.27±81.3. Interestingly, although the overall proficiency was lower with dbGLOVE, seven subjects were able to type faster with our device. This may be related to prior training (experimental data show that no significant training effect occurred during the collection process), as they are part of a group of individuals who participated to other experiments, and who received several hours of training, in total. However, in several cases, the distance between dbGLOVE and the keyboard is less than 20 characters. Conversely, in other circumstances, the keyboard overperforms dbGLOVE by 150+ keystrokes. As a result, users are able to use dbGLOVE proficiently and to type fast, but still the keyboard has better performances.

In addition to speed, we measured accuracy, calculated as the ratio between correct and total keystrokes. Using the keyboard, subjects had an average accuracy of 97.23±3.06%. Indeed, many were able to complete the experiment without any errors. Conversely, using dbGLOVE, participants reached an average accuracy of 93.36±5.45%. Figure 4.5 summarizes the experimental results. Although no subjects were able to achieve 100%, their performances with our device are statistically comparable to those obtained using the keyboard. Moreover, experimental data show that the majority of errors occur on the distal and on the proximal phalanxes, where subjects can indicate two letters that are distinguished using different touch cues. By weighting the effect of the germane load due to the representation of the alphabet, actual accuracy is 96.71±3.5%, showing a difference less than 1.2% with the keyboard. As a result, we can conclude that the device is comparable to a keyboard in terms of accuracy. Moreover, we believe that the difference in speed is related with accuracy, in the sense that even if subjects were able to type at higher speed, they were more cautious in the use of dbGLOVE and, consequently, they achieved lower KPM rates (see next studies).

All subjects were able to recognize all the stimuli. As a result, the calibration routine discussed in Section 2.1 is successful in determining individuals' Minimum Perceived Thresholds and in identifying the frequency and intensity range. In Task II, we measured the performances of the device in delivering correct stimuli to subjects. To this end, we evaluated the number of letters visualized by subjects as a measure of the speed at which subjects are able to read using dbGLOVE. However, in order to prevent subjects from just guessing, we also measured the accuracy, calculated, as in the previous task, as the number of correct answers over the total.

In Task III, subjects were blindfolded and they executed the same guided input routine described previously. In order to compensate for the training effect, we allowed blindfolded subjects some time to use the device. All subjects were able to complete the task, and they felt the device comfortable and easy to use in circumstances of deprived vision. The clockwise organization of the layout, combined with the clear positioning of letters over the palm, provided them with means for interacting with the device without actually seeing their hands. Figure 4.6 shows a comparison between the speed obtained with a standard keyboard, dbGLOVE and dbGLOVE in circumstances of deprived vision. Indeed, participants' average speed in typing letters dropped to 50.26±22.62 (-43.09), as a demonstration of the complexity of the task. In fact, without any visual reference, they had to stress their memory to remember letters' positions. Two participants overperformed in the task, showing an average KPM of 106.5. However, all other subjects' rates are below 100.

In regard to accuracy, as represented by Figure 4.7 the loss is minimal, and it is not statistically significant, taking into consideration the compensation for double letters that are on the same phalanxes. The average accuracy is 94.74±4.25

Indeed, acquired data refer to individuals who had the opportunity of learning the Malossi alphabet, and trained extensively with the devices. As a result, no differences were found between standard keyboard and dbGLOVE as input peripheral, in terms of accuracy. This indicates that our system could be used as an alternative to existing devices, at the cost of typing speed. In this regard, the KPM rates may have been affected by accuracy, in the sense that participants could have focused on accuracy, thus, taking speed into less consideration.

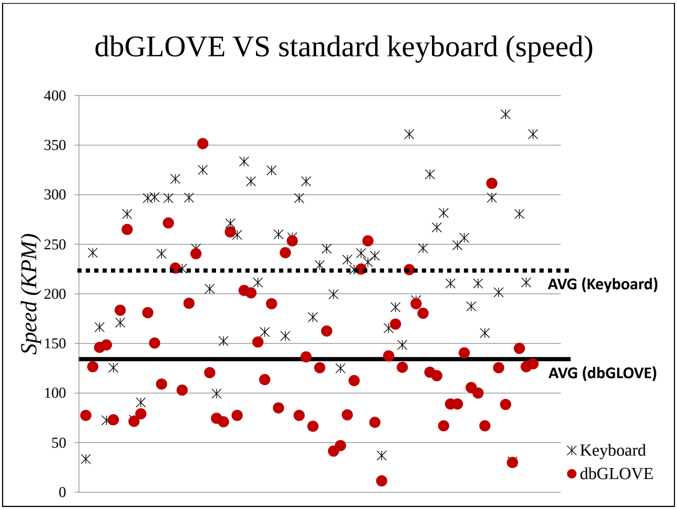


Figure 4.4: Speed comparison between dbGLOVE and a standard keyboard.

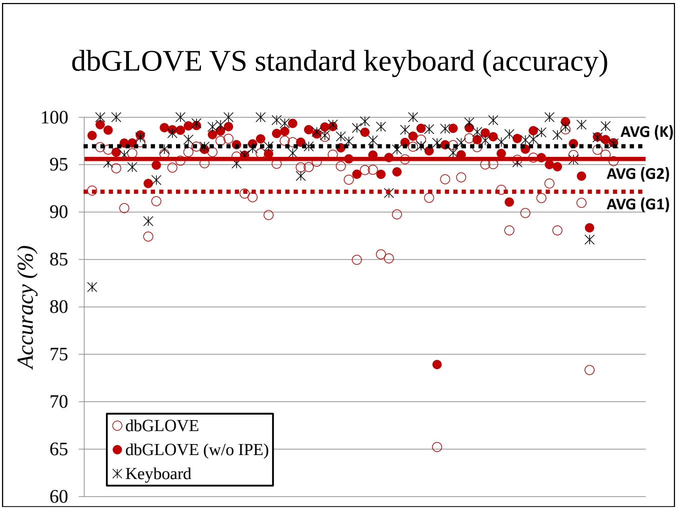


Figure 4.5: Accuracy comparison between dbGLOVE and a standard keyboard.

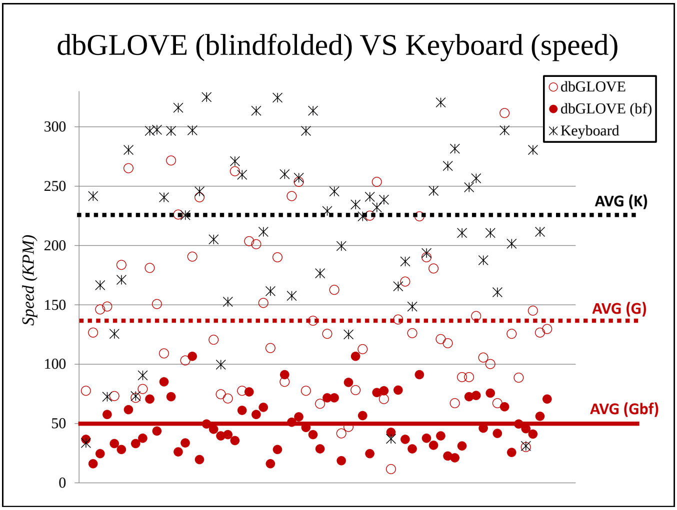


Figure 4.6: Speed comparison between dbGLOVE in conditions of deprived vision, and the keyboard.

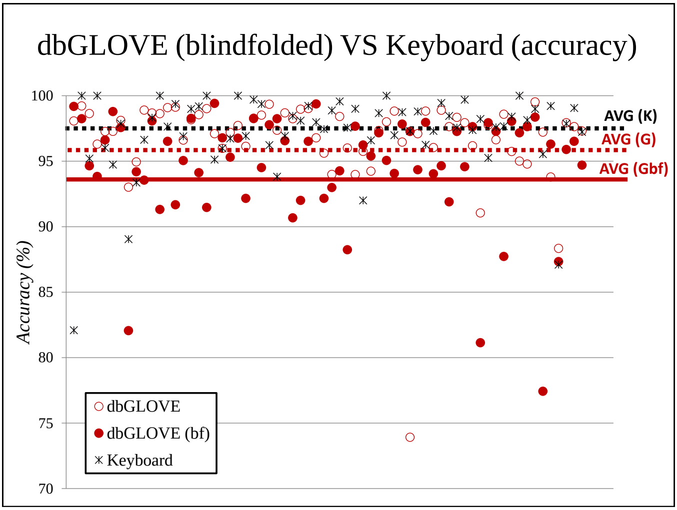


Figure 4.7: Accuracy comparison between dbGLOVE in conditions of deprived vision, and the keyboard.

4.2.2 Study II - Comparing the learning curve of dbGLOVE with standard devices

One of the critical factors that prevent users from learning new communication systems is the long time required for achieving sufficient proficiency with the language. In this regard, tactile codes and languages based on alphabets have an advantage with respect to other types of communication systems. The latter have their own interpretation of words and syntax and, thus, they are as difficult as learning a new language from scratch. Although they may require some adjustments to cope with the specific features of touch, tactile communication systems based on alphabets have shorter learning curve, as they enable individuals to reuse their prior knowledge in terms. Nevertheless, communication systems based on alphabets are not similar, and therefore their learning curve can be different.

The Malossi alphabet is known for its simplicity and for its short learning curve. Consequently, it is employed as among the first communication languages that are taught to young children who are deafblind, or to people who become deafblind in their later life. Being based on simple touch cues, and on tactile stimulation on parts of the hand that are easily recognizable, it is extremely convenient in situations of cognitive impairments as well. However, no measurements exist about its performance with respect to traditional communication systems. Furthermore, as dbGLOVE is the very first system based on the Malossi alphabet, there is no prior study in the scientific literature about the difference, in terms of learning curve, between dbGLOVE and standard input peripherals. This study aims at evaluating the time required for learning the Malossi alphabet with respect to a keyboard.

Furthermore, as it is designed to be a natural interface, our hypothesis was that people who have previous knowledge of the Malossi alphabet but who are novice of dbGLOVE, are immediately able to use the device.

Objectives

The previous study demonstrated that dbGLOVE can effectively be utilized as an input and output device. Experimental data showed performances comparable with that of a standard keyboard. Moreover, dbGLOVE is suitable for being utilized in situations of deprived vision. In this study, our objective was measuring the learning curve in the use of dbGLOVE with respect to standard input devices. Although the proficiency in the use of human-computer interfaces mostly depends on the time spent in using them after they have been adopted, the learning phase plays a crucial role in the adoption process, as it represents the entry barrier. Therefore, the main purpose of the experiment was to evaluate the applicability of dbGLOVE in the early stage phase of learning, and its acceptance level. We conducted a controlled experiment regarding both the input and the output features of dbGLOVE. Specifically, we focused on the following objectives:

1. determine the training needed by subjects in order to reach an adequate language proficiency using dbGLOVE;
2. compare the training time in subjects who already learned the language and in subjects who are completely novice;
3. evaluate the effort (i.e., cognitive load and training time) required by dbGLOVE in comparison with a standard keyboard;
4. validate dbGLOVE as a natural interface supporting the seamless migration from standard Malossi alphabet.

We focused on verifying whether dbGLOVE is able to support users in reaching the same typing performances as with a standard keyboard, after a given training time. Our main expectation is that participants who are already trained with the keyboard would be able to obtain the same performances with dbGLOVE. As many blind and deafblind users (especially who lost their vision later in their life) are able to utilize standard input devices, the purpose of the study is evaluating if they can obtain the same proficiency if provided with dbGLOVE.

Experimental tasks

In order to realize a comparison of the training time required by dbGLOVE with respect to standard input devices (i.e., a keyboard), we needed to evaluate how much time the keyboard requires subjects for training. However, as people usually have some experience in the use of a keyboard, we designed one of the experimental tasks (i.e., Task III) so that it rendered participants new to the use of the keyboard. In each of the three tasks, participants were involved in a guided input task similar to that of the experiment discussed previously. To this end, subjects were presented with sequences of words randomly chosen from a list of the 500 most commonly used words in the English language, and they were required to type them back using a keyboard with a standard QWERTY layout, dbGLOVE, and a keyboard with a changed layout. Prior to the experiment, the list was filtered to eliminate words shorter than four characters. All the tasks consisted of 3 runs each lasting 120 seconds, with an inter-run interval of 2 minutes. Tasks II and III were executed after Task I. However, their order was randomly shuffled to improve the accuracy of the data collection process, and to evaluate the bias due to two subsequent tasks involving the use of the keyboard in a different way.

Task I - Guided input with standard keyboard

In the first task, we acquired subjects' typing proficiency with a conventional input device. They were provided with a visual interface showing the target word, and they were asked to type it back using a standard PC keyboard with the QUERTY layout. This allowed us to acquire the target typing speed that subjects are able to achieve after being trained in the use of the device.

Task II - Guided input with the Malossi alphabet

In Task II, subjects were asked to realize the same procedure described in Task I. However, they were provided with dbGLOVE, and they were required to type the word back by pressing and pinching areas corresponding to letters. By doing this, we could acquire the typing proficiency of subjects who have no prior experience of the use of the device. However, some participants had previous experience with the Malossi alphabet, whereas others were novice. This allowed us to evaluate the impact of prior knowledge of the communication system on the training time.

Task III - Guided input with keyboard having different layout
During Task III, subjects were required to type words on a keyboard having a different layout with respect to the QWERTY system. This allowed us to take keyboard-trained subjects back to the moment in which they were novice. The layout was designed in a structured way in order to introduce some logical pattern, as in the Malossi system. Specifically, letters of the alphabet were placed in a vertical order, as shown in Figure 4.8

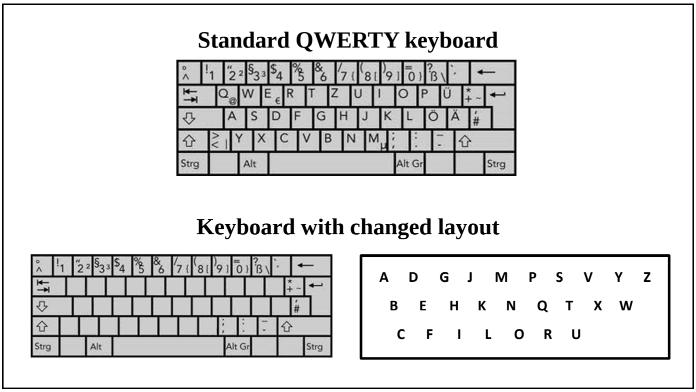


Figure 4.8: Layouts of the standard and the modified keyboard.

Experimental setup and protocol

Prior to the experiment, subjects received instruction about the tasks by a technician. Before each task, they were given some time to try the device. Then, they were provided with a visual display showing the target words. Typing the correct letter allowed subjects to continue, whereas wrong keystrokes locked participants in on the same character. Participants could read letters on the keys of the two keyboards, and on the input areas of dbGLOVE. In order to motivate the subjects, their overall performances were ranked and the top three participants were rewarded with a small prize. A countdown keylogger running in background recorded participants' keystrokes, and it logged the corresponding time.

We calculated the number of Words Per Minute (WPM) and the Keystrokes Per Minute (KPM). Moreover, we recorded two types of errors, that is, incorrect letters and biased letters. The former represents inconsistent keystrokes. Conversely, the latter represent two different circumstances depending on the device. In the keyboard with changed layout, biased letters occur because of subject's prior knowledge of the device: for instance, subjects press a key that in the standard layout would be correct. In dbGLOVE, biased letters represent pinch cues occurring instead of touch cues, and vice versa. They are mostly due to the cognitive stress of the experiment. Both are typical artifacts of cognitive overload, and specifically, *germane* load [103, 104].

We evaluated the training level by comparing the distance, in terms of accuracy and speed, between the performances obtained with dbGLOVE and with the keyboard with changed layout, with respect to the standard QWERTY keyboard.

Participants

54 volunteer participants were involved in the study. They were 22 female and 32 male. All had a normal sight, hearing and tactile sensitivity (we did not measure the different acuities, as the experiment focused on the input features of the device, only). Subjects ranged in age from 21 to 38 with an average of 33. All use computers on a

daily basis (1.5-8 hours usage per day). 27 were novice for the Malossi alphabet (13 female, 14 male), the others were familiar with the Malossi alphabet. All had no prior knowledge of the device, but some of them had prior experience with vibrotactile feedback, as they were involved in other experiments and in the evaluation discussed in Section 2.1. Subjects participated on a voluntary basis and they were not paid or rewarded. All subjects were right-handed as assessed by the Edinburgh inventory [55]. All subjects were prepared to the experiment by a technician who gave them instructions about the test and the experimental tasks.

Results and discussion

All subjects were able to understand the tasks and the functioning of the device. They defined Task II and III as entertaining. As in the previous experiment, we measured speed and accuracy. We employed the same metric, that is, Keystrokes Per Minute, for measuring the former. Figure 4.9 show the experimental results, and specifically, the speed reached by subjects over the 9 runs. Using the standard keyboard, participants obtained a rate ranging between 200 and 250 keystrokes per minute, with an average of 215.81 ± 10.59.

As expected, subjects had lower performances using the keyboard with the changed layout (CK), and dbGLOVE, because they were novice with respect to the layouts. Also, the training effect is evident both in dbGLOVE and in CK (+113.77 and +70.57, respectively). In more detail, subjects had an average initial speed of 31.11 and 45.3 with dbGLOVE and CK, respectively. Using our device, participants reached a speed of over 100 keystrokes per minute during third run, with a difference in KPM of about 100 with CK. However, the training effect with dbGLOVE ended after the fifth run, when subjects reached a typing speed of about 150 keystrokes per minute. On the contrary, using the keyboard with the changed layout, subjects had a longer training curve: the effect lasts in run 9, where subjects' performances with CK are 115.87 (-29 KPM with respect to our device). Experimental data show that dbGLOVE was able to support participants in achieving 118.89 KPM, that is, almost the average speed observed in the previous study, in 9 runs, only.

In regard to accuracy, the standard keyboard obtained the best results, with an average of 97.61$\pm$0.7, without any training effect, as expected. Conversely, both CK and dbGLOVE show an increasing trend starting at 56.43% and 60.32%, respectively. Also, they show an improvement of 20.07% and 34.79%, respectively. As a result, after 9 runs, the average accuracy with dbGLOVE is 95.11%, which is comparable with that of the standard keyboard. Conversely, participants reached 76.5% using CK, showing lower but adequate training in accuracy. Experimental data show that subjects were able to achieve a typing accuracy of about 90% after run 4.

Finally, we evaluated cognitive load. As letters in the Malossi alphabet require different actions in order to be triggered (i.e., touch or pinch), as in the previous experiment, we evaluated the relative error by grouping letters into significant subsets. Specifically, we defined different weights for errors occurring in the same area (i.e., where two letters can be activated), such as the distal phalanx or the proximal phalanx (error weight = 0.5), and for errors involving different areas of the palm (error weight = 1) . In fact, the former case might demonstrate that although subjects understood the language, they were confused by the experiment itself; conversely, the latter may represent that they did not have sufficient time to memorize the exact position of sensors. Figure 4.13 shows the germane load in dbGLOVE and in CK.

In regard to the methodology employed in our experiment, and specifically, with respect to Task III changing the layout of a device participants already use may have altered their performances in the study. However, there are two factors that have to be considered: prior knowledge of the input system, regardless of the device, may have helped participants in performing the experimental tasks, whereas modifications to the layout may have introduced additional cognitive load with respect to the task. Although these factors may compensate one another, we took into consideration errors due to the changed layout by logging errors that are caused by keystrokes due to the persistence of the standard layout in subjects' memory. To this end, we weighted differently genuine errors (error weight = 1) and errors due to germane load (error weight = 0.5), as in the case of dbGLOVE.

Although data show the weighted accuracy calculated by taking into consideration the presence of double letters, the conclusions of our study hold without compensating the germane load, as well, because it is comparable, as depicted by Figure 4.13.

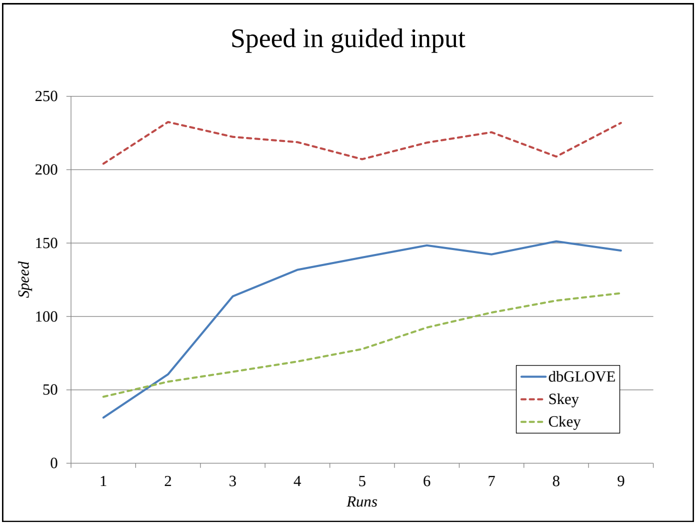


Figure 4.9: Comparison of speed over time.

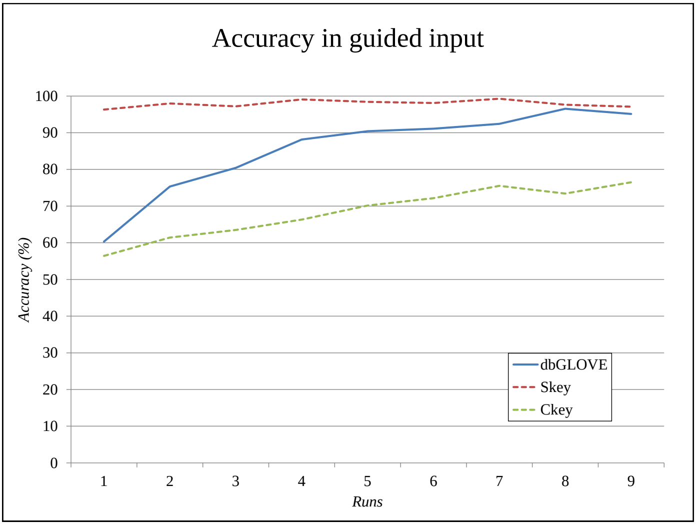


Figure 4.10: Comparison of accuracy over time.

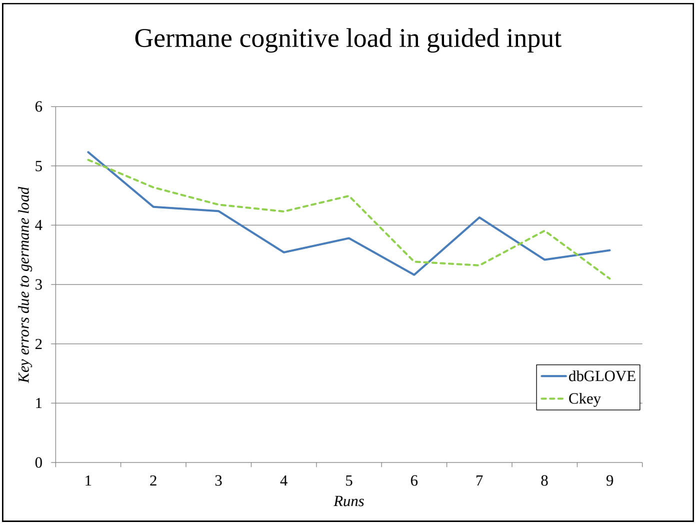


Figure 4.11: Germane load in dbGLOVE and the keyboard with changed layout.

4.2.3 Study III - A comparative study of the learning curve in the Malossi and in the Braille systems

Basically, this study follows up the previous experiment, as its purpose was to evaluate the learning curve of the Malossi alphabet with respect to the most important touch-based communication system employed by the blind population, the Braille alphabet. Both the Malossi and the Braille alphabets were invented by sensory-impaired individuals, and both rely on prior knowledge of language, because they conform to the syntax and grammar of common verbal languages.

Comparing the Malossi alphabet and the Braille system is extremely interesting as their implementations are based on two different tactile stimuli. The former involves vibration, whereas the latter employs static pressure. Also, although both languages are based on alphabets, one utilizes on-body signing, that is, it associates letters to different areas of the body. Conversely, the Braille system utilizes six small-size dots to encode characters. Several studies in the literature demonstrate the efficiency of the Braille alphabet in encoding information. As it is based on a binary system, it is extremely powerful: each configuration can encode one among 256 symbols. Conversely, the Malossi alphabet is limited to 26 characters. Although representing less information is a drawback, it represents an advantage in terms of learning curve.

Objectives

In this study, our objective was measuring the learning curve in the use of dbGLOVE with respect to the Braille system. Therefore, the main purpose of the experiment was to understand whether dbGLOVE and the Malossi alphabet can be implemented as a substitute of the Braille system for supporting everyday interaction. As we did not have sufficient funds to acquire a Braille keyboard, we conducted an experiment regarding output, only. However, as the experiment focuses on the time required to learn the language, we assume that sending and receiving messages are two similar functions built on top of language knowledge and, thus, they can be evaluated separately. Specifically, we focused on the following objectives:

1. determine the training required to decode messages from the Malossi alphabet;

2. evaluated the training time required to decode messages from the Braille alphabet;

Specifically, our main hypothesis is that dbGLOVE is suitable for substituting Braille displays in everyday interaction, and particularly, in the first stage of deafblindness, that is, when individuals require an immediate system for basic communication. In this regard, our hypothesis was that dbGLOVE has a shorter training time with respect to Braille cells.

Experimental tasks

The experimental tasks were designed similarly to Task II in Study I. As the experiment focuses on the output layer, in order to realize a comparison between the training time required by dbGLOVE with respect to a Braille-based device, we evaluate subjects' accuracy and speed in recognizing letters in the form of vibrotactile or pressure cues, respectively. To this end, in each of the two tasks, participants were involved in a guided output routine: they were presented with sequences of letters randomly chosen, and they were required to speak them back to the technician. We employed single letter instead of using words, as the latter could have introduced some error in the experiment routine. Specifically, the predictability of the last letters could have biased the experimental results. Differently from other experiments, as both the Malossi and the Braille alphabets were given to subjects without prior training, learning required some time. All the tasks consisted of 30 runs each consisting in 240 seconds, with an inter-run interval of 2 minutes. Each trial had duration of 5 seconds. Runs were divided into groups of 10, and each group was executed within several days from one another.

Task I - output with dbGLOVE

In task I, we evaluated the learning curve of dbGLOVE with respect to the output function in sending meaningful tactile stimuli to the user. Participants were presented with sequences of letters represented into a vibrotactile form by the actuators embedded into the device. The different areas of the hand associated with the letters were stimulated with vibrotactile patterns simulating touch and pinch cues, and participants were asked to speak the letter to the technician. The objective of the subject was identifying as many letters as possible.

Task II - output with Braille cell

The procedure in Task II was exactly the same as that in Task I. We evaluated the performance of Braille cells in sending perceivable tactile stimuli to the user. Participants were presented with sequences of letters via a single Braille cell. They were asked to decode the configuration of the dots, and to speak the letter back to the experimental technician.

Experimental setup and protocol

A device consisting of one piezoelectric Braille cell was utilized in Task II. We employed an International Building Standard [46] compliant cell (2.5mm for horizontal and vertical dot-to-dot distance, with a dot diameter of 1.5mm - 1.6mm and a dot height ranging from 0.6mm to 0.9mm) similar as that employed in the device described in Section 3.1. Its activation was $\sim$100 milliseconds, which is comparable with that of vibrotactile actuators, given the timing of the experimental task. Prior to the experiment, subjects were provided with a preliminary explanation of the Malossi and the Braille alphabets. Also, before each task, they were given some time to try the stimulation devices. In each trial, individuals had 5 seconds to speak the letter back to the technician.

We evaluated the training level by comparing accuracy and speed.

Specifically, we calculated the recognition speed as the number of Letters Per Minute (LPM). Moreover, we logged the accuracy in recognizing letters. In this regard, we associated a trial timeout to an error, as if the wrong letter was recognized. With respect to the task involving Malossi, we also logged the number of errors due to germane load, that is, letters biased due to the fact that they are on the same phalanx.

Participants

13 volunteer participants were recruited for this experiment. They were 5 female and 8 male. All had a normal sight, hearing and tactile sensitivity (we utilized the calibration routine of dbGLOVE for estimating their Minimum Perceived Threshold). Subjects ranged in age from 18 to 25 with an average of 22. All use computers on a daily basis (1.5-8 hours usage per day). They were all novice of the Malossi alphabet and of the Braille system. All had no prior knowledge of the device; two of them had prior experience with vibrotactile feedback, as they were involved in the study discussed in Section 2.1. Subjects participated on a voluntary basis and they were not paid or rewarded. All subjects were right-handed as assessed by the Edinburgh inventory [55]. All subjects were prepared to the experiment by a technician who gave them instructions about the test and the experimental tasks.

Results and discussion

As in the previous studies, in this experiment we evaluated language proficiency using speed and accuracy as the main metrics. Initially, subjects were not trained in the use of the Braille and of the Malossi alphabets, and therefore, their cognitive load was higher: first they had to learn how to code and decode messages into two alphabetic tactile codes, and then, they had to learn two novel communication systems implemented by means of technological aids. All the subjects were able to understand the task.

Figure 4.13 represent the experimental data about speed acquired in task I and II. In order to evaluate speed, as in the previous experiment, we calculated the number of letters that subjects were able to process, that is, the number of answers they were able to give before the run timeout. Subjects started at very low speed. Initially, participants were able to recognize only a few of the characters being displayed, with an average of 30.82 and 45.29 letters displayed to participants using the Braille cell and dbGLOVE, respectively. During the experiment, we registered an increasing trend in speed. Also, the training effects persists until the last run, when the performances of dbGLOVE and the Braille cell are 212.17 and 93.24 letters displayed (on average), respectively. Consequently, the improvement is +166.87 and +62.41 with our device and with the Braille cell.

In regard to accuracy, results show an increasing curve in the use of both devices. Participants using dbGLOVE started at 20.11%, and they increased their performance by 76.3% after 30 runs, thus, reaching an average performance of 96.41%. The training effect vanished at run 24, when subjects' performances were over 90%. Conversely, using the Braille cell, participants found more difficult to decode the letter by reading the dots. They began with an accuracy of 15.14%, and they improved their performance by 44.01%. In run 30, subjects' accuracy was 59.15%, -37.26% with respect to dbGLOVE. Figure 4.13 details the trend in accuracy.

As shown by diagrams, the Malossi alphabet implemented in dbGLOVE outperforms the Braille alphabet both in speed and accuracy, in people with no previous training in both the communication systems. As a result, dbGLOVE can be utilized as a substitute of systems implementing the Braille alphabet, especially in circumstances in which a shorter learning curve is required.

Unfortunately, we could not compare the Malossi alphabet with gestural alphabets, because they are harder to implement and to experiment. However, non-alphabetic languages having their own syntax are known for their longer learning curve.

This study does not aim at criticizing the Braille system. On the contrary, it is an assessment of the language that best fits the need of a communication system that can be learned with ease. Moreover, learning the Malossi alphabet can be the first step towards a more sophisticated communication system that is more suitable for individuals who have developed their cognitive and sensory abilities, or who need access to more advanced capabilities in addition to basic communication.

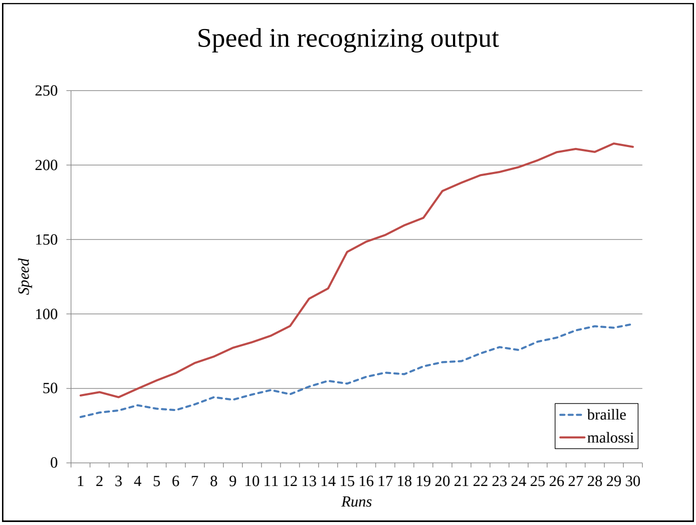


Figure 4.12: Speed in learning Braille and Malossi.

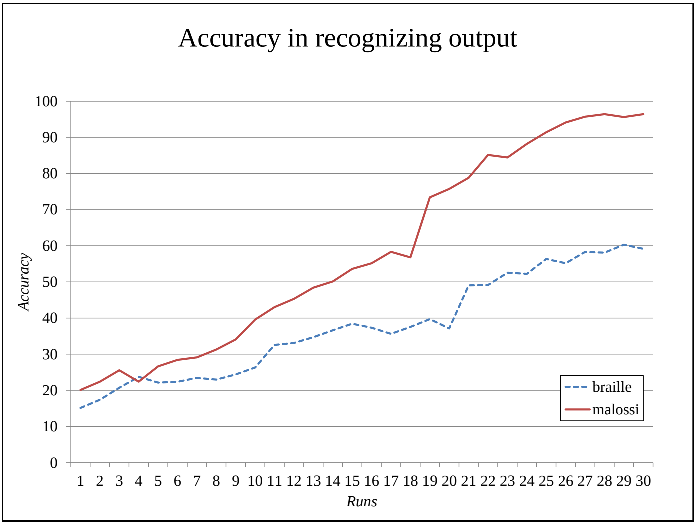


Figure 4.13: Accuracy in learning Braille and Malossi.

4.2.4 Study IV - Determining feedback strategies in mechanical and capacitive input

Nowadays, the use of capacitive sensors is increasing. Several products are based on capacitive touch displays and interfaces. They are less expensive than discrete switches, they have better form factor, they are more versatile, and even flexible. As a result, capacitive sensors are perfect for replacing tactile switches in dbGLOVE, as they would render the pad thinner, lighter, and more durable. Furthermore, interacting with capacitive sensors is more natural than using switches, which often fail in recognizing input because users are not able to find the exact spot in which to press them. However, the main drawback is that capacitive interfaces offer no feedback that a button has been pressed.

Receiving immediate feedback on touch actions is fundamental. When interacting with objects and with the environment, the sense of touch inherently provides humans with feedback about their activity. Touching objects results in the stimulation of mechanoreceptors in response to objects' surfaces and to the intensity of the action. Also, through the sense of touch, or through vision or hearing, it is possible to discover any changes in the objects as a result of actions. Moreover, when two individuals communicate using the Malossi alphabet they use some form of immediate feedback upon touch and pinch cues. Specifically, back-channel communication is employed to signal that a letter has been received. Back-channel feedback is a common feature found in all forms of communication. Back-channeling refers to the listener responding to the information received by the sender. This is realized by the receiver to inform the sender so that the latter is aware of the former's response. In spoken English, this could refer to facial expressions, or to short sounds that let the speaker know the listener is following and understanding what is being said. Also, in the American Sign language, the Y hand shape is utilized to allow the signer to know the recipient of the conversation is following. In using Malossi with a deafblind individual, the individual taps the signer's hand after each letter. Moreover, if the sender is not deaf and the receiver can speak, usually, the latter repeats each letter verbally.

Conversely, when touching interactive devices, some type of feedback by the system is necessary in response to actions, in order for users to be alerted on whether the system was able to identify their action. Usually, visual or quick auditory cues are employed to signal that the system changed its state in reaction to touch events. Also, several devices incorporate sensors that produce feedback independently from the system. For instance, the mouse is equipped with touch-responsive sensors that provide both tactile and auditory feedback as a result of button click, regardless of whether the device is connected to a computer. In addition to the button click, the computer may produce additional visual or auditory feedback depending on the element being clicked.

Tactile micro-switches inherently implement mechanical feedback, thanks to a responsive membrane that produces the *click* sound, which is also perceivable through touch. Conversely, other types of sensors, such as capacitive sensors, do not provide any tactile or auditory feedback, as they consist in a single layer having no moving parts. Moreover, as the feedback of tactile micro-switches is mechanical, it does not require any electrical supply, and they do not require the host device to be powered. Conversely, in capacitive sensors, generating feedback in response to touch actions requires some basic circuit or even some advanced processing, depending on the application. Although haptics technology based on vibration can simulate the feeling of pressing tactile switches, several issues have to be taken into consideration. Among the fundamental issues in designing feedback for capacitive input, there is response time. This is immediate in tactile switches: as soon as they are pressed, mechanical feedback occurs. Also, an auditory and tactile cue is generated when they are released. Conversely, vibrotactile actuators may introduce some delay due to their activation time, though it is extremely quick. Other elements to be considered are frequency, intensity, duration and pattern. They have to be carefully chosen in order to avoid both conflict between different letters and interference with output. Indeed, all these issues are task critical, because of the application scenario of our device.

In this study, we evaluated the possibility of replacing tactile micro-switches with capacitive sensors. To this end, it is fundamental to identify an effective feedback method that enables users to determine whether touch and pinch cues have correctly been recognized by the device.

dbGLOVE equipped with capacitive sensors

Thanks to the modular architecture of the system, substituting tactile micro-switches with a capacitive system was extremely easy, as it only required to modify the physical layer, and specifically, to replace the sensors, without any changes in the other layers.

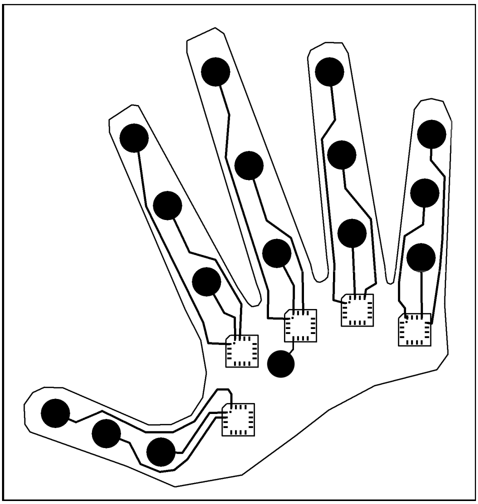


Figure 4.14: Location of capacitive actuators and schematic

Objectives

Our experiment focused on feedback, because it is the fundamental change between switches and capacitive sensors. The entire study was a comparison between mechanical feedback and vibrotactile feedback. The objective of the experiment was three-fold:

1. assess individuals input performances with mechanical and capacitive sensors;
2. identify how vibrotactile and mechanical feedback affect users' performances in input tasks;
3. evaluate individuals' preferences with respect to vibrotactile and mechanical feedback.

In order to accomplish the objectives, quantitative measurement of performance is not sufficient to capture individuals' experience with the two input and feedback modalities. Therefore, we utilized qualitative measures for evaluating participants' preferences in terms of user experience.

Experimental tasks

Task I and II were similar, and they focused on assessing individuals' preferences with respect to mechanical or vibrotactile feedback. To this end, we provided participants with two prototypes of dbGLOVE, one equipped with tactile micro-switches and the other having capacitive sensors. In each of the first two tasks, participants were involved in a guided input task, that is, subjects were presented with sequences of words randomly chosen from a list of the 500 most commonly used English words, and they were required to type them back the two prototypes of dbGLOVE.

Task I - input with mechanical sensors and feedback

In Task I, no feedback was provided except the inherent mechanical response of tactile sensors. Consequently, participants received feedback immediately, and it was represented by the area of the hand in which touching or pinching occurred.

Task II - input with capacitive sensors and vibrotactile feedback
During this task, feedback was generated as vibrotactile stimuli reproducing the letter. As a result, subjects could distinguish the letter by discriminating the intensity and frequency of the stimulus.

Experimental setup and protocol

Prior to the experiment, subjects received adequate training about the device and the experimental tasks. During the tasks, experimental data were logged to measure subjects' performances. At the end of the tasks, participants were asked to give a qualitative evaluation of their experience with the feedback modalities. Also, we had a short interview with each of the participants to evaluate their results and their answers. The first two tasks consisted of 3 runs each lasting 120 seconds, with an inter-run interval of 2 minutes. As in the other experiments, we measured the performances in KPM (i.e., speed) and accuracy. Differently from the other experiments, subjects were not provided with a display, as the objective of the study was to evaluate the effectiveness of the feedback given by the device, only. As a result, words were displayed using an audio speaker. Subjects were not notified of errors during the task. Instead, they were given the possibility to retry the letter if they felt they did not stroke it. By doing this, we avoided to give subjects immediate feedback about their input performances, in order to obtain more realistic judgments when they were asked to answer the questionnaire.

Participants

The same participants involved in Study I were employed in this experiment. They were 64 volunteer (26 female and 38 male, aged from 19 to 53) having normal sight, hearing and tactile sensitivity. All use computers on a daily basis (1.5-8 hours usage per day). They were not novice in regard to the Malossi alphabet. However, they had no prior knowledge and experience of the device. In fact, this study was realized before Study I. Some of the participants had prior experience in vibrotactile feedback, as they were involved in the experiment discussed in Section 2.1. Subjects participated on a voluntary basis and they were not paid or rewarded. All subjects were right-handed as assessed by the Edinburgh inventory [55]. They were prepared to the experiment by a technician who gave extensive training about the Malossi alphabet, and information about the test and the experimental tasks.

Results and discussion

All subjects were able to understand the task, and they had no particular difficulty in using the two prototypes. Although they had some training, we observed a little training effect that persists in both tasks. In regard to speed, participants achieved an average of 137.71 and 132.08 with capacitive and mechanical sensors, respectively. However, the difference is not significant, if considering the entire group. Nevertheless, we noticed that there are two subgroups: generally, subjects having higher typing speed achieve higher performances with capacitive input. On the contrary, subjects who have lower keystroke per minute rates have a preference for mechanical input. The former subset shows higher performance deviation (10.08) with respect to subjects who prefer mechanical input (4.45). Figure 4.15 reports the experimental results.

In regard to accuracy, subjects achieved significantly better performances with mechanical input, achieving 86.11%. Conversely, they scored lower with capacitive input, in which they had an accuracy of about 74.44%. As shows in Figure 4.16, Again, we found that subjects who are able to type faster have better performance with capacitive input, while subjects who type at low rates have a preference for mechanical feedback. Moreover, as shown in Figure 4.17, we found higher germane load in capacitive input, where there is a significant distance between performances on the intermediate phalanxes

(75.36% on average where there is only one letter per phalanx) and that of the distal and proximal phalanxes (where there are two letters per phalanx), having an average accuracy of 62.05% (-13.05%).

Although capacitive and mechanical input are comparable in terms of performance, from a quantitative point of view, we could see that subjects have a preference for mechanical input. Moreover, by interviewing participants and by analyzing the results of the questionnaire, we evaluated that subjects perceived capacitive as having higher usability. Also, they had a strong preference for vibrotactile feedback with respect to mechanical response. Participants rated the perceivability of capacitive actuators as poor both in the distal and in the proximal phalanxes. Conversely, they show a small preference of capacitive input over mechanical sensors in intermediate phalanxes. This is consistent with participants' quantitative performances, and particularly, with the figures obtained in the analysis of cognitive load. Therefore, one of the main design challenges with respect to dbGLOVE is reducing the ambiguity between letters that are in the same parts of the hand. This can be realized in several ways, such as by introducing disambiguation algorithms that allow distinguishing letters in the distal and in the proximal areas regardless of the actual touch or pinch cue applied by users.

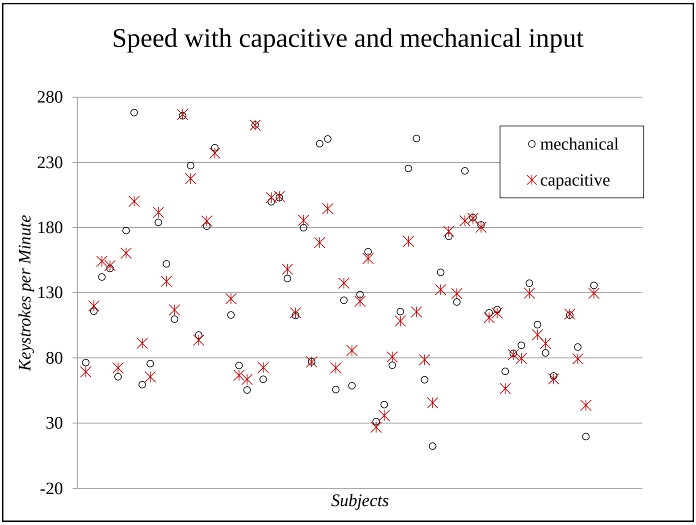


Figure 4.15: Comparison of the speed of capacitive and mechanical input.

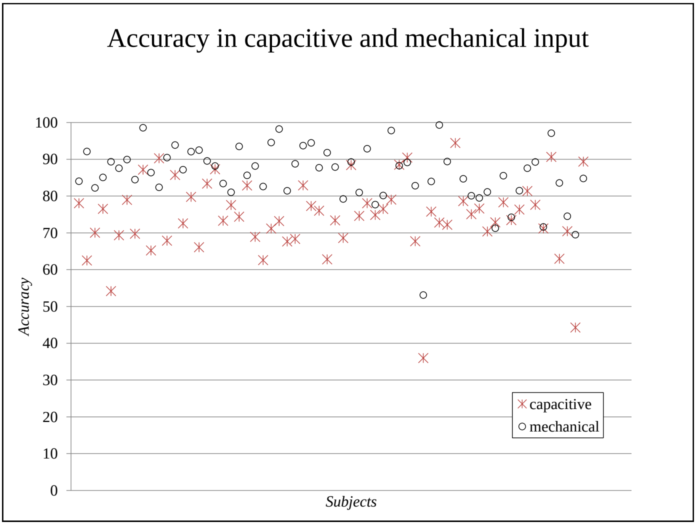


Figure 4.16: Comparison in the accuracy of capacitive and mechanical input.

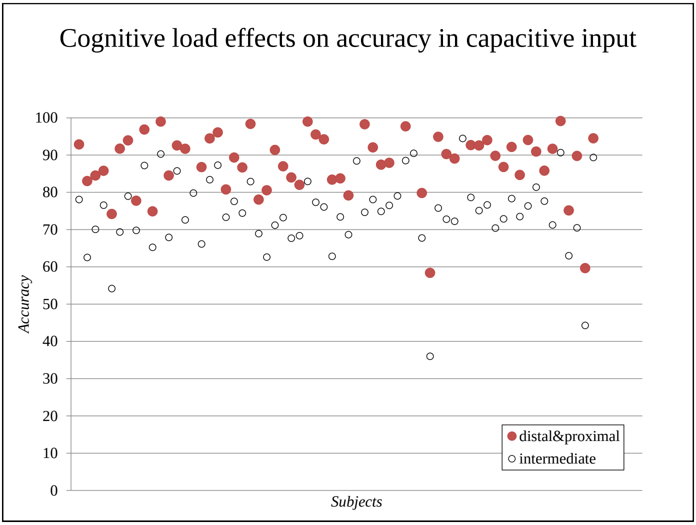


Figure 4.17: Germane load in capacitive input.

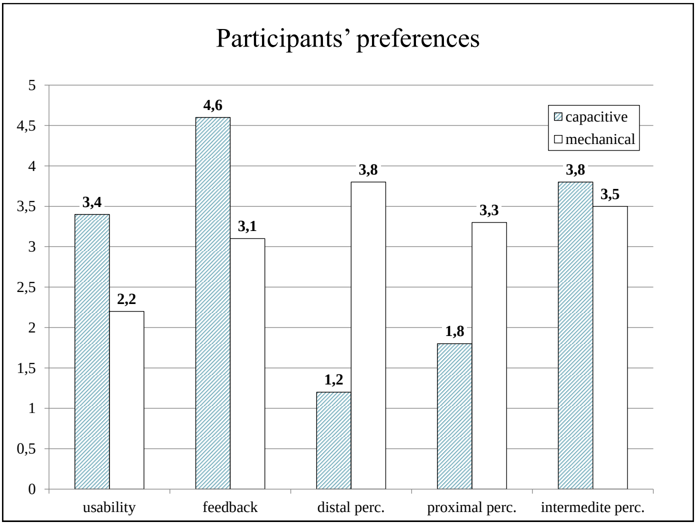


Figure 4.18: Results of the questionnaire.

Bibliography

[1] The development of intersensory temporal perception: An epigenetic systems/limitations view. Lewkowicz, David J. Psychological Bulletin, Vol 126(2), Mar 2000, 281-308. doi: 10.1037/0033-2909.126.2.281

[2] Klatzky, R. L., Lederman, S. J., AND Metzger, V. A. (1985). Identifying objects by touch: An expert system. Perception AND Psychophysics, 37, 299-302.

[3] Leslie Lamport, *LaTeX: A Document Preparation System*. Addison Wesley, Massachusetts, 2nd Edition, 1994.

[4]

[5] Reed, Charlotte M., Delhorne, Lorraine A., Durlach, Nathaniel I., Fischer, Susan D. A Study of the Tactual and Visual Reception of Fingerspelling. J Speech Hear Res 1990 33: 786-797

[6] Weinstein, S. Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex, and Laterality. In The Skin Senses; Kenshalo, D. R., Ed.; Charles C. Thomas: Springfield, IL, 1968; pp 195-222. Copyright 1968 Charles C. Thomas.

[7] George A. Gescheider, Stanley J. Bolanowski, Tyler C. Greenfield, and Katyarina E. Brunette. Perception of the tactile texture of raised-dot patterns: A multidimensional analysis. Somatosensory & Motor Research 2005 22:3, 127-140

[8] Reed, Charlotte M., Delhorne, Lorraine A., Durlach, Nathaniel I., Fischer, Susan D. A Study of the Tactual Reception of Sign Language. J Speech Hear Res 1995 38: 477-489

[9] Chomsky, Carol. Analytic Study of the Tadoma Method: Language Abilities of Three Deaf-Blind Subjects. J Speech Hear Res 1986 29: 332-347

[10] Charlotte M. Reed and Nathaniel I. Durlach. Note on Information Transfer Rates in Human Communication. Presence: Teleoperators and Virtual Environments 1998 7:5, 509-518

[11] Jack M. Loomis and Carter C. Collins. Sensitivity to shifts of a point stimulus: An instance of tactile hyperacuity. ATTENTION, PERCEPTION, & PSYCHOPHYSICS. Volume 24, Number 6 (1978), 487-492, DOI: 10.3758/BF03198771

[12] Roger W. Cholewiak and Amy A. Collins. Vibrotactile localization on the arm: Effects of place, space, and age. ATTENTION, PERCEPTION, & PSYCHOPHYSICS. Volume 65, Number 7 (2003), 1058-1077, DOI: 10.3758/BF03194834

[13] Jan B. F. Van Erp, Hendrik A. H. C. Van Veen, Chris Jansen, and Trevor Dobbins. 2005. Waypoint navigation with a vibrotactile waist belt. ACM Trans. Appl. Percept. 2, 2 (April 2005), 106-117. DOI=`10.1145/1060581.1060585`. Online at `http://doi.acm.org/10.1145/1060581.1060585`

[14] Schwitzgebel, Robert L . Survey of electromechanical devices for behavior modification. Psychological Bulletin, Vol 70(6, Pt.1), Dec 1968, 444-459. doi: 10.1037/h0026833

[15] Jan BF Van Erp . Presenting directions with a vibrotactile torso display. Ergonomics. Vol. 48, Iss. 3, 2005

[16] Bark, K., Wheeler, J.W., Premakumar, S. , Cutkosky, M.R. Comparison of Skin Stretch and Vibrotactile Stimulation for Feedback of Proprioceptive Information. Haptic interfaces for virtual environment and teleoperator systems, 2008, Pages 71-78.

[17] Jones L A, Kunkel J, Piateski E, 2009, "Vibrotactile pattern recognition on the arm and back" Perception 38(1) 52 Ű 68

[18] Lam, Amy R. Vibrotactile pattern recognition on the torso with one and two dimensional displays. PhD Dissertation, 2006. Online at `http://dspace.mit.edu/handle/1721.1/36738`

[19] R. Schweizer, M. Maier, C. Braun, N. Birbaumer. Distribution of mislocalizations of tactile stimuli on the fingers of the human hand. Somatosensory & Motor Research 2000 17:4, 309-316

[20] Norton, Susan J., Schultz, Martin C., Reed, Charlotte M., Braida, Louis D., Durlach, Nathaniel I., Rabinowitz, William M., Chomsky, Carol. Analytic Study of the Tadoma Method: Background and Preliminary Results. J Speech Hear Res 1977 20: 574-595

[21] ANSI/NISO Z39.98-2012, Authoring and Interchange Framework for Adaptive XML Publishing Specification Details. Online at: `http://www.niso.org/apps/group_public/project/details.php?project_id=99`

[22] Howard P. Parette and Dianne H. Angelo. Augmentative and Alternative Communication Impact on Families: Trends and Future Directions. J Spec Educ Spring 1996 30: 77-98, doi:10.1177/002246699603000105

[23] Reed, C.M., Delhorne, L, and Durlach, N. A Study of th Tactual and Visual Reception of Fingerspelling, Journal of Speech and Hearing research, 33, December 1990, 786-797.

[24] The V-Sign project. Online at: `http://vsign.nl/EN/vsignEN.htm`

[25] Fabio Buttussi , Luca Chittaro , Daniele Nadalutti. Abstract H-Animator: A Visual Tool for Modeling, Reuse and Sharing of X3D Humanoid Animations. Proceedings of Web3D 2006: 11th

International Conference on 3D Web Technology, ACM Press, New York, April 2006, pp. 109-117.

[26] William C. Stokoe, Jr. Sign Language Structure: An Outline of the Visual Communication Systems of the American Deaf. J. Deaf Stud. Deaf Educ. (Winter 2005) 10(1): 3-37 doi:10.1093/deafed/eni001

[27] Steve McCall, Graeme Douglas, and Mike McLinden. An investigation into the potential of embossed ŚdottedŠ Moon as a production method for children using Moon as a route to literacy. British Journal of Visual Impairment January 2007 25: 86-96,doi:10.1177/0264619607071775

[28] Tan, H.Z., Durlach, N.I., Rabinowitz, W.M., Reed, C.M., Information Transmission with a Multi-finger Tactual Display, Proceedings of International Sensory Aid Conference, 1996.

[29] Barber M. (2007) ŚImitation, interaction and dialogue using Intensive Interaction: tea party rulesŠ, in Support Learning, 22: p.124-30.

[30] Nicholls, Gaye H., Mcgill, Daniel Ling. Cued Speech and the Reception of Spoken Language. J Speech Hear Res 1982 25: 262-269

[31] H L Goh, B A Iwata, B A Shore, I G DeLeon, D C Lerman, S M Ulrich, and R G Smith. An analysis of the reinforcing properties of hand mouthing. J Appl Behav Anal. 1995 Fall; 28(3): 269Ű283. doi: 10.1901/jaba.1995.28-269

[32] Daland R. Juberg, Kathleen Alfano, Robert J. Coughlin, and Kimberly M. Thompson. An Observational Study of Object Mouthing Behavior by Young Children. Pediatrics 2001; 107:1 135-142; doi:10.1542/peds.107.1.135

[33] Jansson G, Petrie H, Colwell C, Kornbrot D, Fänger J, König H, Billberger K, Hardwick A. Furner S (1999) Haptic virtual en-

vironments for blind people: exploratory experiments with two devices. Int. J. of Virtual Reality, 4:(1), 10-20

[34] Firth, G., Elford, H., Leeming, C., AND Crabbe, M. (2008) ŚIntensive Interaction as a Novel Approach in Social Care: Care StaffŠs Views on the Practice Change ProcessŠ, in Journal of Applied Research in Intellectual Disabilities, 21, p.58-69.

[35] Stillman, R.D. and Battle, C.S. (1984) "Developing prelanguage communication in the severely handicapped: An interpretation of the Van Dijk Method." Seminars in Speech and Language, 4 (3), 159-170.

[36] Krufka SE, Barner KE, Aysal TC. Visual to tactile conversion of vector graphics. IEEE Trans Neural Syst Rehabil Eng. 2007 Jun;15(2):310-21.

[37] Blinn, James F. "Simulation of Wrinkled Surfaces", Computer Graphics, Vol. 12 (3), pp. 286-292 SIGGRAPH-ACM (August 1978)

[38] Rowland, C. and Schweigert, P. (1990) Tangible Symbol Systems: Symbolic communication for individuals with multisensory impairments. Communication Skill Builders.

[39] CJ Dunst, E Gorman. Tactile and Object Exploration Among Young Children with Visual Impairments. Center for Early Literacy Learning. Year 2011, Volume 4, Number 2. Online at `http://mtdeafblind.ruralinstitute.umt.edu/MainMenu/CommunicationStrategies/CELLreviews_4-21.pdf`

[40] Bailey, B.R. (1992) - Developing textured communication symbols for communication use. Traces (Vol. 2, 1).

[41] http://www.brailleauthority.org/tg/web-manual/index.html

[42] Ricento, Thomas. An Introduction to Language Policy: Theory and Method: Volume 1: Language and Social Change, Wiley-Blackwell, 2006, ISBN 1-4051-1498-3, ISBN 978-1-4051-1498-1.

[43] Freeman, P. (1975). Understanding the Deaf/Blind Child, Heinemann Health Books, London.

[44] Mc Innes, J. AND Treffery, J. (1982). Deafblind Infants and Children: A Developmental Guide, University of Toronto Press, Toronto.

[45] http://www.icevi.org/publications/ICEVI-WC2002/papers/02-topic/02-joint.htm

[46] RNIB Scientific Research Unit Scientific and technological reports "Braille Cell Dimensions" (online)

[47] Jemni, M., Elghoul, O.: Towards Web-Based automatic interpretation of written text to Sign Language. In: ICTA 2007, Hammamet, Tunisia, April 2007, pp. 12-14 (2007)

[48] Papadogiorgaki, M., Grammalidis, N., Makris, L., Sarris, N., Strintzis, M.G.: Vsign Project. Communication (September 20, 2002), http://vsign.nl/EN/vsignEN.htm

[49] Ehrhardt, U., Davies, B.: A good introduction to the work of the eSIGN project. eSIGN Deliverable D7-2 (August 2004)

[50] Weisenberg, J. (2009) Audience Effects in American Sign Language Interpretation. Published dissertation. Stony Brook University. New York

[51] Sandler, W. (2009). Symbiotic symbolization by hand and mouth in sign language. Semiotica. 174 (1/4), 241-275

[52] Hohenberger, A. and Happ, D. (2001): The Linguistic Primacy of Signs and Mouth Gestures over Mouthing: Evidence from Language Production in German Sign Language (DGS). In: P. Boyes

Braem AND R. Sutton-Spence (Eds.), The Hands are the Head of the Mouth: The Mouth as Articulator in Sign Language. Hamburg: Signum, 153-189.

[53] Tabak, J. (2006). Significant Gestures. Westport, CT. Praeger Publishers.

[54] Geldard, F., and Sherrick, C., The cutaneous rabbit: A perceptual illusion," Science, 178, 1972, 178-179.

[55] Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia, 9, 97-113

[56] C.J. Hasser, A.S. Goldenberg, K.M. Martin, and L.B. Rosenberg, "User performance in a GUI pointing task with a low-cost force-feedback computer mouse," ASME Dynamics Systems and Control Division, vol. 64, pp. 151-156, 1998

[57] B. Petzold, M.F. Zaeh, B. Faerber, B. Deml, H. Egermeier, J. Schilp, and S. Clarke, "A study on visual, auditory, and haptic feedback for assembly tasks", Teleoper. Virtual Environ., vol. 13, no. 1, pp. 16-21, 2004.

[58] B. L. Richardson and M. A. Symmons, Vibrotactile devices for the deaf: are they out of touch? The Annals of Otology, Rhinology AND Laryngology. Supplement, vol. 166, pp. 458?461, 1995.

[59] R. Kuc, ?Binaural sonar electronic travel aid provides vibrotactile cues for landmark, reflector motion and surface texture classification,? IEEE Transactions on Biomedical Engineering, vol. 49, no. 10, pp. 1173?1180, 2002.

[60] Nicholas, J. AND Koppen, A. (2007). Understanding the tactile brain. Conference proceedings. 14th Deaflind International (Dbl) World Conference, Western Australia, Perth.

[61] N. Caporusso, L. Mkrtchyan, L. Badia. (2010) A Multimodal Interface Device for Online Board Games Designed for Sight-Impaired People. IEEE Transactions on Information Technology in Biomedicine 14:2, 248-254 Online publication date: 1-Mar-2010.

[62] Human-centred computing: cognitive, social and ergonomic aspects di Don Harris,Constantine Stephanidis

[63] Chase, W.G. AND Simon, H.A. (1973). "Perception in chess". Cognitive Psychology 4 (1): 55Ű81. doi:10.1016/0010-0285(73)90004-2.

[64] IBCA | International Braille Chess Association. Online at `http://www.ibca-info.org/`

[65] Röder, B., and Neville, H.J. (2003). Developmental functional plasticity. In Plasticity and rehabilitation. J. Grafman and J. Robertson, eds. (Amsterdam: Elsevier), pp.231-270.

[66] T. Nobels, F. Allemeersch, and K. Hameyer, "Design of Braille cell setting actuators for the application in the Braille mouse concept," KIEE Int. Trans. on Electrical Machinery and Energy Conversion Systems, vol. 4B, no. 1, pp. 12-19, 2004.

[67] A.B. Vallbo and R.S. Johansson, "Properties of cutaneous mechanoreceptors in the human hand related to touch sensation", Hum. Neurobiol., vol. 3, no. 1, pp. 3-14, 1984.

[68] P. Le Blanc and T. R. Maher, "Braille mouse having character code member actuated by single solenoid," (online) http://www.freepatentsonline.com/5195894.html

[69] N. Kawakami "Tactile Communication system," (online) http://www.star.t.u-tokyo.ac.jp/projects/tactile-display/index.html

[70] D. Shapiro, "Magnetic game board especially for sightless individuals," (online) http://www.freepatentsonline.com/3746343.html

[71] CrissCross Technologies website "Tactile Chess Sets," (online) http://www.crisscrosstech.com/usbca/sets.html

[72] International Braille Chess Association website, (online) http://www.usuarios.com/ib316564/competitions.html

[73] R. Velázquez, Wearable Assistive Devices for the Blind. Chapter 17 in A. Lay-Ekuakille AND S.C. Mukhopadhyay (Eds.), Wearable and Autonomous Biomedical Devices and Systems for Smart Environment: Issues and Characterization, LNEE 75, Springer, pp 331-349, 2010.

[74] Torrens, G.E., Black, K., Chapter 5, Equipment design in Inclusive physical activity and disability sport, In. Design for sport, (eds)

[75] Asseman, F.; Bronstein, A. M.; Gresty, M. A. Guidance of Visual Direction by Topographical Vibrotactile Cues on the Torso. Experimental Brain Research 2008, 186, 283-292.

[76] Bles, W., Ed. Spatial Disorientation Training - Demonstration and Avoidance; RTO-TR-HFM- 118; Research and Technology Organization and North Atlantic Treaty Organization: Neuilly-sur-Seine Cedex, France, 2008.

[77] Brewster, S. A.; King, A. The Design and Evaluation of a Vibrotactile Progress Bar. Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems, Pisa, Italy, 2005.

[78] Brill, J. C.; Terrence, P. I.; Stafford, S.; Gilson, R. D. A Wireless Tactile Communications System for Conveying U.S. Army Hand-Arm Signals. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, San Francisco, CA, 2006; pp 2247-2249.

[79] Brill, J. C.; Terrence, P. I.; Downs, J. L.; Gilson, R. D.; Hancock, P. A.; Mouloua, M. Search Space Reduction via Multi-Sensory Directional Cueing. Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting, New Orleans, LA, 2004; pp 2134-2136.

[80] Brown, A. G.; Iggo, A. A Quantitative Study of Cutaneous Receptors and Afferent Fibres in the Cat and Rabbit. Journal of Physiology 1967, 193, 707-733.

[81] Brown, L. M.; Brewster, S. A.; Purchase, H. C. Multidimensional Tactons for Non-Visual Information Presentation in Mobile Devices. Proceedings of the Eighth Conference on Human-Computer Interaction With Mobile Devices and Services, Helsinki, Finland, 2006; Vol. 159, pp 231-238.

[82] Calhoun, G.; Draper, M.; Ruff, H.; Fontejon, J. Utility of a Tactile Display for Cueing Faults. Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting, Baltimore, MD, 2002; pp 2144-2148.

[83] Calhoun, G. L.; Ruff, H. A.; Draper, M. H.; Guilfoos, B. Tactile and Aural Alerts in High Auditory Load UAV Control Environments. Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, Orlando, FL, 2005; pp 145-149.

[84] Calhoun, G.; Draper, M.; Ruff, H.; Fontejon, J.; Guilfoos, B. Evaluation of Tactile Alerts for Control Station Operation. Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting, Denver, CO, 2003; pp 2118-2122.

[85] Calhoun, G. L.; Fontejon, J. V.; Draper, M. H.; Ruff, H. A.; Guilfoos, B. J. Tactile Versus Aural Redundant Alert Cues for UAV Control Applications. Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting, New Orleans, LA, 2004; pp 137-141.

[86] Carlander, O.; Eriksson, L. Uni- and Bimodal Threat Cueing With Vibrotactile and 3D Audio Technologies in a Combat Vehicle. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, San Francisco, CA, 2006; pp 1552-1556.

[87] Chen, J. Y. C.; Terrence, P. I. Effects of Tactile Alerts on Concurrent Performance of the GunnerŠs and Robotic OperatorŠs Tasks in a Simulated Mounted Environment; ARL-TR- 4227; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2007.

[88] Chen, J. Y. C.; Terrence, P. I. Effects of Tactile Cueing on Concurrent Performance of Military and Robotics Tasks in a Simulated Multitasking Environment. Ergonomics 2008, 51 (8), 1137-1152.

[89] Cholewiak, R. W.; Collins, A. A. Vibrotactile Localization on the Arm: Effects of Place, Space, and Age. Perception AND Psychophysics 2003, 65 (7), 1058-1077.

[90] Cholewiak, R. W.; Brill, J. C.; Schwab, A. Vibrotactile Localization on the Abdomen: Effects of Place and Space. Perception AND Psychophysics 2004, 66 (6), 970-987.

[91] Craig, G.; Jennings, S.; Cheung, B.; Rupert, A.; Schultz, K. Flight-Test of a Tactile Situational Awareness System in a High-Hover Task. Proceedings of the Annual Helicopter Society 60th Annual Forum, Baltimore, MD, 2004; pp 836-842.

[92] Davis, B. M. Effects of Tactical Navigation Display Modality on Navigation Performance, Situation Awareness, and Mental Workload. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, San Francisco, CA, 2006; pp 2089-2093.

[93] Davis, B. M. Effects of Visual, Auditory, and Tactile Navigation Cues on Navigation Performance, Situation Awareness, and Mental Workload; ARL-TR-4022; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2007.

[94] Diamond, D. D.; Kass, S. J.; Andrasik, F.; Raj, A. K.; Rupert, A. H. Vibrotactile Cueing as a Master Caution System for Visual Monitoring. Human Factors and Aerospace Safety 2002, 2 (4), 339-354.

[95] Dobbins, T.; Samways, S. The Use of Tactile Navigation Displays for the Reduction of Disorientation in Maritime Environments. RTO Meeting Proceedings, La Coruña, Spain, 2002; Vol. 86, pp 33-1-33-4.

[96] Dorneich, M. C.; Ververs, P. M.; Whitlow, S. D.; Mathan, S. Evaluation of a Tactile Navigation Cueing System and Real-Time Assessment of Cognitive State. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, San Francisco, CA, 2006; pp 2600-2604.

[97] Elliott, L. R.; Duistermaat, M.; Redden, E. S.; Van Erp, J. Multimodal Guidance for Land Navigation; ARL-TR-4295; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2007.

[98] Elliott, L. R.; Van Erp, J. B. F.; Redden, E. S.; Duistermaat, M. Field-Based Validation of a Tactile Navigation Device. IEEE Journal, Transactions on Haptics, 2010, 99.

[99] Elliott, L. R.; Redden, E. S.; Pettitt, R. A.; Carstens, C. B.; Van Erp, J.; Duistermaat, M. Tactile Guidance for Land Navigation; ARL-TR-3814; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

[100] Elliott, L. R.; Coovert, M. D.; Prewett, M.; Walvord, A. G.; Saboe, K.; Johnson, R. A Review and Meta Analysis of Vibrotactile and Visual Information Displays; ARL-TR-4955; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, September 2009.

[101] Ferris, T. K.; Sarter, N. B. Cross-Modal Links Among Vision, Audition, and Touch in Complex Environments. Human Factors 2008, 50 (1), 17-26.

[102] Ferris, T.; Penfold, R.; Hameed, S.; Sarter, N. The Implications of Crossmodal Links in Attention for the Design of Multimodal Interfaces: A Driving Simulation Study. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, San Francisco, CA, 2006; pp 406-409.

[103] Fred Paas, Alexander Renkl, John Sweller. Cognitive Load Theory and Instructional Design: Recent Developments. Educational Psychologist, Vol. 38, Iss. 1, 2003

[104] Fred Paas, Juhani E. Tuovinen, Huib Tabbers, Pascal W. M. Van Gerven. Cognitive Load Measurement as a Means to Advance Cognitive Load Theory. Educational Psychologist, Vol. 38, Iss. 1, 2003

[105] Fuchs, S.; Johnston, M.; Hale, K. S.; Axelsson, P. Results From Pilot Testing a System for Tactile Reception of Advanced Patterns (STRAP). Proceedings of the Human Factors and Ergonomics Society 52th Annual Meeting, New York, NY, 2008; pp 1302-1306.

[106] Geldard, F. A. Adventures in Tactile Literacy. American Psychologist 1957, 12, 115-124. Geldard, F. A. Some Neglected Possibilities of Communication. Science 1960, 131, 1583-1588.

[107] Gemperle, F.; Ota, N.; Siewiorek, D. Design of a Wearable Tactile Display. Proceedings of the 5th IEEE International Symposium on Wearable Computers, Zurich, Switzerland, 2001; pp 5-12.

[108] Gemperle, F.; Hirsch, T.; Goode, A.; Pearce, J.; Siewiorek, D.; Smailigic, A. Wearable Vibro- Tactile Display, 1 May 2003. http://www.ices.cmu.edu/reports/040403.pdf. (accessed 27 August 2009).

[109] Gilson, R. D.; Redden, E. S.; Elliott, L. R. Remote Tactile Displays for Future Soldiers; ARL-SR-0152; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2007.

[110] Glumm, M. M.; Kehring, K. L.; White, T. L. Effects of Tactile, Visual, and Auditory Cues About Threat Location on Target Acquisition and Attention to Visual and Auditory Communications; ARL-TR-3863; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

[111] Glumm, M. M.; Kehring, K. L.; White, T. L. Effects of Multimodal Displays About Threat Location on Target Acquisition and Attention to Visual and Auditory Communications; ARL-TR-4074; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2007.

[112] Greenspan, J. D.; Bolanowski, S. J. The Psychophysics of Tactile Perception and Its Peripheral Physiological Basis. In Pain and Touch; Kruger, L., Ed.; Academic Press: New York, 1996; pp 25-103.

[113] Haas, E. C.; Edworthy, J. Designing Urgency Into Auditory Warnings Using Pitch, Speed and Loudness. Computing AND Control Engineering Journal 1996, 7 (4), 193-198.

[114] Haas, E.; Stachowiak, C. Multimodal Displays to Enhance Human Robot Interaction On-the- Move. Proceedings of Performance Metrics for Intelligent Systems Workshop, Gaithersburg, MD, 2007; pp 135-140.

[115] Haas, E.; Fields, M.; Hill, S.; Stachowiak, C. Extreme Scalability: Designing Interfaces and Algorithms for Soldier-Robotic Swarm Interaction; ARL-TR-4800; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2009a.

[116] Haas, E. C.; Stachowiak, C.; White, T.; Pillalamarri, K.; Feng, T. Tactile and Auditory Cues to Communicate Multiple Levels of Information. Proceedings of the International Multisensory Research Forum (IMRF), New York, NY, 2009b.

[117] Hoggan, E.; Brewster, S. Designing Audio and Tactile Crossmodal Icons for Mobile Devices. Proceedings of ACM Inter-

national Conference on Multimodal Interfaces, Nagoya, Japan, 2007.

[118] Johnson, K. O. The Roles and Functions of Cutaneous Mechanoreceptors. Current Opinions in Neurobiology 2001, 11, 455-461.

[119] Johnson, K. O.; Phillips, J. R. Tactile Spatial Resolution. I. Two-Point Discrimination, Gap Detection, Grating Resolution, and Letter Recognition. Journal of Neurophysiology 1981, 46 (6), 1177-1191.

[120] Jones, M. B.; Vierck, C. J. Length Discrimination on the Skin. American Journal of Psychology 1973, 86, 49-60.

[121] Jones, L. A.; Sarter, N. B. Tactile Displays: Guidance for Their Design and Application. Human Factors 2008, 50 (1), 90-111.

[122] Jones, L. A.; Lockyer, B.; Piateski, E. Tactile Display and Vibrotactile Pattern Recognition on the Torso. Advanced Robotics 2006, 20, 1359-1374.

[123] Jones, L. A.; Kunkel, J.; Piateski, E. Vibrotactile Pattern Recognition on the Arm and Back. Perception 2009, 38, 52-68.

[124] Kaaresoja, T.; Linjama, J. Perception of Short Tactile Pulses Generated by a Vibration Motor in a Mobile Phone. Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Pisa, Italy, 2005; pp 471-472.

[125] Krausman, A. S.; White, T. L. Tactile Displays and Detectability of Vibrotactile Patterns as Combat Assault Maneuvers Are Being Performed; ARL-TR-3998; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006a.

[126] Krausman, A. S.; White, T. L. Using the Tactile Modality as a Communication Medium for Dismounted Soldiers. Proceedings

of the Human Factors and Ergonomics Society 51st Annual Meeting, Baltimore, MD, 2006b; pp 1158-1162.

[127] Krausman, A. S.; White, T. L. Detection and Localization of Vibrotactile Signals in Moving Vehicles; ARL-TR-4463; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2008.

[128] Krausman, A. S.; Elliott, L. R.; Pettitt, R. A. Effects of Visual, Auditory, and Tactile Alerts on Platoon Leader Performance and Decision Making; ARL-TR-3633; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2005.

[129] Krausman, A. S.; Pettitt, R. A.; Elliott, L. R. Effects of Redundant Alerts on Platoon Leader Performance and Decision Making; ARL-TR-3999; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2007.

[130] Levine, M. W.; Shefner, J. M. Sensation AND Perception, 2nd ed.; Brooks/Cole: Pacific Grove, CA, 1991.

[131] Lindeman, R. W.; Yanagida, Y.; Sibert, J. L.; Lavine, R. Effective Vibrotactile Cueing in a Visual Search Task. Proceedings of IFIP INTERACT03 Human-Computer Interaction, Zurich, Switzerland, 2003; pp 89-96.

[132] Lindeman, R. W.; Sibert, J. L.; Mendez-Mendez, E.; Patil, S.; Phifer, D. Effectiveness of Directional Vibrotactile Cueing on a Building-Clearing Task. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Portland, OR, 2005; pp 271-280.

[133] Macefield, V. G. Physiological Characteristics of Low-Threshold Mechanoreceptors in Joints, Muscle and Skin in Human Subjects. Proceedings of the Symposium From Osseointegration to Osseoperception: The Functional Translation, Sydney, Australia, 2005; Vol. 32, pp 135-144.

[134] Matlin, M. W. Perception; Allyn and Bacon: Newton, MA, 1983.

[135] McGrath, B. J.; Estrada, A.; Braithwaite, M. G.; Raj, A. K.; Rupert, A. H. Tactile Situation Awareness System Flight Demonstration Final Report; USAARL Report No. 2004-10; Naval Aerospace Medical Research Laboratory: Pensacola, FL, 2004.

[136] McKinley, R.; Gallimore, J.; Lanning, C.; Simmons, C. Tactile Cueing for Target Acquisition and Identification; AFRL-HE-WP-TP-2005-0009; U.S. Air Force Research Laboratory: Wright-Patterson Air Force Base, OH, 2005.

[137] Merlo, J. L.; Gilson, R.; Hancock, P. A. Crossmodal Congruency Benefits for Tactile and Visual Signaling. Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting, New York, NY, 2008; pp 1297-1301.

[138] Merlo, J. L.; Terrence, P. I.; Stafford, S.; Gilson, R. D.; Hancock, P. A.; Redden, E. S.; Krausman, A.; Carstens, C. B.; Pettitt, R.; White, T. L. Communicating Through the Use of Vibrotactile Displays for Dismounted and Mounted Soldiers. Proceedings of the 25th Army Science Conference, Orlando, FL, 2006.

[139] Mohebbi, R.; Gray, R.; Tan, H. Z. Driver Reaction Time to Tactile and Auditory Rear-End Collisions Warnings While Talking on a Cell Phone. Human Factors 2009, 51 (1), 102-110.

[140] Mortimer, B. J. P.; Zets, G. A.; Cholewiak, R. W. Vibrotactile Transduction and Transducers. Journal of the Acoustical Society of America 2007, 121 (5), 2970-2977.

[141] Myles, K.; Kalb, J. T. Vibrotactile Sensitivity of the Head; ARL-TR-4696; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2009.

[142] Oskarsson, P.; Eriksson, L.; Lif, P.; Lindahl, B.; Hedström, J. Multimodal Threat Cueing in Simulated Combat Vehicle. Pro-

ceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting, New York, NY, 2008; pp 1287-1291.

[143] Pettitt, R. A.; Redden, E. S.; Carstens, C. B. Comparison of Army Hand and Arm Signals to a Covert Tactile Communication System in a Dynamic Environment; ARL-TR-3838; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

[144] Piateski, E.; Jones, L. Vibrotactile Pattern Recognition on the Arm and Torso. Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Pisa, Italy, 2005; pp 90-95.

[145] Redden, E. S. Findings from a Multi-Year Investigation of Tactile and Multi-Modal Displays. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, San Francisco, CA, 2006; pp 1697-1700.

[146] Redden, E. S.; Carstens, C. B.; Turner, D. D.; Elliott, L. R. Localization of Tactile Signals as a Function of Tactor Operating Characteristics; ARL-TR-3971; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

[147] Rothenberg, M.; Verrillo, R. T.; Zahorian, S. A.; Brachman, M. L.; Bolanowski, S. J. Vibrotactile Frequency for Encoding a Speech Parameter. Journal of the Acoustical Society of America 1977, 62 (4), 1003-1012.

[148] Rupert, A. H.; McGrath, B. J.; Griffin, M. A Tool to Maintain Spatial Orientation and Situation Awareness for Operators of Manned and Unmanned Aerial Vehicles and other Military Motion Platforms. RTO Meeting Proceedings, La Coruña, Spain, 2002; Vol. 86, pp 31-1-31-15.

[149] Savick, D. S.; Elliott, L. R.; Zubal, O.; Stachowiak, C. The Effect of Audio and Tactile Cues on Soldier Decision Making and Navigation in Complex Simulation Scenarios; ARL-TR-4413;

U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2008.

[150] Schiffman, H. R. Sensation and Perception; Wiley: New York, 2000. Sekuler, R.; Blake, R. Perception, 3rd ed.; McGraw-Hill: New York, 1990.

[151] Sherrick, C. E.; Cholewiak, R. W. Cutaneous Sensitivity. In Handbook of Perception and Human Performance; Boff, K., Kaufman, L., Thomas, J. L., Eds.; Wiley: New York, 1986; 12-1-12-58.

[152] Sklar, A. E.; Sarter, N. B. Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event-Driven Domains. Human Factors 1999, 41 (4), 543-552.

[153] Smets, N. J. J. M.; te Brake, G. M.; Lindenberg, J.; Neerincx, M. A. Effects of Mobile Map Orientation and Tactile Feedback on Navigation Speed and Situation Awareness. Proceedings of the 10th International Conference on Human Computer Interaction With Mobile Devices and Services, Amsterdam, the Netherlands, 2008; pp 73-80.

[154] Sorkin, R. D. Design of Auditory and Tactile Displays. In Handbook of Human Factors; Salvendy, G., Ed.; Wiley: New York, 1987; pp 549-576.

[155] Stevens, J. C.; Choo, K. K. Spatial Acuity of the Body Surface Over the Life Span. Somatosensory and Motor Research 1996, 13 (2), 153-166.

[156] Stevens, J. C.; Green, J. C. History of Research on Touch. In Pain and Touch; Kruger, L., Ed.; Academic Press: New York, 1996; pp 1-23.

[157] Tan, H. Z.; Gray, R.; Young, J. J.; Traylor, R. A Haptic Back Display for Attentional and Directional Cueing. Haptics-e [Online] 2003, 3 (1).

[158] Terrence, P. I.; Brill, J. C.; Gilson, R. D. Body Orientation and the Perception of Spatial Auditory and Tactile Cues. Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, Orlando, FL, 2005; pp 1663-1667.

[159] Tilak, R.; Xholi, I.; Schowalter, D.; Ferris, T.; Hameed, S.; Sarter, N. Crossmodal Links in Attention in the Driving Environment: The Roles of Cueing Modality, Signal Timing, and Workload. Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting, New York, NY, 2008; pp 1815-1819.

[160] Vallbo, Å. B.; Olausson, H.; Wessberg, J.; Kakuda, N. Receptive Field Characteristics of Tactile Unites With Myelinated Afferents in Hairy Skin of Human Subjects. Journal of Physiology 1995, 483.3, 783-795.

[161] Van Erp, J. B. F. Tactile Displays in Virtual Environments. Proceedings of the RTO HFM Workshop, The Hague, The Netherlands, 2000; pp 10-1-10-7.

[162] Van Erp, J. B. F. Guidelines for the Use of Vibro-Tactile Displays in Human Computer Interaction. Proceedings of Eurohaptics, Edingburgh, UK, 2002; pp 18-22.

[163] Van Erp, J. B. F. Presenting Directions With a Vibrotactile Torso Display. Ergonomics 2005, 48 (3), 302-313.

[164] Van Erp, J. B. F. Tactile Displays for Navigation and Orientation. Perception and Behavior; Mostert AND Van Onderen: Leiden, The Netherlands, 2007.

[165] Van Erp, J. B. F. Absolute Localization of Vibrotactile Stimuli on the Torso. Perception and Psychophysics 2008, 70 (6), 1016-1023.

[166] Van Erp, J. B. F.; Van Den Dobbelsteen, J. J. On the Design of Tactile Displays; TNO-Report TM-98-B012; TNO Human Factors Research Institute: Soesterberg, The Netherlands, 1998.

[167] Van Erp, J. B. F.; Werkhoven, P. Validation of Principles for Tactile Navigation Displays. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, San Francisco, CA, 2006; pp 1687-1691.

[168] Van Erp, J. B. F.; Self, B. P. Introduction to Tactile Displays in Military Environments. Van Erp, J. B. F., Self, B. P., Eds.; In Tactile Displays for Orientation, Navigation and Communication in Air, Sea, and Land Environments; RTO-TR-HFM-122; Research and Technology Organization and North Atlantic Treaty Organization: Neuilly-sur-Seine Cedex, France, 2008; pp 1-1 - 1-18.

[169] Van Erp, J. B. F.; Veltman, J. A.; Van Veen, H. A. H. C.; Oving, A. V. Tactile Torso Display as Countermeasure to Reduce Night Vision Goggles Induced Drift. Proceedings of the RTO HFM Symposium, La Coruña, Spain, 2002; pp 49-1-49-8.

[170] Van Erp, J. B. F.; Van Veen, H. A. H. C.; Jansen, C.; Dobbins, T. Waypoint Navigation With a Vibrotactile Waist Belt. ACM Transactions on Applied Perception 2005, 2 (2), 106-117.

[171] Van Erp, J. B. F.; Groen, E. L.; Bos, J. E.; Van Veen, H. A. H. C. A Tactile Cockpit Instrument Supports the Control of Self Motion During Spatial Disorientation. Human Factors 2006, 48 (2), 219-228.

[172] Van Erp, J. B. F.; Eriksson, L.; Levin, B.; Carlander, O.; Veltman, J. A.; Vos, W. K. Tactile Cueing Effects on Performance in Simulated Aerial Combat with High Acceleration. Aviation, Space, and Environmental Medicine 2007, 78 (12), 1128-1134.

[173] Verrillo, R. T. Effect of Contactor Area on the Vibrotactile Threshold. Journal of the Acoustical Society of America 1963, 35, 1962-1966.

[174] Verrillo, R. T. Vibrotactile Thresholds for Hairy Skin. Journal of Experimental Psychology 1996, 72 (1), 47-50.

[175] Von Békésy, G. Synchronism of Neural Discharges and Their Demultiplication in Pitch Perception on the Skin and in Hearing. Journal of the Acoustical Society of America 1959, 27, 830-841.

[176] Weber, E. H. The Sense of Touch; De Tactu translated by Ross, H. E., Der Tastsinn translated by Murray, D. J.; Academic Press: New York, 1978 (original works published in 1834).

[177] Weinstein, S. Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part Sex, and Laterality. In The Skin Senses; Kenshalo, D. R., Ed.; Charles C. Thomas: Springfield, IL, 1968; pp 195-222.

[178] White, T. L.; Kehring, K. L.; Glumm, M. M. Effects of Unimodal and Multimodal Cues About Threat Locations on Target Acquisition and Workload. Military Psychology 2009, 21 (4), 497-512.

[179] Wickens, C. D. Multiple Resources and Performance Prediction. Theoretical Issues in Ergonomics Science 2002, 3 (2), 159-177.

[180] Bulatov, V., Gardner, J. (1998). Visualization by People without Vision. Proceedings of the Workshop on Content Visualization and Intermediate Representations, Montreal, CA, August 15, 1998, pp 103-108.

[181] Gardner, J. (2002). Hands-on Tutorial on Tiger and Win-Triangle. Proceedings of the 2002 CSUN International Conference on Technology and Persons with Disabilities, Los Angeles, CA, March 20-23, 2002. http://www.csun.edu/cod/conf/2002/proceedings/300.htm.

[182] Gardner, J., Bulatov, V. (1998). Non-Visual Access to Non-Textual Information through DotsPlus and Accessible VRML. Computers and Assistive Technology ICCHP'98. Proceedings of the 15th IFIP World Computer Congress, 31 August - 4 September, 1998, Vienna and Budapest, Edwards, A., Arato, A., Zagler,

W. eds, Austrian Computer Society on behalf of the IFIP, Vol 118 pp 136-140.

[183] Gardner, J., Bulatov, V. (2001). Smart Figures, SVG, and Accessible Web Graphics. Proceedings of the 2001 CSUN International Conference on Technology and Persons with Disabilities, Los Angeles, CA, March 21-24, 2001. http://www.csun.edu/cod/conf/2001/proceedings/0103gardner.htm

[184] Gardner, J., Bulatov, V. (2004). Complete Access to All Paper and Computer Forms, Tables, and Charts. Proceedings of the 2004 CSUN International Conference on Technology and Persons with Disabilities, Los Angeles, CA, March 17-20, 2004. http://www.csun.edu/cod/conf/2004/proceedings/162.htm

[185] Gardner, J., Bargi Rangin, H., Bulatov, V., Kowallik, H., Lundquist, R. (1997). The Problem of Accessing Non-Textual Information on the Web. Proceedings of the 1997 Conference of the W3 Consortium, Santa Clara, CA, April, 1997. http:/dots.physics.orst.edu/publications/www6.html

[186] Landau, S. (2003). Use of the Talking Tactile Tablet in Mathematics Testing. Journal of Visual Impairment and Blindness, 97, 85-96.

[187] Loetzsch, J. (1994). Computer-Aided Access to Tactile Graphics for the Blind. Proceedings of the 4th International Conference on Computers Helping People, Vienna 1994, Lecture Notes in Computer Science, 860, Springer-Verlag, 575-581.

[188] Loetzsch, J., Roedig, G. (1996). Interactive Tactile Media in Training Visually Handicapped People. New Technologies in the Education of the Visually Handicapped, Proceedings of the Conference, Paris, June 10-11, 1996, Burger, D. (Ed) INSERM John Libbey 1996, 155-160.

[189] Parkes, D. (1988). Nomad: an Audio-Tactile Tool for the Acquisition, Use and Management of Spatially Distributed Informa-

tion by Partially Sighted and Blind Persons. Proceedings of the Second International Symposium on Maps and Graphics for Visually Handicapped People, King's College, University of London, eds Tatham, A. F., and Dodds, A. G., 24-29.

[190] Parkes, D. (1991). Nomad: Enabling Access to Graphics and Text Based Information for Blind, Visually Impaired and Other Disability Groups. Conference Proceedings, Vol. 5. World congress on Technology 1991, Arlington, Virginia, 690-714.

[191] Parkes, D. (1995). Access to Complex Environments for Blind People Multi-Media maps, Plans and Virtual Travel. Proceedings of 17th International Cartographic Conference, Barcelona, V. 2, 2449-2460.

[192] Parkes, D. (1998). Tactile Audio Tools for Graphicacy and Mobility. A Circle is either a Circle or it is not a Circle. The British Journal of Visual Impairment, 16, 98-104.

[193] Sahyun, S., Bulatov, V., Gardner, J., Preddy, M. (1998). A How-to Demonstration for Making Tactile Figures and Tactile Formatted Math Using the Tactile Graphics Embosser. Proceedings of the 1998 CSUN International Conference on Technology and Persons with Disabilities, Los Angeles, CA, March 1998. Online at `http://www.csun.edu/cod/conf/1998/proceedings/csun98_103.htm`

[194] Sahyun, S., Gardner, J., Gardner, C. (1998), Audio and Haptic Access to Math and Science - Audio graphs, Triangle, the MathPlus Toolbox, and the Tiger printer. Computers and Assistive Technology, ICCHP '98, Proceedings of the 15th IFIP World Computer Congress, 31 August - 4 September 1998, Vienna and Budapest, Edwards, A., Arato, A., Zagler, W. eds, Austrian Computer Society on behalf of the IFIP,V. 118, 521-523.

[195] W3C (2005) Scalable Vector Graphics, retrieved February 2011 from `http://www.w3.org/Graphics/SVG/`