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"*It's like holding a human heart*": the design of Vital + Morph, a shape-changing interface for remote monitoring

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Abstract Based on the concept of data *physicalization*, we developed Vital + Morph, an interactive surface for remote connection and awareness of clinical data. It enables users located in remote places to monitor and feel the vital signs measured from a hospitalized person through shape-change. We propose shape-changing interfaces as a way of making data *physicalization* a richer, intriguing and memorable experience that communicates complex information and insights about data. To demonstrate and validate our proposed concept, we developed an exploratory study about the design and its implications. For evaluating the social impact of shape-changing interfaces in the context of remote monitoring, we presented Vital + Morph in several Media Art festivals. We collected and analyzed the feedback from the visitors during the exhibitions, and discussed the possibilities of the proposed system. A preliminary evaluation shows how shape-changing displays are perceived by users, which establishes not only the potential benefits but also highlights the concerns that several users have raised. Through this study, we aim to contribute to the design of remote monitoring systems by providing a novel approach for displaying clinical data that consider the richness of the physical world. In today's information-driven society, we should not just focus on how abstract data are collected and analyzed, but also on how it can be presented and incorporated into our daily lives.

Keywords Shape-changing interfaces · Remote monitoring · Information technologies · Haptics · Vital signs

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1 Introduction

Remote monitoring can be regarded as a subdivision of telemedicine that involves the use of audio, video, telecommunication and information processing techniques to remotely monitor patient status. Usually, the data collected are displayed on screens and monitors. However, the commonly used numerical and waveform visualization techniques and pixel-based displays are unable to adequately depict the embodiment of data and to intuitively represent data in forms easy for our consumption and comprehension (Van de Moere 2008).

Data collection and analysis is usually perceived to be within the exclusive domain of scientific enquiry. The most common image that comes to our mind whenever data are mentioned is a series of numbers presented in a spreadsheet. However, because of the widespread use of embedded sensor networks and mobile systems, data have penetrated our everyday lives, which has raised a new set of questions. Most of these questions pertain to the integration and engagement of data. Many questions are also related to the methods used for displaying data and making it comprehensible to humans. This is done by the visual representation of data present in the form of a sheet filled with numbers as histograms or charts. We can notice that in the common discourse there is a tendency to talk about data in a general and abstract manner.

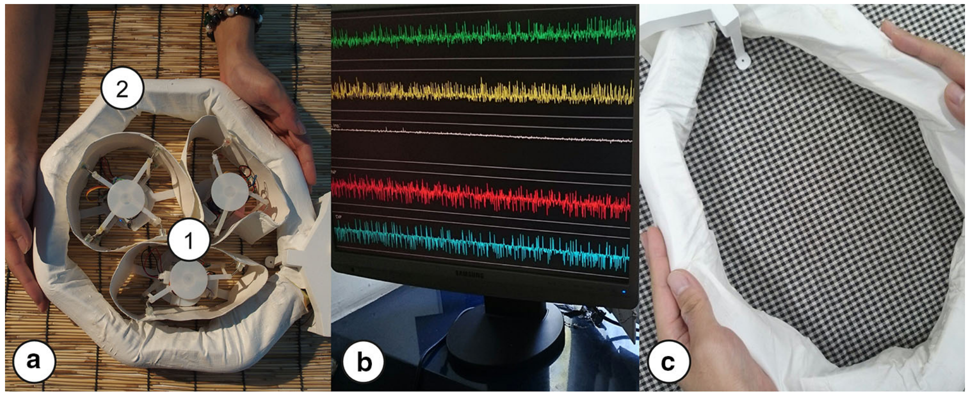


Fig. 1 A complete view of Vital + Morph and its main components: **a** the Vital + Morph interface, composed of (*1*) the Vitals, and (*2*) Morph; **b** a software that simulates the functions of a vital signs monitoring station; **c** another morph that can be placed at a different place from **a** and can communicate with it

This attitude reveals a belief that data can be disembodied from its source. However, data are not neutral; it can actually help people take appropriate action. In the healthcare domain, the expert who can analyze and interpret a patient's data has become extremely critical. In addition, medical device firms often make it very difficult for patients to access their own data (Iaconesi and Persico 2016). However, we are witnessing the emergence of a tendency that Nafus (2016) calls the *domestication of data*, which can be defined as the process of consumption and adoption of data using widely available technologies such as personal computers or mobile phones. Though, in the past, even these technologies were originally designed for very specific applications, they have quickly proliferated once people started adopting them in their everyday lives. The concept of *domestication of data* does not refer to a process of making people 'data scientists'. On the contrary, it concentrates on emerging and possible ways of using, sharing, and engaging with abstract data, which also include clinical data. To become a part of our everyday experience and environment, data will need to be transformed from an abstract entity to an explicit and tangible material entity. Here, tangible does not necessarily mean that abstract data can be touched or grasped; it just implies the presence of data in the physical world to help people relate to its existence (Ishii and Ullmer 1997).

Even though digital and information technologies have commonly been described as 'immaterial', in recent years, there has been a resurgence in the interest in exploring the material qualities of abstract data. Driven by the increasing prevalence of Internet of Things (IoT), this discussion has been taken up in fields such as Media Art and human–computer interaction (HCI). The notion of *neomateriality* (Paul 2015) captures such emerging forms of reality wherein digitally augmented objects and appliances transform everything into information. Materials that are shaped by information objects mirror a reality composed of embedded processes and data. Recently, in HCI, the practice of data *physicalization* (Jansen et al. 2015) has been introduced as a novel paradigm for making abstract data perceptible to humans by encoding it into the physical qualities of materials. In contrast to common approaches like data visualization and data sonification, *physicalization* has the potential to open new ways of physically engaging people with information (Willett et al. 2017). The emergent area of research on shape-changing interfaces is directly related to such issues. The goal of shape-changing interfaces is to represent the continuous change in the flow of digital information using novel materials that can depict data based on its physical qualities.

In this study, we introduce the development and evaluation of Vital + Morph (Fig. 1), a shape-changing interface used for remote monitoring through data *physicalization*. Vital + Morph is composed of a series of reactive materials that can physically represent the vital signs of a patient located remotely in real time, for the benefit of his/her parents and friends. Through this research, we aim to explore how the engagement and awareness of physiological measurements of a remote patient can be improved through dynamic *physicalization* and shape-change. We will test our system for a specific case based on a fictional scenario of remote monitoring, involving a patient hospitalized in the Intensive Care Unit (ICU). The patient's vital signs are physicalized at a remote location using the Vital + Morph technique. Through this study, we will review the conceptual spectrum of representing abstract information in a physical manner and relate it to the emerging field of shape-changing displays. The design metaphors, technical implementation, and system evaluation will be described in detail. To assess and prove the proposed concept, we will present an exploratory study in two steps. The first step involves the evaluation of the system's basic performance. The second step is a user study conducted during two festivals of Media Art, where Vital + Morph was presented as an interactive installation.

2 Design concept: bio-inspired principle

By designing Vital + Morph, we explored a bio-inspired approach not only as an aesthetic element, but also as a way to find novel designs for distributing abstract data in space, exploring ways to relate the data to material properties, and enabling interactions from the system's characteristics.

2.1 Life, data, and materials

The continuous production of information and communication of data are usually expressed through verbs such as "stream" and "flow". It is very common to refer to processes such as "data streaming" and "information flow". Such expressions evoke the image of the relentless movement that characterizes natural elements like air and water. In fact, this analogy can be extended to physiological processes like blood circulation or respiration. By observing such expressions, we can note that the invisible behavior of our information society is characterized by elements of movement, changes in time, and production of energy. However, this flow cannot be physically perceived by humans. As a simple example, we cannot hold a stream of water; we can just feel it by inserting the hands into a torrent. Similarly, the flow of electrons or the waves of a Wi-Fi network cannot be physically grasped. The use of such expressions in daily life suggests that maybe the next step in information society will involve us getting physically closer and connected to the unstoppable flow of digital information and data production. Shape-changing interfaces seem to be a suitable way of facilitating such a shift. However, there is still a big gap: the difficulty in finding materials that can offer the same malleability that we can observe in simulations with 3D computer graphics and real-time synthesis of digital sounds. We have imagined and designed a novel material, a material capable of adapting its own characteristics to the flow, frequency and amplitude of the information, in our case, the vital signs. It should be similar to a rheological material, which is a material that can change its physical state in response to a received stimulus. For this, we have developed a perceptually equivalent system, which can mimic the behavior and qualities of this imaginary material.

2.2 Diatoms

Biological organisms have inspired artists, designers and engineers since a long time. Especially, architects have often referred to organisms for finding novel forms, and structural and aesthetic solutions. The impact can also be observed in product design, wherein the curved and organic styles have been used for rethinking the shape and form of different objects such as cars and photographic cameras. However, such bio-inspired approaches were only used for designing and shaping static objects and architectural elements (Lynn 1999). Moreover, information flow and data production happens in time. In his seminal work on biology, D'Arcy Thompson (1992) analyzes the evolution of organisms from the point of view of his theory of transformation. He noticed that the form of an organism and its evolution is an event in space and time. Most importantly, he said that from a mathematical point of view "organic form is found […] to be a function of time" (Thompson 1992). The aspect of time and its relations with shape-change thus becomes very important. Biological organisms are also well known for their efficient use of material, energy, and management of complex processes. Among the vast variety of these organisms, diatoms generate considerable interest. Diatoms are a large group of microscopic single-celled algae, which can be found in nearly every habitat characterized by water. They possess some interesting functional, structural and topological characteristics. We took some elements of diatoms as a reference for designing the functions, behavior, and appearance of Vital + Morphs:

(a) *Transformation of external stimuli*: Diatoms are regarded as one of the largest groups of photoplanktons, which are organisms that, through a process of photosynthesis, take the sun's energy and convert it into nutrients. Because of this characteristic, diatoms represent one of the most vital components in ocean and fresh water ecosystems.

Implementation: Vital signs represent the 'nutrient' of the material that is brought to life by translating abstract data into physical motion and shape-change.

(b) *Deformability*: Diatoms not only take nutrients from light, they also absorb them through water. This is made possible by the elaborate perforations on their shell, made of a silica-based material. The cell wall is composed of a cytoskeletal structure called frustule that consists of two halves. The combination of the structural and the material qualities allows diatoms to perform significant deformations of their overall structure to withstand high loads.

Implementation Deformability became an important aspect of the design of our interface. We decided to distribute different degrees of deformability among the different elements. One element is deformed by the received data to display it through its surface, while another can be actively deformed by the users.

(c) *Morphology* Diatoms grow as single cells. However, they can form filaments and simple colonies. Such colonies are composed of cells connected usually by organic threads or by attaching to different substrates like plants.

Implementation From these characteristics, we derived the modularity and spatial configuration of the global Vital + Morph interface as a colony of *physicalizations*.

(d) *Monitoring and information retrieval* Diatoms are often specific to particular habitats because they exhibit tolerance to different environmental variables such as the chemical composition of the water in which they live. As a result, diatoms are used extensively in environmental assessment and monitoring. Since the silica walls do not decompose, diatom shells found in marine and lake sediments are used to interpret historical conditions of the environment.

Implementation Even though in Vital + Morph we have not incorporated the possibility of retrieving historical information, this function of diatoms, which allows them to display information through the characteristics of their shapes, is a fundamental concept used for the design of the interface.

3 Background and related work

Our research builds on three main strands of related work. First, we will discuss the most common strategies used in clinical environments for making physiological data perceptible to users such as physicians. In contrast to these approaches, we will then introduce some alternative methods for presenting abstract data in home-like environments. Special attention will be given to examples that explore the presentation of data through static physical artifacts, the concept termed as data *physicalization*. Lastly, we will extend such ideas through shape-changing interfaces and review examples from recent literature. Throughout this section, we will detail the background research and the open issues related to our research.

3.1 Vital signs and remote monitoring

Vital signs are measurements of the body's most basic functions widely evaluated in healthcare. These measurements are taken to assess the general physical health conditions of a patient, to detect potential diseases in advance, and to assess progress toward recovery. There are four primary vital signs which are considered standard in most medical settings: body temperature, heart rate, respiratory rate, and blood pressure. For the simplest cases, the measurement and monitoring of vital signs are performed directly by clinicians using their own senses or with the use of technological aids such as thermometers and stethoscopes. Such direct monitoring is a practice that connects the clinician and the patient through physical contact when they are at the same location. However, with the introduction of information technology in clinical environments, the act of measurement and analysis has become increasingly distinct (Nangalia et al. 2010). Now, between the clinician and the patient, multiple stages and processes have been devised. Measurements of vital signs are conducted using appropriate sensors and transmitted from the patient to clinician. Such measurements can be integrated with other historical data describing the state of the patient to provide in-depth analysis and to facilitate decision-making. Such a practice is commonly referred to as remote monitoring, which can be defined as the use of telecommunication technologies to provide and support healthcare when physical distance separates the participants. Patients and clinicians can be in different cities, countries, continents, or even in planets (Korhonen et al. 2003; Cermack 2006). One of the first successful applications of remote monitoring was observed in 1961, when the physiological data of the first human in space—the Russian astronaut Yuri Gagarin—were continuously monitored by doctors on earth. Recently, in HCI, several researchers have proposed the inclusion of family members and online communities in remote monitoring to make it a less socially disorganizing experience (Johnson and Ambrose 2006).

3.2 Perceptualization of physiological data

Even though many efforts have been made to develop new bio-sensing techniques and signal processing algorithms, little study has been conducted on the *perceptualization* of physiological data (Jovanon et al. 2001; Maciejewski et al. 2005). By the term *perceptualization,* we refer to the process of translation of abstract data and information into modalities that appeal to a variety of human senses. In remote monitoring, the most commonly used sense is the visual sense. Data are commonly presented through dedicated displays (CRT and digital screens) that visualize the different vital signs through time-series plots such as waveforms, and numerical values (Kusunoki et al. 2013). Such displays are an essential part of clinical care. However, such a way of presenting physiological measurements through waveform can be dated back to the first recording of a human electrocardiogram (ECG) done in 1887 by Augustus Waller. Even with the introduction of computer-based monitoring, such displays and visualizations have undergone little change (Görges and Staggers 2008). Only small enhancements, such as color displays or the inclusion of trending have been incorporated into displays (Drews and Westenskow 2016). Along with the visual, the auditory and haptic senses are also being addressed. Sound is mostly used for alerting clinicians of critical events with acoustic feedback-like alarms (Dubus and Bresin 2014). Vibro-tactile displays attached on the physicians' fingers have also been proposed and tested in a possible combination with auditory notifications (McLanders et al. 2014).

In recent years, multimodal type of displays has started to attract the attention of researchers and clinicians (Bitterman 2006). However, little attention has been directed towards finding alternative modalities for displaying clinical data that can be understood by ordinary people. If we are evaluating the possibility of integrating remote monitoring into daily-life environments, different strategies for the *perceptualization* of vital sign measurements should be considered.

3.3 Ambient displays

One way of making abstract data perceptible and integrating it with our living environments is through ambient displays (Wisneski et al. 1998). These are interfaces that convey information and abstract data to the user by encoding information in elements available in living environments, and presenting changes through output modalities such as light, sound, and motion embedded in devices that resemble household appliances (Heiner et al. 1999). The idea of *ambient media* emerged with the introduction of the concept of Ubiquitous Computing (Weiser 1991), and later, with the vision of Tangible Bits (Ishii and Ullmer 1997). This vision was driven by the idea of giving a physical form to digital information by making bits tangible and directly manipulable through a seamless coupling between physical objects and abstract data in the real world by creating a proximity quality to everyday human activities. Computation is widely spread in our environment, but digital information does not possess any inherent spatial layout or presence in the physical world. Ambient displays have gained an increasing interest in the community of HCI and Media Art, resulting in a growing body of research that explores the design space and possible usage of ambient media. However, it was very difficult to introduce such displays in the market and most of them still remain as prototypes. Through repeated user tests it was noticed that even if the comprehension of an ambient display increases over time, the display usage decreases over a long period of time (Mankoff et al. 2003).

3.4 Data physicalization

Recent innovations in low-cost fabrication and embedded computing have sparked a new interest in how physical artifacts can present and integrate digital information into our environment. Along with techniques such as data visualization and sonification, Jansen et al. (2015) have proposed data *physicalization*. Data *physicalization* is a way of encoding abstract data into material properties and using the inherent capabilities of objects to communicate meaning and functionality using the natural affordances they possess. This can lead to alternative representation media that learn from humans' experiences and interpret the world around them. However, physical representations of abstract data have been developed by humans since centuries. Such a way of representing information also played a role in shaping the horizons of science and culture in the last century. Let us look back at the molecular models of Penicillin created by Dorothy Crowfoot Hodgkin in 1945, or the physical model of myoglobin developed in 1958 by Kendrew and colleagues. Such *physicalizations* enabled better understanding of complex data sets and gave spatial representation to elements such as molecules. Data *physicalization* offers a multitude of potential benefits over its purely visual and sonic counterparts (Willett et al. 2017). First, abstract data encoded in the material qualities of a physical object can be directly manipulated. Such characteristics are very different from those of ambient displays, which are mostly based on ephemeral elements (such as light and air) and are mostly designed as peripheral devices. Second, the physical modality can offer a wider range of new possibilities for interaction compared to on-screen visualizations since *physicalizations* require active engagement from the user. If ambient displays are good at showing changes of data over time, data *physicalizations* can better embody information in objects that can be grabbed and actively explored by users. Third, data *physicalizations* can be integrated into the life and environment of users, allowing the presentation of abstract information in a more direct, complex and even pleasurable way compared to other types of media used for information presentation (Brown and Hurst 2012).

Data *physicalizations* can have also an artistic purpose. Digital data have rapidly become a new "material" used by artists to investigate the contemporary landscape. This trend was exemplified by the term *information aesthetics* (Manovich 2008), which describes visually pleasing artifacts that communicate information. An interesting example of information aesthetics is a *data sculpture* (Van de Moere 2008), which is a direct representation of data in a physical form with its only function being to convey the suitable meaning to viewers. However, the data mapping metaphor employed in *data sculpture*s may not be immediately understandable. This forces viewers to reflect on the process and on how data are embodied in a physical form. Moreover, viewers must interpret these data-driven objects by the affordances the objects convey. Information translated into physical artifacts can be grabbed, touched, and carried like souvenirs or jewelry. An interesting example of a *data sculptures* is the "Chemo Singing Bowl" (Barrass 2016). This is a 3D-printed sounding sculpture which embodies the data of blood pressure recorded over a period of 1 year from a patient who underwent chemotherapy for breast cancer.

However, despite the many examples that have been proposed, any investigation on the social impact and usage of such type of displays is still at a nascent stage.

3.5 Shape-changing interfaces

While static *physicalizations* can be useful and attractive, they must be designed and fabricated in advance, and modifications of their physical characteristics are often limited once created. If we refer to the original definition of ambient displays, we can see that its proposition was to turn everyday architectural spaces into interfaces. By changing the state of physical matter, *ambient media* can contain and be controlled by data-driven values. Even if a lot of work was done in controlling elements such as light and sound for the sake of deploying information, we are still exploring ways to make physical form equally mutable and controllable. Recent approaches tried to explore this possibility of controlling the physical characteristics of the interface (Vertegaal et al. 2008). Previous studies in the field of tangible user interfaces (TUIs) made use of physical actuation and motion as a way of embodying digital information (Pangaro et al. 2002). This was viewed as a 'logical step' in TUIs, where "physical, tangible elements are not merely dynamically coupled to the digital attributes and information, but are themselves dynamic, self-reconfigurable devices that can change their physical properties depending on the state of the interfaces, the user, or the environment" (Poupyrev et al. 2007). Mechanical actuation has been used to preserve the consistency between the digital and the physical world. Examples include dynamic force-feedback displays for virtual reality (Iwata et al. 2001, 2005) or physical *renderings* of computer-simulated 3D models.[1]

The definition of shape-changing interfaces was introduced for the first time by Coelho and Zigelbaum (2011) for describing an emergent class of interfaces that aims to make use of computationally enabled materials and soft mechanics for the creation of transformable surfaces. This concept was driven mainly by the availability and the growing volume of research on the so-called *smart materials*. Shape-changing materials can be defined as materials that undergo a mechanical deformation under the influence of direct or indirect stimuli. Information delivery is a key use of shape-change and dynamic *data physicalization* can be considered as one of its most interesting and challenging fields of applications.

However, most of the current dynamic *physicalizations* make use of widely used visual metaphors borrowed from data visualization such as pie charts[2] and animated bar charts (Follmer et al. 2013; Hardy et al. 2015; Taher et al. 2017). These shape-changing interfaces support the translation of pixel-based data by translating the change in a pixel's value into corresponding changes in height. This is only one of the many possibilities that can be explored, such as the mapping of data to physical variables of materials such as smoothness, hardness, sponginess, all of which provide additional feedback and methods for data *physicalization* (Jansen et al. 2013). Shape-changing interfaces have been also explored in the field of telepresence, such as rendering of physical parts of a distant user (Leithinger et al. 2014), or supporting intimate connections by enriching mobile phones with shape-changing characteristics (Hemmert et al. 2013, Park et al. 2015). Even though most of the examples mentioned above are presented using mechanical or pneumatic actuation, the long-term goal of such research is to directly control and make use of material properties on a molecular level, and embody digital information directly into material properties. This has led to exploration of techniques mutated from chemistry and synthetic biology such as the use of magnetorheological materials (Wakita et al. 2010) and dynamic skin synthesized by living cells (Yao et al. 2015). The vision of "Radical Atoms" (Ishii et al. 2012) represents one of the main driving forces in this research area because it poses some very fundamental questions: how to interact with physical interfaces that transform their shape, conform to the constraints and inform users? But even as many researchers have tried to answer such questions in different ways in recent years, the answers are still not clear and are mostly tentative.

Though such a long-term goal seems very exciting and promising, the research on shape-changing interfaces is still at a very nascent stage. As noted by Rasmussen et al. (2012) there is a lack of application focus on specific scenarios, and the direction this research will take is still not clear. In addition, there are no shared or proven evaluation methods for such interfaces. This is because most of the research is focused on exploring and developing enabling technologies. The lack of adequate studies makes it difficult to evaluate or imagine the potential social impacts and implications of shape-changing interfaces.

We can see that even though the *perceptualization* of vital signs has been investigated, only visual and auditory displays have been considered. We have observed that there are very few studies that have used dynamic physical interfaces to present and display data, and even fewer studies have investigated the interactions and social impact of such shape-changing interfaces. Through Vital + Morph, we aim to contribute to the current research on dynamic data *physicalizations* by exploring the relations between physiological data, materials, and shape-change in the context of remote monitoring. We are particularly interested in investigating design metaphors that differ from current examples through a bio-inspired design.

4 Design requirements and system configuration

Vital + Morph is composed of two main elements: (1) five self-actuated devices enclosed in (2) a deformable container. We named the former Vitals and the latter Morph (Fig. 2). In this section, we introduce the design guidelines and functions of Vital + Morph. We will simulate a

[1] https://artcom.de/en/project/kinetic-sculpture/.

[2] https://www.microsoft.com/en-us/research/project/physical-charts/.

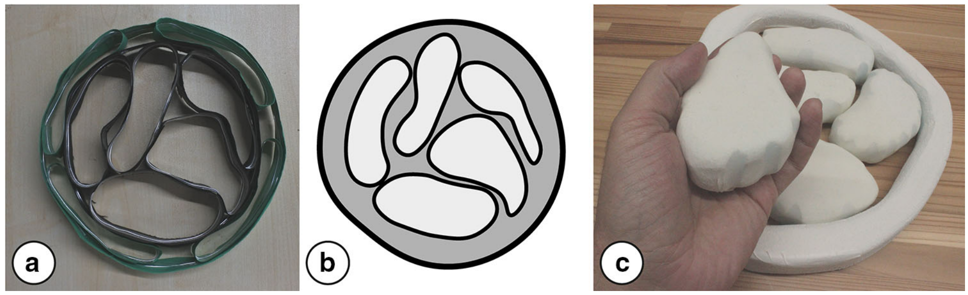


Fig. 2 Three studies of the form and spatial layouts of Vital + Morph inspired by diatoms: **a** a paper model; **b** a graphical representation; **c** a physical model used for testing the possible shapes and dimensions

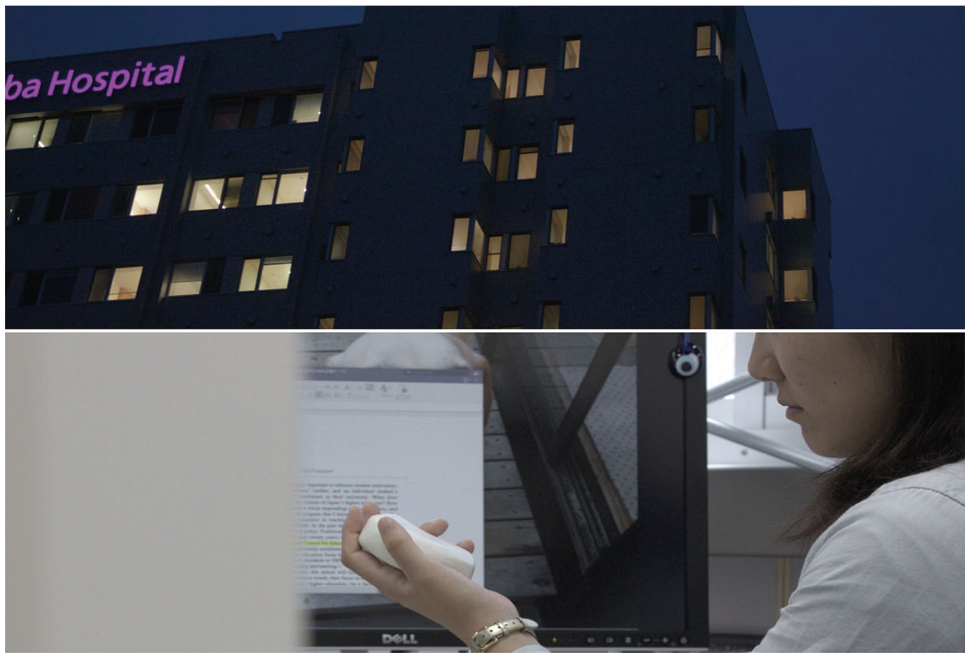


Fig. 3 A representation of the envisioned scenario: remote monitoring of a hospitalized person by a family member through the use of Vital + Morph

fictional scenario that we have developed to place Vital + Morph in context, and help readers understand the aims of the project better. This scenario will also provide a reference for the user study and future applications that will be discussed later in this study. Lastly, we present the design metaphor chosen for designing the appearance and the functions.

4.1 Fictional scenario

Mrs. Ohnuki lives in Japan with her husband Mr. Antonini and their two children. Mr. Antonini's mother, named Giovanna, is hospitalized in Italy following a difficult surgery. Since the couple lives in Japan, it is difficult for them to remain updated about the condition of Giovanna, which is quite complex. She suffers from respiratory issues caused by the surgery and also due to her age, which is 80 years. The family in Japan has a Vital + Morph installed in their living room, barring the heart rate monitor, which Takeo, Mrs. Ohnuki's son, keeps near his bed. In the morning, the family members meet around the display and monitor the Vitals. They notice that the indicator associated with the respiration is moving slow, while the one that indicates the pulmonary arterial pressure is behaving erratically. Before leaving home, Mr. Antonini takes these two Vitals with him. The other family members decide to split the others. In the evening, when they all come back home, they will put them back together. Before leaving, Mrs. Ohnuki slowly moves the Morph (Fig. 3).

4.2 Design guidelines

To implement our concept, we conceived three main design guidelines. The first concerns the Vitals, the second the Morph, and the third is a combination of both. The different characteristics expressed by these guidelines will be assessed and tested later in this study (Sects. 5 and 6) through an evaluation of the system performances and a use case.

(1) *Dynamic physicalization of vital signs* The Vitals should not be designed for just analyzing data, but also for interpreting, or feeling, it. Each Vital must be able to

receive a specific stream of data, display it through shape-change of its surface, and address either the visual or the tactile channel. In the current application, we choose five vital elements, since this is the number of the fundamental vital signs. In this case, the Vitals should also act as a physical surrogate of a remotely located patient. With respect to the form factor, the Vitals should be self-contained and autonomous (both in terms of power and communication capabilities) and have a shape and dimension suitable for a human hand. The user must be able to grab the Vitals from inside the Morph, and carry them around.

(2) *Mediated remote touch* The Morph must perform two functions: (1) it should act as a constraint for the Vitals by delimiting the area where they can be placed; (2) it should be suitable for remote communication through *shape-sharing*. If the Vitals are used for displaying the vital signs received from the Hospital, the Morph is conceived with the opposite function. It should enable two-way communication between the two places. By linking two Vital + Morphs through an internet connection, it should be possible for the patient and his/her relatives to communicate through the Morphs. The deformations caused on one side are reflected on the other interface. Like the Vitals, the shape-changing characteristics of the Morph should be able to address and appeal to both the visual the haptic senses.

(3) *Social connectedness and co-monitoring* By coupling the Vitals with the Morphs, a physical display can be created. The relation between the Morph and Vitals should be spatial. When both are combined, the five *physicalizations* (i.e., the Vitals) can be observed together in the same space, next to each other. Users at home can get an overview of the overall status of the vital signs measured on the patient. Comparisons can be made by looking at the Vitals. Substantial changes in data can be detected by just observing the characteristics of shape-change, such as frequency and speed. The Morph should also invite users to stay around it, to encourage group activity. Users should also be able to remove the Vitals from the Morph. In this case, the monitoring should become a more private and intimate experience. In addition, users must be able to carry the Vitals to different places, as we had discussed in the fictional scenario.

5 Technical implementation and system evaluation

In this section, we introduce the process of implementation of Vital + Morph. Its main components include a software that simulates a vital sign monitoring station and the physical elements including the Vitals and the Morphs. We will also discuss the data selected for the current prototype.

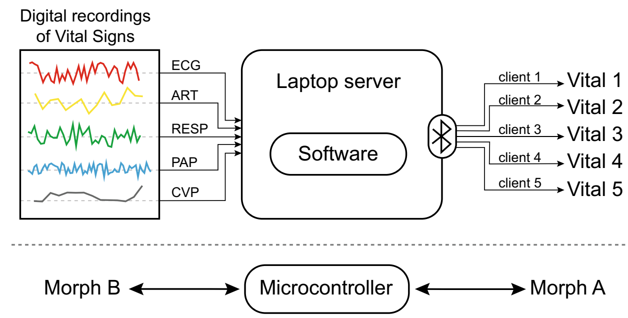


Fig. 4 Representation of the communication flow in the Vital + Morph system

The system architecture is shown in Fig. 4: a customized software running on a laptop, which reads the recordings of the vital signs and transmits them wirelessly to the Vitals. Another subsystem manages the communication between the two Morphs through a microcontroller.

5.1 Simulation of a vital sign monitoring station

5.1.1 Data selection

The signals used for this prototype are actual recordings of a patient's vital signs. We carefully select a specific dataset from the PhysioBank, a public database of physiological data.[3] To make it similar to the scenario described in Sect. 3, we selected a 24-h recording of an 80-year-old woman hospitalized after surgery, who suffers from respiratory problems. Such a dataset helps us present a more realistic version, which also includes actual problematic and critical situations encountered. From the selected dataset, we extracted five vital signs: heart rate (pulse), arterial blood pressure (ART), pulmonary arterial pressure (PAP), central venous pressure (CVP), and respiratory rate.

5.1.2 Software

We developed a software for simulating the tasks of a vital sign monitoring system and for managing the wireless communication. First, the software reads a text file that contains the recordings of each vital sign. Since these recordings have a very high fidelity and speed, we perform a down-sampling of the dataset. Second, each data element is scaled and formatted for transmission to the corresponding Vital element. For the communication protocol, we choose Bluetooth. To keep a flexible environment, the data are directly mapped to the control of the Vitals' actuators. In the current version of the system, we employed a direct mapping between the vital signs and the actuators that they are going to control (Fig. 5). Using the

[3] https://physionet.org/physiobank/.

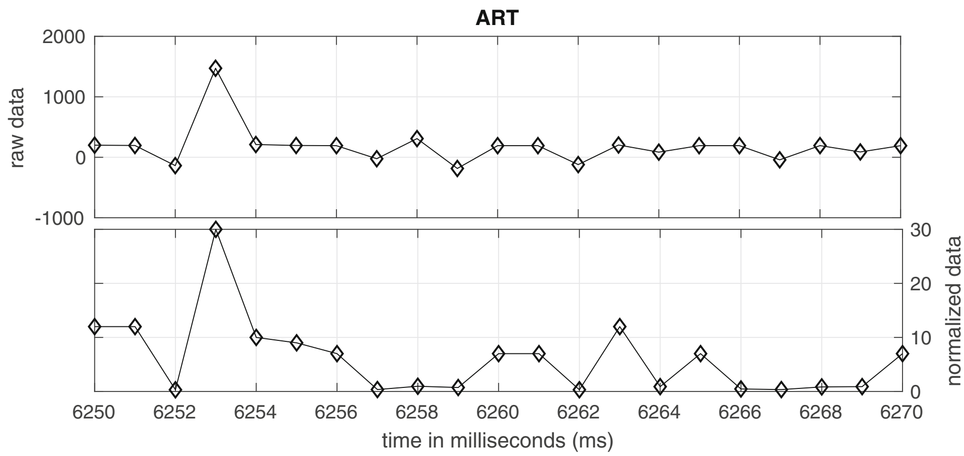


Fig. 5 A sample of the arterial pressure (ART) measurements that show the relations between the raw signal (original recordings of vital signs) and the normalized version processed by the software

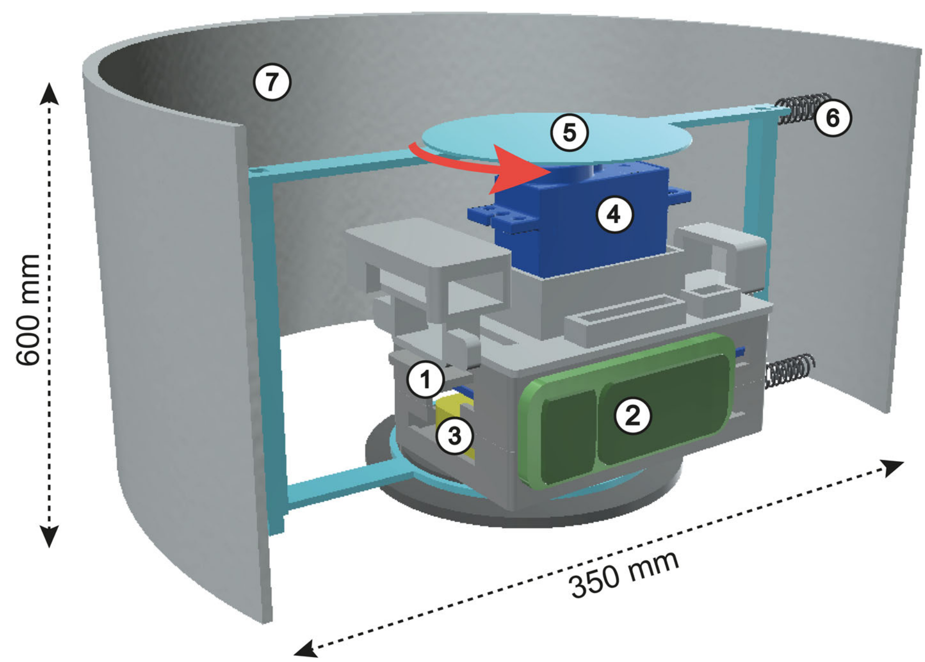


Fig. 6 A section of the Vital highlighting the different components: *1* microcontroller, *2* bluetooth transceiver, *3* lithium–polymer battery, *4* servo motor, *5* shaft and direction of rotation, *6* spring, *7* paper cylinder

software, it is also possible to control the frequency of the input data and to change the level of the mapping between the signal and the degrees of rotation for controlling the rotation of the actuator in the Vitals. A standard wave plot-style visualization is also provided, which serves as a quick debugging element and shows the vital signs to the audience in a form that they can easily understand.

5.2 Physical objects

5.2.1 Vitals

The Vitals are composed of an actuation system, a microcontroller, a Bluetooth transceiver, and a power source encapsulated in a custom-made structure and surrounded by a deformable cylindrical surface (Fig. 6). To implement the desired shape-changing features, we designed an actuated surface that resembles the features of the bio-inspired material described in the previous section. Our aim is to provide a physical shape-changing display that can represent the differences in the behavior of data over time through deformations. Their surface should be able to deform continuously and reproduce each stream of data consistently.

The biggest challenge was the implementation of the mechanism for deformation. Some work has already been done regarding soft robotics involving the design and implementation of simple robots that are able to deform and adapt themselves to the changing conditions of the environment. An interesting example is the circular robot developed by Sugiyama and Hirai (2006). This robot is modeled as a rheological object and it is composed of a series of eight shape-memory alloys (SMAs) type actuators attached to a rubber shell. When such actuators contract, they cause a deformation of the shell. For the sake of portability and autonomy, we adopted a similar approach but with a single actuator—a micro servo type of motor. This enables the precise control of angular position, velocity and acceleration. Since the deformation of the surface is caused by a single actuator, a series of customized horns have been developed. Each servo motor is equipped with four extended horns, two on the upper part connected directly to the active shaft of the motor, and two in the lower part, connected to the extensions attached to the passive one. The horns on the top of the actuator are then vertically linked to a passive rotational shaft placed on the bottom of the structure. Such extensions are then attached to the surface through four small springs. The deformation is caused by the rotary motion of the servo motor. The data are received by the microcontroller that controls the angular position (degrees). When the shaft of the servo rotates, the springs pull the surface and this causes a deformation. When the actuator is at 0° of rotation, it means that the data received are at the minimum value. In such a case, the Vital appears to be a static cylinder. Since the movement of the actuator is transmitted to the surface through springs, they not only deform the surface, but also produce a noticeable force every time the servo motor rotates. In other words, each time the values change from low to high (and vice versa) the actuator moves and the springs release a force (Fig. 7). For the deformable surface, we used a cylinder made of paper that was coated with a layer of liquid latex. This helps increase the deformation effect, prevents tearing of the paper, and makes the material feel similar to the human skin. The cylindrical surface is then attached to the bottom of the actuation module through a plastic stand. This prevents the cylinder from moving freely and also enhances the quality of the shape-changing effect. In addition, we have fabricated a skin made of a four-way stretchable fabric that can allow the elements to be covered and to hide the entire mechanism, if so desired.

5.2.2 Morphs

The Morph is designed as a robotic input–output surface, composed of a closed link system of actuators and joints (Fig. 8). In the current implementation, the Morph is presented in two synchronized deformable surfaces, which can be placed in two different environments. In contrast to the shape-change of the Vitals, where the deformation occurs in response to data, the deformation in the Morph is produced by the direct action of the users. When a user deforms one element, it transmits its current shape to the other that will then reproduce it. This action can also be done in both ways. We have defined this function as *shape-sharing*. This concept describes the usage of paired remote

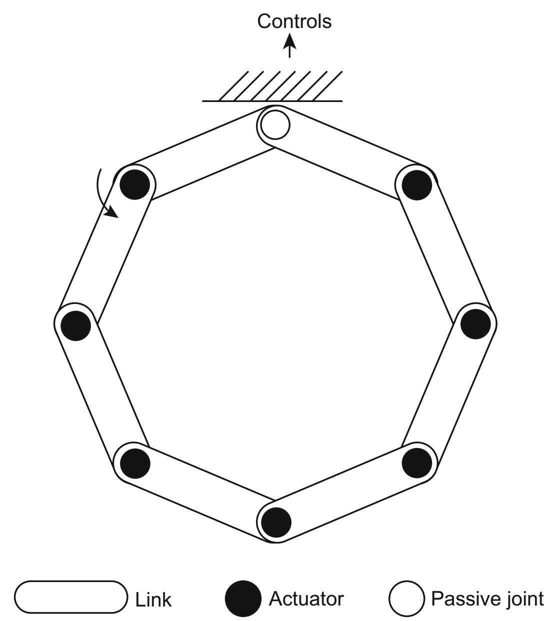


Fig. 8 Closed link system of the Morph elements

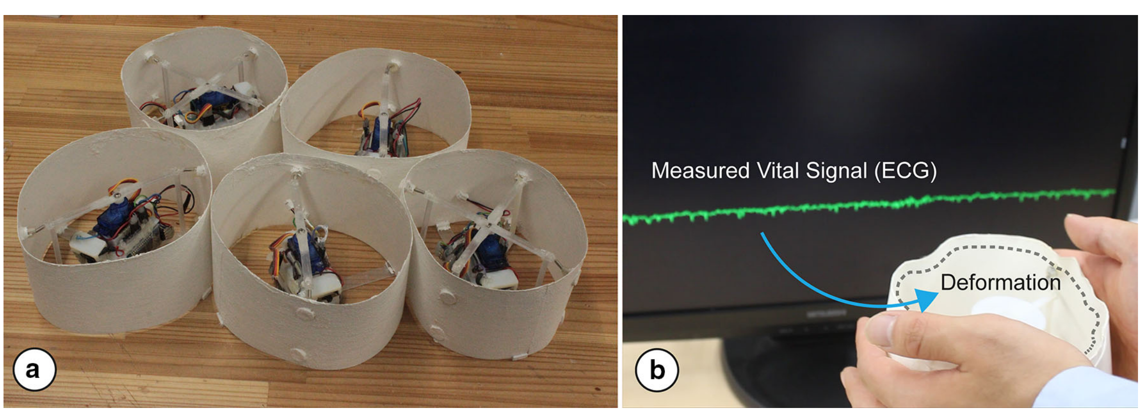


Fig. 7 **a** The five Vitals used in Vital + Morph. **b** The deformations produced by the data stream on one Vital (ECG)

robotic systems for teleoperation, and it was previously introduced by Sekiguchi et al. (2001) to describe their RobotPHONE system. This system uses two robotic arms placed in different locations. Such robotic elements are embedded into a stuffed puppet and are arranged in a master–slave configuration. Using the concept of a telephone call, wherein a user applies a force to one arm and transmits the movement to the paired device, we adapted it for designing the Morph by abolishing the master–slave relation between the two devices, and instead established an equal relation between the devices. The Morphs have a circular shape that mirrors that of the Vitals. Both the Morphs are composed of a series of eight actuators linked together. We choose an analog-feedback servo motor, which combines position sensing and mechanical movement in a single element. Then, the motors are connected to each other using a customized linkage.

In the current version, the two Morphs are connected and synchronized through a microcontroller (Arduino Mega), which implements a direct mapping between the position sensor of the actuators in one Morph and the position control of the motors in the linked Morph, and vice versa. An internet-based version is currently under development.

Finally, the actuators are covered with a soft surface composed of an elastic fabric reinforced internally with a sponge material. This element helps enrich the tactile qualities of the device, and makes it more appealing by hiding the mechanical components (Fig. 9).

6 Performance evaluations of the system

In this section, we present an evaluation of the basic performances of Vital + Morph. Such tests serve to assess two main design requirements: the ability of the Vitals to produce haptic feedback through shape-change and to confirm that the two interconnected Morphs can transmit their shape correctly.

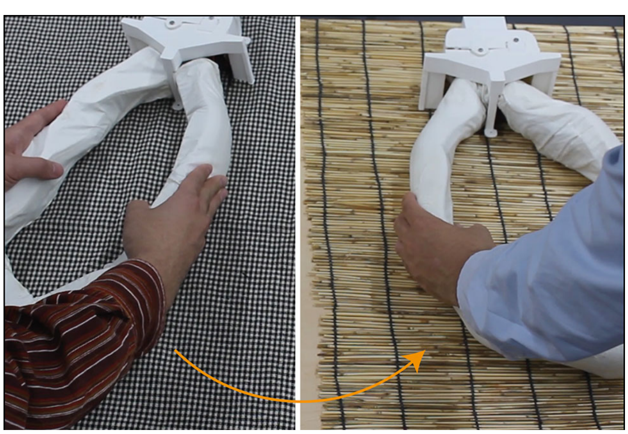


Fig. 9 Two interconnected Morphs

6.1 Haptic quality of data physicalization

To prove the effectiveness of our implementation, we measured the force produced by one Vital element corresponding to the changes in data. The force was measured through a series of tests by attaching a piezoelectric force sensor to a user's index finger and recording the moments when the surface of one of the Vitals touches it. From the sensor, we also recorded the variations in the voltage for a period of 10 min. We repeated the measurement for each different type of data. At the same time, the position of the actuator was also recorded. Figure 10 depicts two samples: one is related to the ECG and the second is for respiration. It is observed that a force is generated when there is a consistent change in the data (peaks). At its highest value, the recorded force corresponds to 0.8 N, which is enough to be perceived by an average user. The respiration data analysis shows the reason that the values are very low and not changing, which indicates a critical condition of the patient. Visually this is represented by an almost static appearance on the device. When a user looks at the Vitals, the deformation of the surface makes the flow of the data in time visually perceptible. In addition, the user can also feel the changes in the data by touching. Even a small variation can produce a noticeable force. Through such an evaluation, we can confirm that the Vitals can provide haptic feedback based on one important characteristic of the data, such as the maximum change. This shows that dynamic data *physicalization* can address not only the vision, but also the sense of touch.

6.2 Shape-sharing capabilities

To assess the amount of error that occurs in the transmission of shape between two linked Morphs, we performed a series of measurements to compare the area of the *sender* and the *receiver* Morph. We selected three main gestures, which have been derived through the observation of users (see Sect. 8). These are (1) horizontal squeeze, (2) vertical squeeze, and (3) a gesture randomly selected that cannot be classified into the previous two categories (Fig. 11). The first two gestures represent the maximum contraction possible, respectively, horizontally and vertically. On the other hand, the third category of gesture includes more subtle deformations that can involve only some parts of the shape, or simple variations of the static circular shape. The test was performed by placing two Morphs close to the each other. We recorded 10 trails per gesture with a video camera. After the acquisition, we selected and isolated the frames where the transmission of the shape happened.

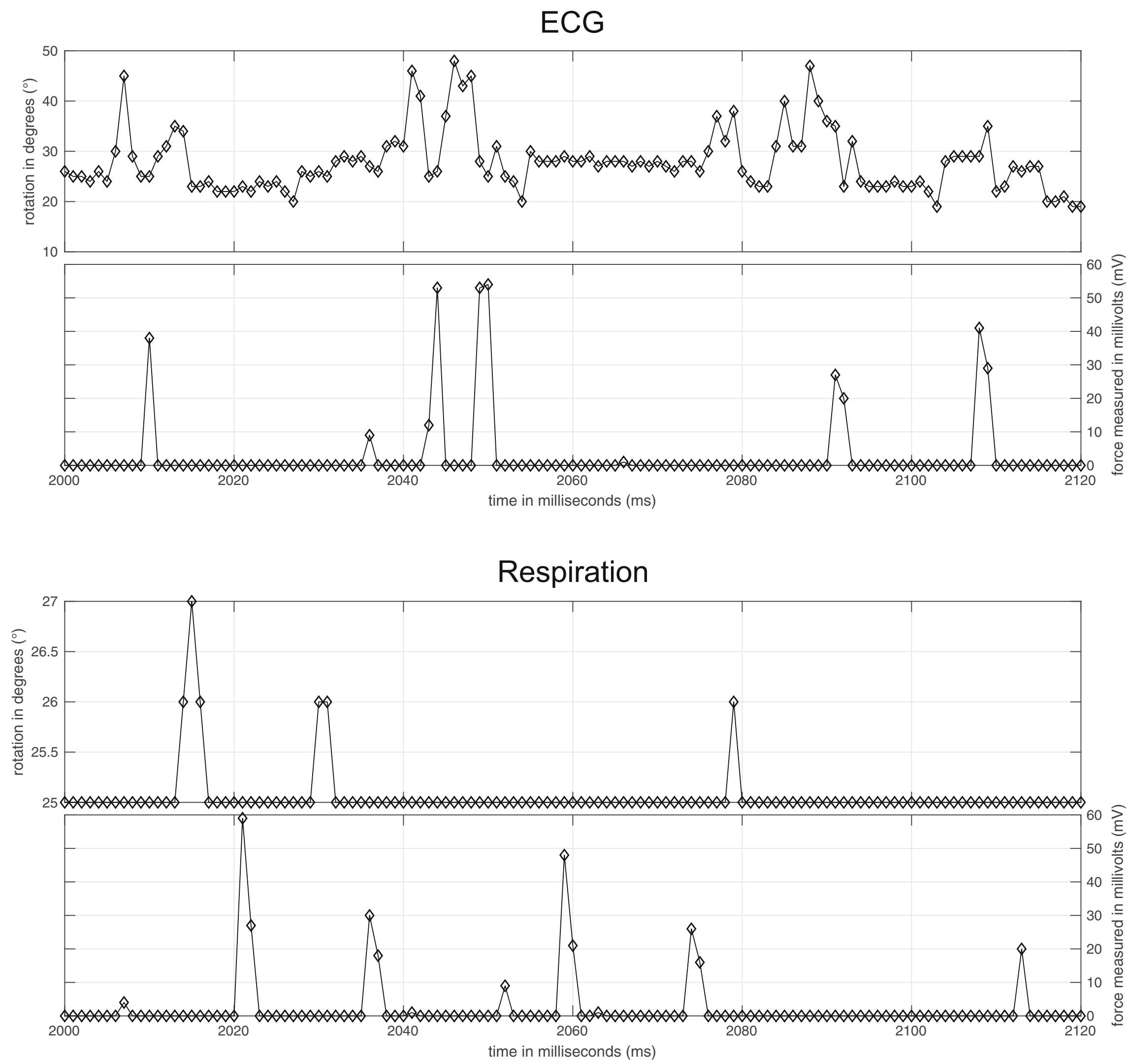


Fig. 10 Two samples that show the relation between the position of the actuator (corresponding to the measured vital sign) and the force measured on a user's finger. The chosen samples are for the electrocardiogram and the respiration impedance

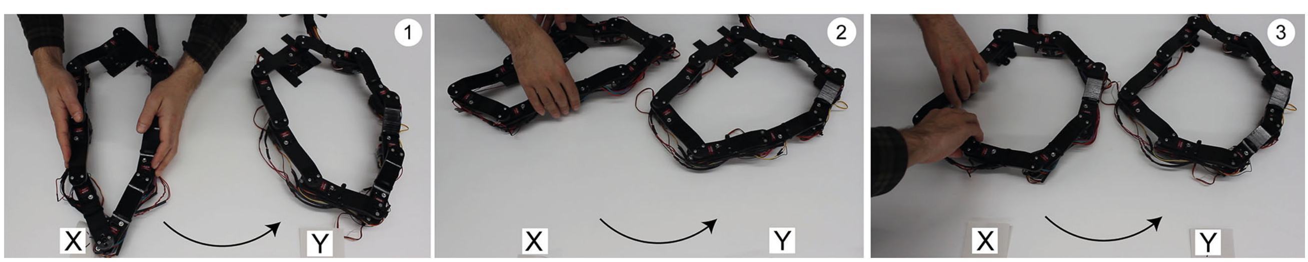


Fig. 11 Examples of the reproduction of the shape between a transmitting (*X*) and a receiving (*Y*) Morph. Three different gestures are presented: *1* horizontal squeeze, *2* vertical squeeze, *3* other type of deformation

Then, we have traced the area of each shape. Since it represents a complex and non-uniform curve, we simplified its geometry. By superimposing a grid made of equal cells, we calculated the area of each shape using the Pick's theorem. For each gesture, we calculated the mean area for the sender (X) and the receiver (Y). Then, we derived the difference between the two areas and consequently the percentage of the error in the transmission. It was found that the lowest error is observed in gesture 3 (+0.02%). The error observed in the gesture number 1 and 2, respectively, are +0.3% for the horizontal and +0.2% for the vertical squeeze. Since these two gestures represent very extreme contractions, we can conclude that it is very difficult to reproduce extreme contractions or expansions. One of the reasons can be found in the friction produced between the actuators at the surface.

Another element that is relevant to shape transmission is time, which dictates how fast the deformation is and for how long the act of deformation is performed. We have observed that slow deformations (>45 s) generate better results in shape reproduction while faster deformations are more likely to negatively affect the accuracy of transmission.

7 User study in media art exhibitions: aims and issues

Vital + Morph was exhibited at the Arts Electronica Festival (Linz, Austria) and the Tsukuba Media Art Festival (Tsukuba, Japan), respectively, in September and December 2016. The former is one of the major international events in the field of Media Art, while the latter is a local event mostly attended by families and amateur enthusiasts. During these occasions, we had the opportunity of observing how a varied audience interacts with Vital + Morph, and of investigating their reactions and opinions. We conducted a user's study using a mixed method of observations, notations and non-structured interviews. Through this study, we wanted to assess the social acceptance of Vital + Morph and examine how shape-change is perceived by users. Moreover, we were also interested in obtaining a better understanding of the social impact of such interfaces, the concerns they raise and the opportunities they present.

7.1 User studies in media art exhibitions

In the past, we have found that media art exhibitions represent an interesting platform for testing interactive systems outside the laboratory (Iwata 2005). Hands-on demonstrations in an open environment should not just be considered a way of testing an interactive device, but also an essential step of the research process. This is more relevant for systems and interfaces characterized by unconventional interactions and unique appearances. Venues like Media Art festivals and exhibitions can provide many benefits for a qualitative research. First, they help reach a very large group of possible users, composed of people of different ages, genders, nationalities, and degrees of expertise with interactive technologies. Second, such events remain open for a long period of time, allowing people to freely try and evaluate the system. Third, by interacting with the audience, it is possible to conduct unstructured interviews.

7.2 Problem statement

The evaluation and assessment of shape-changing interfaces is a problematic aspect that characterizes this research area. Due to their unique characteristics, shape-changing interfaces cannot be compared to other systems. Moreover, there are no standardized measurements and frameworks available for performing an effective evaluation. In particular, the investigation of the social acceptance of shape-changing interfaces is still one of the biggest unanswered questions in the research community (Rasmussen et al. 2012). To our knowledge, only one study has been published (Park et al. 2015) with the aim of investigating the effect of shape-change in a real-life scenario, using an ethnographic method. However, this study was limited to shape-change applied to existing mobile devices and between loving couples.

For our study, due to the difficulties of testing the system in a real scenario (hospital), we have designed an ambient installation where Vital + Morph was placed. It represents an approximation of the experience we wanted to assess. This approach is used in many exhibits and museums for providing a context in which artifacts can be better understood by visitors.

7.3 Test environment and exhibition design

Vital + Morph was presented to the audience through a setting that can help them contextualize the system into an environment that tries to explicitly replicate the scenario we had developed in Sect. 3. The spatial arrangement, lighting, and furnishing are used for supporting the narration of the story. The exhibition space consisted of a unique room that we divided in two spaces: a "home" area and a "hospital" area. These spaces are divided by a curtain (Fig. 12).

When the audience first enters the room, they get into the "home" area, and the "hospital" space is hidden behind the curtain. The "home" area plays the role of a living room where people can meet and gather around Vital + Morph. The interface is placed on the top of a white plinth (100 × 50 × 50 cm). A spotlight is used for highlighting these elements. When the audiences cross the curtain, they find themselves in the "hospital" area. On one side of the room, we created a simple version of an ICU with a bed and a monitor, which represents the stream of vital signs with a standard wave plot visualization. Near the bed, on a second white plinth, we placed a second Vital + Morph, but without the Vitals and only the shape-sharing interface. In this area, the plinth is shorter (50 × 50 × 50 cm), because we wanted to force the audience to interact with the interface by sitting on the bed,

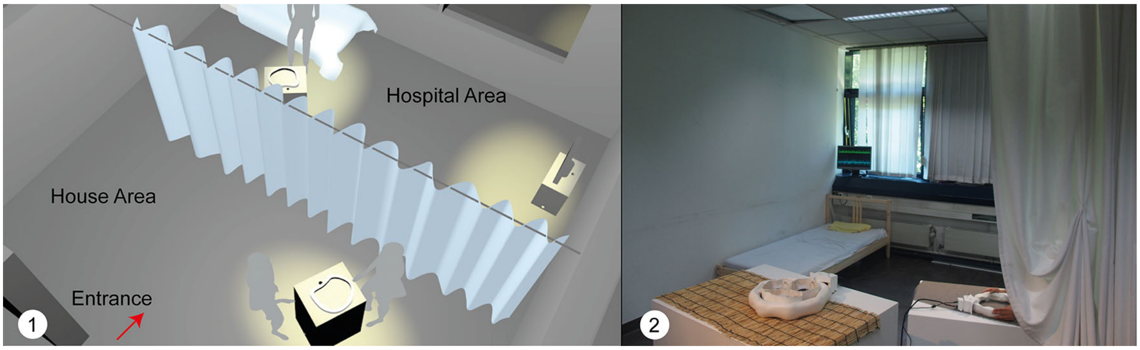


Fig. 12 *1* Plan of the installation; *2* the actual set up at the Arts Electronica Festival

like any hospitalized person will do. The bed and the second Vital + Morph are also highlighted using two spotlights.

7.4 Subjects

During the exhibition at the Arts Electronica Festival, more than 600 people visited the installation. The festival lasted for 5 days, and the exhibition was opened for 8 h per day. We observed around 200 people actively interacting with Vital + Morph, out of which we interviewed 40 people. In this context, the audience was composed of a very wide variety of respondents with an almost equal distribution between males and females, with an average age ranging between 15 to 70 years. Most of the visitors were from European countries (especially Austria, Germany, and Italy), but we also tried to include visitors from the UK, USA and countries like China, Japan, and South Korea. On the other hand, at the Tsukuba Media Art Festival, majority of the audience was Japanese. Moreover, here, the gender distribution was almost equal, with a similar range of age, but a significant proportion of visitors included families with young children. The Tsukuba Media Art Festival lasted for 8 days, open for 7 h each day. Being a local venue, the number of visitors was lower as compared to the Arts Electronica Festival: with 200 people visiting our installation and 100 interacting with our system. Here, we interviewed 20 participants. In both the exhibitions, the audience was composed of first-time users of Vital Morph.

7.5 Methodology

Each visitor was introduced to the installation with a verbal explanation of the aims and the concept of the installation. This was done through an oral narration of the fictional scenario. Till then, we had not informed the users about the interactions and usages of the system. They were then able to test Vital + Morph without any constraint and for as long as they wanted to. During the two exhibitions, most of the visitors came in groups of two to six people. We observed the users and noted down the sequence of their interactions. After the observation stage, we asked the users some specific questions to assess the perceptual qualities of the interface. Lastly, we encouraged the visitors to talk freely about their overall experience with the system and to give their opinions regarding the social impact of Vital + Morph. We collected the answers and then selected the most common and significant responses to arrive at relevant results.

8 Results

In this section, the results of the user study are presented. The results of the observations regarding the behavior of the users towards Vital + Morph are then assessed by a series of interviews with the aim of probing the experience of the visitors.

8.1 Observations of users' behavior

Through a constant observation of the behavior of the visitors, we recognized a series of recurrent interactions that the users performed with Vital + Morph. These actions were categorized by following the chronological order in which they happened and divided into four *macro-interactions*. By *macro-interactions*, we mean a general interaction that groups some different variations of a similar interaction. Such kind of classification is required because shape-changing and organic interfaces allow for continuous interactions. These are characterized by different levels of nuances that are very difficult to categorize with the use of strict terminologies. The observations that follow have helped us to validate the effectiveness of the interactions possible with Vital + Morph.

Observing and exploring At first, we noticed that almost all users (97%) were observing the Vital + Morph placed in the "house" area. If it was a group, they were gathering around the plinth where Vital + Morph was placed. Very few visitors (3%) went behind the tent before stopping in the first part of the installation. After a period of observation that typically lasted between 1 min to 3 min, the users started to touch the different parts of the interface. Because of their constant movement, the Vitals were the elements that immediately attracted the visitors' attention.

Re-composing and de-composing After a brief inspection, usually one of the visitors was grabbing one Vital and removing it from the Morph. We have defined such an action as *de-composing*. By holding it in his/her hands, the users started to report to others their feelings and thoughts. If there was a group of people, the person with the Vital was passing it to another user. For example, parents where passing it to their children. After this first exploration, other people where grabbing the remaining Vitals. With the Vitals in their hands, people were commenting to each other and developing a series of thoughts mostly about their tactile experience. In addition, an exchange of different Vitals among users was observed. Phrases like 'pass me the heart beat' or 'take the respiration' were accompanying such actions. Visitors also were moving around the installation while holding the Vitals in their hands. After a period ranging from 2 to 7 min, the users put the Vitals back inside the Morph as a final action. We have named this action as *re-composing*, and it can be viewed as the consequence of the first action of *de-composing*. We observed that most of the people were re-composing the interface together (90%) and only a few left them alone (10%). Subsequently, when Vital + Morph came back to the initial state, the visitors reverted to the observation phase (Fig. 13).

Shape-sharing Between the actions of de-composing and composing, when all the Vitals had been removed from inside the Morph, visitors started to pay attention to the Morph. At this stage, the users where already moving around the installation. The identification of the functions of the Morph was slower compared to those of the Vitals and happened through several steps. Usually, when visitors were crossing the curtain and moving from the "house" area to the "hospital" area, they discovered the other Morph placed near the bed. At this point, a user would sit on the bed and start to touch the Morph. The visitors identified that the two Morphs were connected and synchronized when a person in the "house" area was notifying the other with sentences like 'It's moving!' or other oral comments confirming that the interface was responding. From this moment, the users on the two sides were trying to test and explore the possible ways of interacting with the Morphs. Most of the users were manipulating the Morph with two hands (85%), a few with one hand (5%), and some even with a single finger (8%). Some people performed other actions (2%) such as lifting the Morph. Within the actions performed with two hands the two most

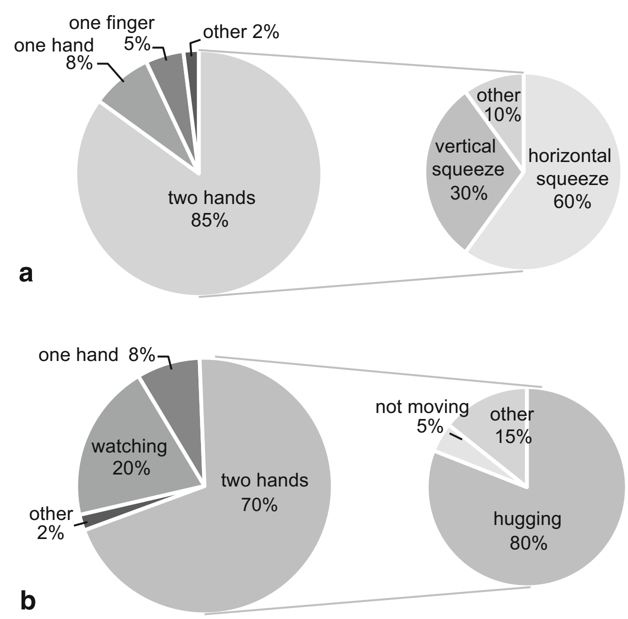
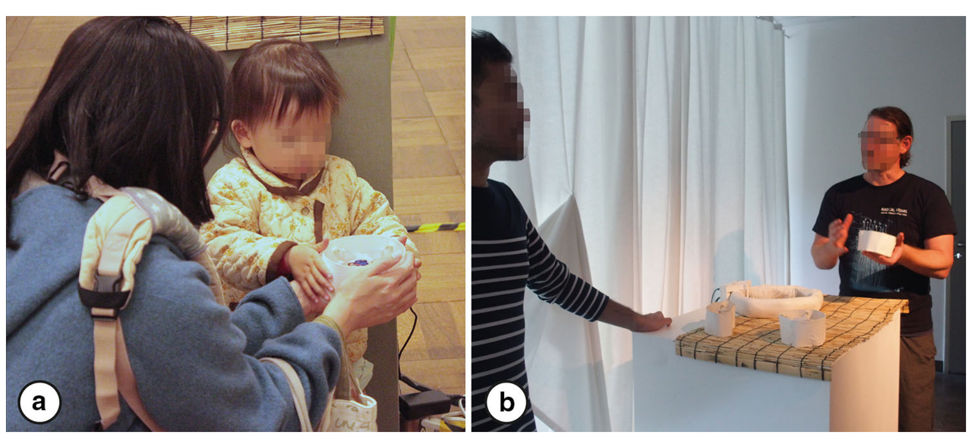


Fig. 14 Interactions with the Morphs as an input device (**a**) and as an output (**b**). Details will be provided in the discussion

Fig. 13 Users interacting with the Vitals at the **a** Tsukuba Media Art Festival and at the **b** Arts Electronica Festival



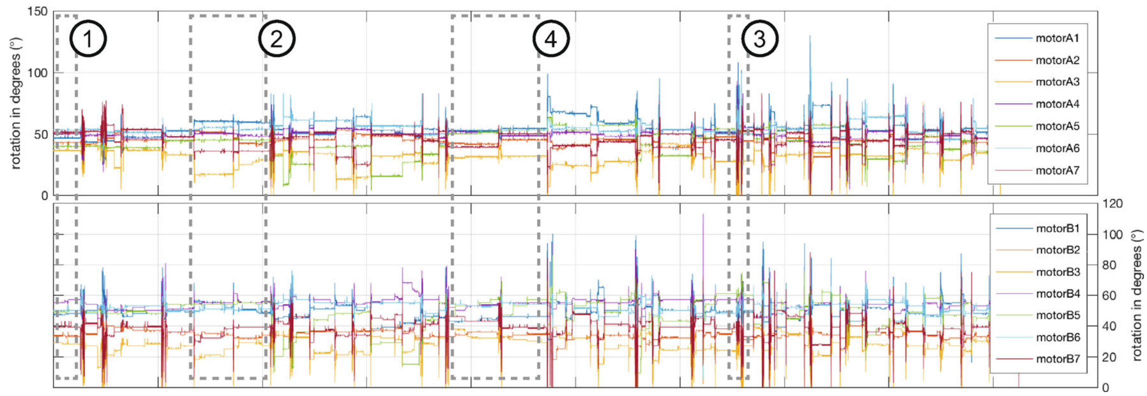


Fig. 15 Recordings of the interactions between two Morphs. We can devise four types of gestures performed by users: *1* still, not moving, *2* vertical squeeze, *3* horizontal squeeze, *4* other type of deformation

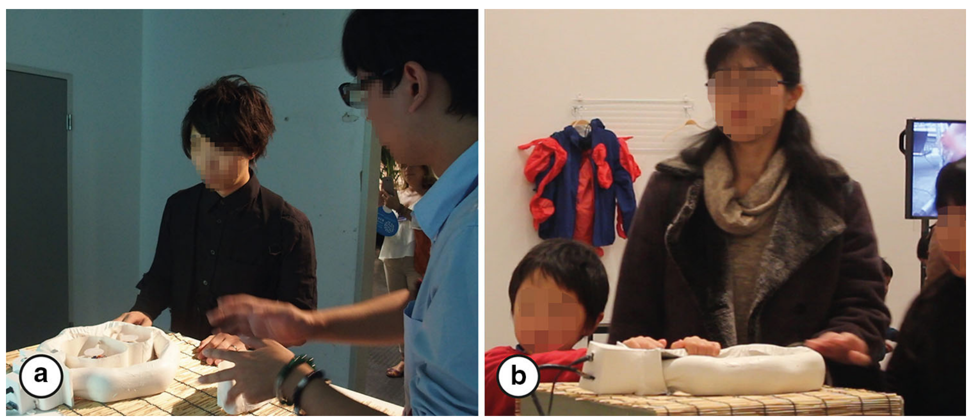


Fig. 16 Visitors interacting with the Morphs: **a** at the Arts Electronica Festival and **b** at the Tsukuba Media Art Festival

common actions were squeezing the interface horizontally (60%) and the vertically (30%). Only a very small percentage of users (10%) tried to perform other types of manipulations (Fig. 14). This can be noticed by looking at the recordings of the position sensors of the actuators in the Morphs. From Fig. 15, it is possible to notice a sample wherein such recurrent actions can be devised. Earlier, we had observed that time was an important element in the development of such actions. We observed that the majority of users (98%) tried to deform the Morph very quickly at first. However, after some attempts, these users were trying to reduce the speed of their movements and performing their actions at a much slower pace. The interaction with the Morphs was usually the longest, ranging from 1 min (the shortest) to 10 min (the longest), with an average of 6 min. However, we noticed that the users that spent more time interacting with the Morphs (> 5 min) were keen to try different manipulations.

Tactile communication The use of the Morphs was not only limited to active deformations of the interface (Fig. 16). It can also reproduce and play back such deformations. Before responding to a stimulus, users where taking time to feel the deformations produced by the Morph on their body. It was interesting to observe how people were experiencing this shape-sharing function as an output. The use of both hands as a way to feel the motion was the most common (90%). It was done by placing the palm of their hands along the sides of the Morph. In addition, we observed many users placing their arms in a manner mimicking the gesture of hugging (10%). Very few tried to use other body parts such as the face (2%).

8.2 Interviews

The analysis of the results of the interview process demonstrated homogeneity in the type of responses from visitors in both the exhibitions. After a process of analysis of the various answers and comments provided by the users, we identified six major topics: emotional response, design choices, tactile and kinesthetic communication, multi-sensory interactions, social impact, and criticalities (Fig. 17).

Emotional response At first, the users were queried about their emotional response to the experience, especially how they perceived Vital + Morph. The most recurrent comment can be summarized with the expression 'it looks like a living organism' (95%). Several visitors

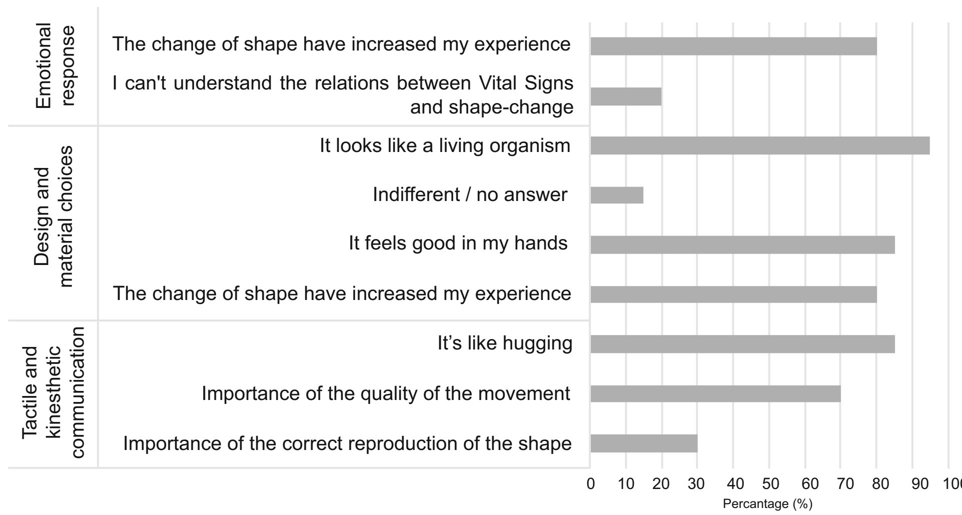


Fig. 17 Results of the interview process. Details are provided in Sect. 8.2

made similar comments using other words such as "organs", "insects", or "hamsters". More detailed comments emerged after visitors held the Vitals on their hands. At this stage, the most recurrent comments were 'it's like holding a human heart', and 'I feel like I'm touching a blob'. Some users also related the feeling to the force produced by the Vitals. One user described 'The force I feel, it's kind of pulsating…It moves in my hands. I can feel something rhythmical. It's constant but sometimes it changes. I think it's something alive'. Irrespective of the kind of vital sign that was displayed, the users strongly identified the system with something living, and related their experience with imaginative ideas, like having a living organ between their hands. Aside from such comments, some users felt a sort of mismatch between the feelings and the ability of understanding the meaning of the shape-change. 'I can feel, yes, but I don't know exactly what it means'. Others were demanding more clarity in the representation of data 'I don't know if this movement is right or wrong' or 'I would like to have a reference point. For example, I don't know how to judge this motion. Is this heart beat rate good or not?' Some of these visitors even commented 'I'm not able to understand the relations between the vital signs and the movement'. However, when asked to comment if the change in shape increased their perception of data, 80% of the visitors answered positively.

Design and material choices Throughout our survey, we recorded a general appreciation of the aesthetics and feel of the interface. Moreover, many users appreciated the tactile qualities of the system. Comments such as 'It feels good in my hands' (60%) and 'I like the feeling when I'm touching it' (40%) were equally distributed towards both the Vitals and the Morphs. Children were especially attracted by the possibility of being engaged in different haptic experiences. Being an interface highly based on tactile elements, Vital + Morph shows that to make shape-changing interfaces acceptable, the choice of the materials used plays a key element in the design.

Tactile and kinesthetic communication The interaction with the Morph elements was another element we assessed during the interviewing process. We were especially interested in understanding if *shape-sharing* can be understood by users and in identifying the ways in which they approach it. Contrary to our expectations, users valued the quality of the movement produced (70%) more than the correct reproduction of the shape. Many commented that there was a difference between fast and slow movements. 'When I'm using it (the Morph) I like to move it fast. When I receive it I like the slow movements'. Then, we asked the visitors to comment about their experience. Most of them were interested in exploring the two-way communication. However, they looked lost and found it difficult to understand how this communication should be performed. 'This seems to be a conversation. Two people communicating…but I have never experienced something like this…however it's fun'. 'I have no idea no idea how to develop a way of communicating. I mean, it seems easy, you have just to move it. But I don't know what it means. Especially I don't know the meaning when I see the answer, when the other person's motion is played on the one I'm facing. I don't know'. Some users highlighted that the absence of audio and video for remote communication resulted in a diminished experience. 'Usually I use the phone or Skype to communicate with friends. This is something that I have never experienced. You have to touch it'. 'I find this way of communication very interesting, normally you share your voice, not movements'. When asked to comment about how they perceived the Morphs, users related it to gestures like hugging and embracing another person. 'For me this is similar to hugging, like when you hold a person with your arms'; 'I will say that it reminds of the gestures you use when you embrace someone, usually a parent, a friend'. A common comment that was following such sentences was highlighting such limitations. Many users felt that to really perceive such tactile communication, temperature is missed. 'In order to communicate the sensation of hugging, and especially the feel that another person is being hugged, besides the force and the shape, warmth of the arms are very important. Without it it's just like cold, like technology' and 'I would like to feel the temperature of the others, like the warmth or coldness of the hands'.

However, 80% of the users said that these characteristics improved their feeling of being connected to another person. An interesting comment was 'It's very abstract but…it makes me imagine the other, what is doing, what is thinking'.

Social impact In the last part of the interview process, we asked the visitors to freely comment on the possible introduction of Vital + Morph in their lives. The majority of users expressed surprise and interest about the system. This could be because most of the visitors had never experienced a shape-changing interface in the past. In addition, the purpose of Vital + Morph generated a positive interest. Especially, visitors of an age exceeding 40 years often related their experience with Vital + Morph with their own personal stories of having parents or relatives hospitalized in reanimation or Intensive Care Units. 'I remember when my mother was hospitalized years ago…I cannot say if I wanted to have this (Vital + Morph) at that time…but it makes me think…actually, I was really nervous sometimes because of the distance…however, I don't know because I have never used something like this (Vital + Morph). But the distance, the sensation of being powerless was high' or 'Last year my brother was in a hospital after a surgery, I was thinking what would have been…because it's true in these situations you are not aware of what is happening, you are distant. You can visit them only few times. Especially like me that I was living far away. He was not able to talk at the phone for weeks'. We should note that many of the oldest members of the audience suggested that an interface like Vital + Morph can be very useful in the current *aging society*, because it can add a more physical and tactile dimension to the possibility of being aware of the conditions of a distant patient. 'You know, here in Japan we are an aging society. People are getting old and the younger are very busy'; another 'I think it can be really useful in the future. We lost contact with people, physical contact. I will encourage such ways to create a more physical contact among people'. We also collected the opinions of a group of four visitors that are working in an Intensive Care Unit in a hospital in Austria. They emphasized on the issues of communication between the ICUs and the outside. In their opinion, finding a novel way to connect people in this situation is very important. 'In an Intensive Care Unit everything is very complex, even the light…the communication is really problematic'; another adds 'I have never thought about this possibility…it's a strange concept', 'it's true communication there (in the ICUs) it's a real problem, especially with the outside'.

Critical points Apart from these comments, we recorded some very critical reactions. One explained that 'it's a very creepy […] I don't want it', another 'It's noisy, it's weird…I don't know…when I see all of these things moving (the Vitals) like this (makes a gesture that mimics their movement, like wobbling) it makes me suffering because seems to me that someone is suffering'. A third articulated her concern more strongly 'I will be really scared of having such device in my house […] and if it will stop ? […] this can become a strong reminder of death'. These visitors were extremely concerned about having this constant presence in their lives and opined that they would find it difficult to handle a surrogate of a person who is probably suffering. The system malfunctions can become a serious issue since they can be related to a much more tragic event. In addition, these users highlight that Vital + Morph can be really invasive in their daily lives, by being a constant reminder of the condition of a loved one.

9 Discussion of the results

Our findings and contributions point to a series of design implications for using dynamic data *physicalization* for remote monitoring. We have identified five main implications that concern the design of the physical interface and the social impact and acceptance of Vital + Morph.

9.1 Data aliveness

As observed by many comments made by users, the association between shape-change and vital signs appears to be very powerful. In addition, having a physical display that exhibits the qualities of a living organism seems to enrich the embodiment of data through shape-change. These claims are also supported by the recent literature in actuated tangible and shape-changing interfaces that has emphasized the importance of designing life-like movements for conveying meanings (Schmitz 2010; Hemmert et al. 2013; Park et al. 2015). However, physical animation is not enough. The combination with tactile feedback proved to be fundamental to let people experience different characteristics of the data displayed by the shape-changing surface of the Vitals. In contrast, users have asked for richer haptic experiences when the only act was a communication between two people, such as in the case of the

Morphs. The interplay between visual and tactile clues in Vital + Morph suggests a careful consideration of the design and distribution of these two sensory characteristics among the interface.

9.2 Physical presence of the abstract

We found that shape-change, either visual, tactile or both is not enough by itself. The type of data that drives the actuation must be clear. As presented in the observations and later observed during the interviews, this association helped users increase their sense of closeness and engagement with the data and the distant persons. Previous studies revealed that sharing physiological signals can facilitate and promote connectedness by making distant people feel closer (Sommerer and Mignonneau 2004; Janssen et al. 2010). It seems that people tend to interpret a shared physiological signal (such as heartbeat) as a part of the other, which suggests to them that a distant person is physically closer. A single signal can become a representation of an entire absent body. This is connected to a phenomenon defined by Garnæs et al. (2007) as "presence-in-absence". According to Slovák et al. (2012), such physical connection can be compared to the one triggered by physical tokens of loved ones that people keep close as a reminder of a distant person. Especially the Vitals have suggested that when an object becomes enhanced with real-time physiological signals, it can serve as a strong representation of the distant other. In addition, the use of tangible objects as "physical surrogates" has proven to be an intuitive method of sustaining long-distance relationships (Greenberg and Kuzuoka 1999). A recent research in social robotics (Nakamichi et al. 2014) opined that even a very simple and almost abstract appearance of an intelligent device can be a very powerful factor for conveying a sense of physical presence.

9.3 Remote monitoring as a tactile experience

As we already noticed, an interesting characteristic of shape-changing interfaces is that they serve as an effective type of multi-sensory display. In the case of Vital + Morph, the visuo-tactile elements are present at the same time, but they become perceptible to the user only when he/she changes the interaction. By only looking at the interface, the temporal characteristics of the signals are revealed. When the user inserts his/her hand in the interface and grabs a Vital, it become conscious of the changes in data through the tactile channel. These two characteristics of the signal do not have to be selected explicitly, but the user has to change the type of interaction. This is achieved in a very natural way, just like grabbing an object. From our point of view, such interactions with shape-changing materials have the potential to shift data exploration from a purely analytic activity to a more phenomenological one. Most of the current research in tactile display employs a co-located tactile and visual feedback through the use of video projection on actuated surfaces (Leithinger et al. 2014; Lindlbauer et al. 2016). Such solutions can obviously enrich the interface with a more detailed and rich feedback, but it still implies a separation, which shape-changing interfaces aim to reduce.

9.4 Sociality and emergence

Remote monitoring was always considered to be an activity performed by specialists. Usually this is also assumed to be an association between a physician and a patient, not other people such as family members. By observing the actions of *de-composing* and *re-composing,* it is possible to notice that Vital + Morph can potentially promote remote monitoring as a social activity. This can be enabled both by the form factor (the use of circular shapes) and functional elements (the modularity of the interface). This is supported by the research on TUIs, where circular tabletop arrangements of digitally augmented objects have shown a high potential to promote collaboration and social inclusion (Kaltenbrunner et al. 2006). However, such elements are derived by the chosen design metaphor, a group of biological organisms called diatoms. A bio-inspired metaphor, if used not only for aesthetic reasons but as a reference for designing a system, can help simplify and organize complex relations and make interactions between users and the interface seem like emergent phenomena.

9.5 Involvement and distance

Translating abstract data into a physical form seems to make users more likely to question the process of how data get represented. This is especially true with very sensitive measurements such as vital signs. As suggested by the comments that we have collected, users reacted by pointing out many issues and made numerous comments, and also offered suggestions. As we mentioned, proper evaluation of shape-changing interfaces for data *physicalization* is a very problematic task. We see our contribution as an addition to the growing variety of alternative data representations. Only by increasing the diversity in the digital ecosystem will it be possible to understand and evaluate which kind of display and metaphor works better, and for which type of data. This will tell the extent to which people would like to be involved in the process of understanding, manipulating, and getting engaged with data. Even if we have reported some very critical comments, they actually reinforce the idea behind the power of dynamic *physicalization* of data. Such a way of representing data does not make people indifferent. Even if it was a minority, we found such critical comments insightful and helpful in addressing some elements that are usually not considered in the design and evaluation of novel shape-changing interfaces.

10 Future work

A lot more work is needed for deploying Vital + Morph in real-life scenarios and it will require some very critical steps. At first, some of the technical issues should be resolved, such as issues related to power and actuation. The progress in embedded systems and novel materials can also help make the Vitals even smaller, so that they can occupy lesser space. Apart from such technical implementations, it is essential to conduct a research involving hospitals, patients and their families. Moreover, if the final goal is the deployment of Vital + Morph in society, the research cannot be dissociated from improvement in policies and infrastructure for sharing private and clinical data among public networks. This is a discussion that goes beyond the scope of this study.

11 Conclusion

Our user study confirmed the effectiveness of the prototype, in terms of social acceptance, conceptual understanding, and design metaphor. Vital + Morph was designed as a new kind of shape-changing interface oriented to ordinary people. We wanted to explore a novel way of getting engaged with vital signs through dynamic data *physicalization*. We gathered very insightful comments, especially the negative comments underlining the fact that such a way of representing abstract data can be very invasive and portent. Despite being critical, users were not indifferent and were proactive in envisioning and proposing specific usage and considering the possible social impact of an interface like Vital + Morph. In addition, even if the research on shape-changing interfaces and data *physicalization* is still in an initial state, with our study, we tried to contribute to this field by providing a novel design metaphor inspired by a bio-inspired principle, which marks a departure from previous examples that have been based on common statistical ways of presenting data through histograms and pie charts. The evaluation of the system in a public space, such as a Media Art installation, presented an alternative way to test novel systems and observe reactions of first-time users. Through the development of Vital + Morph, we hope to contribute to the exploration of novel ways to present data and make remote monitoring a social activity and a new form of data domestication.

In this era, wherein we are witnessing a convergence between digital fabrication, smart materials, and interconnected devices, it is important to develop strategies and methodologies for making abstract data perceptible to users and integrate it into our daily lives.

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