Sensory Substitution Systems

Matthias Schmidmaier

Abstract— Sensory substitution enables the experience of one sense through another one, mostly by using input from artificial modalities. Since the 1960's, sensory substitution devices have been developed to compensate sensory impairments, for example by 'seeing with the tongue'. Thereby sensory substitution studies have provided insight into the functionality and the abilities of the human brain. Above all during the past years, the technological progress enabled interesting new and further developments that in some cases already are suitable for daily use. In addition, sensory substitution technologies have also been used for sensory augmentation. This paper presents several current applications in the fields of accessibility and sensory augmentation. For a better understanding, also a general review of the history and the physiological and technological principles of sensory substitution systems is given. Furthermore, possible future developments of this research area are considered.

Index Terms—sensory substitution systems, sensory augmentation, multimodal human-computer interaction

1 Introduction

'Allowing blind people to see and deaf people to hear' [25]. While some people reading this statement might think about religious miracles, it leads to a field of multimodal human-computer interaction called sensory substitution.

Multimodal HCI systems are defined as systems that receive input information from several modalities, whereas a modality might be seen as a mode of communication according to the human senses or as a human related computer input device. For human-computer communication, several input modalities receive information from a user to enable multimodal interaction with a computer [12]. However, in the context of sensory substitution, modalities are the human senses on which a sensory substitution system is based on.

In general, sensory substitution means the translation of sensory information in order to enable perception through another than the originally responsible sense. For this purpose sensory substitution systems use human-computer interfaces to transmit sensory information captured by an artificial modality to a human sense [30, 16]. In this way, sensory impaired people are enabled to compensate their impairment. Besides this purpose, sensory substitution systems also have been used for brain research and, especially during the past few years, for sensory augmentation, which means the 'addition of information to an existing sensory channel' [5]. Thus, current sensory substitution systems are also developed to enhance the natural human senses, or even add new ones like for example magnetic perception for orientation.

2 History

Until today, Braille can be considered to be the most popular sensory substitution system [4]. This system was developed in 1840 with the intention to aid blind people acquiring visual information through touch [30]. Another successful communication aid is sign language which was developed in the 18th century. According to Bach-y-Rita and Kercel one might even consider reading to be the first sensory substitution system, as auditory information (spoken words) is presented in a visual way (writing) [4]. In 1897 Kazimierz Noiszewski invented the first technical sensory substitution device called Elektroftalm [30]. Using a light sensitive selenium cell, it expressed brightness as auditory information in order to enable blind people distinguishing light and dark spaces. Although this system was evolved several times, for example as head worn vision system (see *Fig. 1*), the pioneer of sensory substitution systems is considered to be Bach-y-Rita [30]. In the 1960s Bach-y-Rita created the Tactile Visual Sensory Substitution (TVSS). The device transmitted camera signals to a grid of 20 x 20 vibro-tactile stimulators. Moving the camera, visually impaired subjects laying on the grid were able to recognize lines and shapes [3]. An important result of testing TVSS was the fact that the system only worked when subjects were able to move the camera during usage. Hence TVSS contributed in a great measure to future studies in brain research, especially concerning brain plasticity [4, 16]. Bach-y-Rita's studies might also be seen as the initiator of the development of sensory substitution systems based on human-machine interfaces. In the following years and decades, devices were not only developed for tactile vision but also for other kinds of substitution like ultrasonic vision (The Sonic Pathfinder, 1984 [16]), audible vision (The vOICe, 1992 [19]), tactile hearing (The Tactaid, 1995 [30]) or tactile balance (Vestibular aid TDU, 1998 [30]).

At the end of the 20th century, due to the fast technological progress of the last decades, a lot of these devices have been evolved to improve quality and suitability for daily use. Furthermore, studies started to deal with the futuristic possibilities of sensory augmentation. Besides for the compensation of sensory impairments, applications have been developed to enhance existing senses or enable even new kinds of perception. An example for a sensory augmentation system is the Tactile Situation Awareness System (TSAS) which has been developed since the end of the 1990s and helps pilots in spatial orientation by tactile feedback [18]. Therefore, current sensory substitution systems can be distinguished in assistive and augmentative devices.

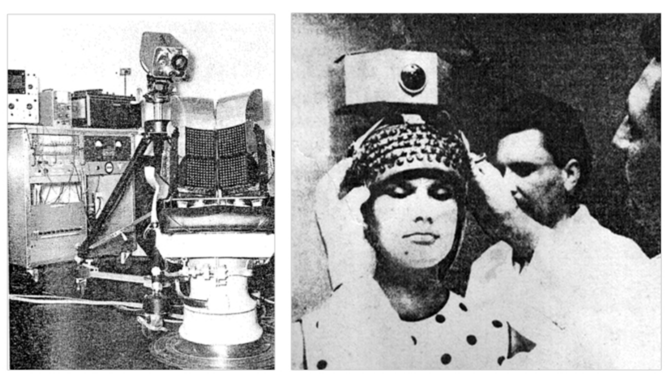

Fig. 1. *Left:* Tactile Vision Sensory Substitution System (Bach-y-Rita et al., 1969) [3]. *Right:* Later version of Noiszewski's Elektroftalm (Starkiewicz, 1970) [17]

3 Physiological principles

The basic physiological principle which enables sensory substitution is the fact that the human brain keeps the ability to use a sense, although

- *Matthias Schmidmaier is studying Media Informatics at the University of Munich, Germany, E-mail: schmidmaier@cip.ifi.lmu.de*

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the related peripheral receptor might not perceive signals anymore. Considering for example the visual system, the optic nerve transforms an image received by the retina into electrical signals which are interpreted in the brain. For substituting a broken retina, signals might be captured by a camera then transformed and sent to the brain, using a human-machine interface [4]. To understand this functionality of sensory substitution, it is important to understand the principles of brain plasticity and human perception.

3.1 Senses and perception

Dealing with sensory substitution, it is recommended to bring to mind how sensing and perception work. The five most known human senses are vision, hearing, touch, smell and taste. But there are also additional senses, such as feeling pain and temperature, the sense of balance or spatial sensation [22]. A human sense is defined as the 'faculty by which stimuli are perceived and conditions outside and within the body are distinguished and evaluated' [22]. That means that information is captured by sense organs and then passed on to the nervous system in order to get processed in the brain. Therefore, perception usually is described as the recognition and interpretation of sensory information.

However, studies on sensory substitution have shown that perception must not only be seen as processing of environmental sensory information. Testing several sensory substitution devices lead to the conclusion that 'there is no perception without action' [16]. It was found that Bach-y-Rita's TVSS only successfully worked if the subjects were able to manipulate the camera themselves. An experiment, run by Lenay and others, delivered equal results: a photoelectric sensor with an angle of sensitivity of about 20 degree was fixed on a finger of a subject. A vibrotactile device notified the user, if the sensor was pointing towards a light source. Blindfolded subjects who were not allowed to move the sensor, were not able to use the stimulation for vision, as they only knew whether there was a point of light in front of their finger or not. Subjects who were allowed to move the sensor, were able to recognize the direction and position of a light source. Thus it has to be assumed that perception does not only depend on sensory, but also on motor information [16].

3.2 Brain plasticity

If necessary, the central nervous system is able to change its structural organization. This adaptability is called brain plasticity [4]. That means that the brain can allocate a modality to a brain area which originally receives information from another one. In this way it is possible to receive sensual information using modalities that originally have not been used for that and thereby to compensate a sensory impairment. So a study with visually impaired people showed that several brain areas which generally are connected to vision have been activated while using a tactile vision substitution system: the visual areas perceived information by using a tactile modality [4].

Another implication of brain plasticity is the fact that the sensory display and the sensor may be relocated without appreciable consequences to the functionality of a sensory substitution device. So for example the tactile display of a TVSS system may be moved from the back to the forehead, without the subject loosing his ability to use the device. Analogous to that, the functionality is not affected if the sensor, in case of TVSS a camera, is shifted from the hand to the head [30]. In summary brain plasticity seems to be an amazing capability that forms the basis for sensory substitution. Hence it should be remembered that its possibilities are associated with a - mostly time-consuming - learning process, which ideally takes place under qualified supervision [16].

4 Technological principles

The first sensory substitution systems developed in the 1960s have mostly been bulky, hardly movable devices. Bach-y-Rita's TVSS for example consisted of a vibrotactile sensory display mounted on a dental chair and a camera on a boom, as seen in *Fig. 1* [3]. During the last decades, technological progress caused enormous changes in hard- and software and therefore enabled suitability for daily-use and high quality stimulation. However, the general composition has not changed until today.

An important part of the technological concept of sensory substitution devices is the sensory display which is responsible for stimulation. The most popular sensory displays during the last decades have been tactile displays [16]. Hence, the architecture of devices and the development and advantages of tactile displays are shown in the following. In addition, the way of classification for sensory substitution systems which is used to categorize the presented applications later in this paper is described.

4.1 Architecture

Sensory substitution systems in general consist of three components as illustrated in *Fig. 2*: a sensor, a coupling device and actuators [30]. Sensors capture information *x(t)* about the environment and transmit it to a coupling device. A sensor can be a modality which simply receives signals, like a camera or a microphone, or also emits signals like a laser or a ultrasound device. Depending on the system, sensing devices may differ in range, location, accuracy or mode of user control. Yet, independent of the kind of its other characteristics, the sensor should enable autonomous handling by the user. As already mentioned in context with senses and perception, the active handling of the sensor device by the subject is an important condition for the successful use of a sensory substitution system. Therefore, also the interaction of the user with the sensor modality is shown in *Fig. 2*.

The coupling device converts the received information into signals *y(t)* for activating a display of actuators (sensory display). This display sends impulses to a human sensory modality which forwards the information to the brain. Depending to the sensory modality, stimulation may be for example realized through loudspeakers or a tactile display. The choice of coupling device and display, strongly depends on the kind of associated human sensory pathways. So for example for a video-based sensor, the human vision information processing capabilities have to be considered [16, 30].

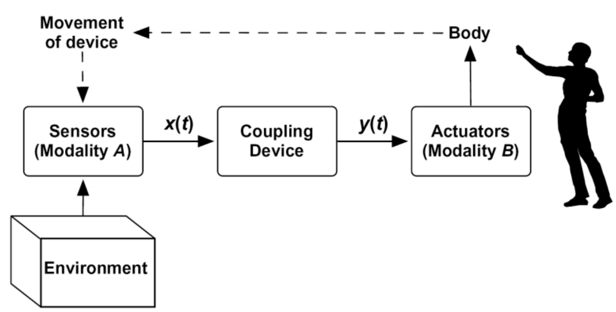

Fig. 2. Structure of a sensory substitution system [30]

4.2 Example: Tactile displays

In general, stimulation is achieved by tactile, auditory or visual displays. As seen in the descriptions of applications below (see also *Table 1*), the most used sensory displays until today have been tactile displays. Furthermore, tactile displays can be designed in several different ways. For this reasons, advantages and methods of tactile displays are shown in the following. Due to the rapid technological progress, current displays are small, energy-saving and relatively low-priced in production. In addition they use actuators like solenoids, eccentric inertial motors, voice coils, piezo-electric transducers and others for stimulation. These characteristics result in several advantages [16, 30]:

- *Suitability for daily use*. The small and energy-saving construction provides high portability and easy hiding of the device. Therefore only the user has access to the stimulation. These facts might, associated with sinking costs, contribute to an increase in usage of sensory substitution systems.

- *No interference with other senses*. Tactile displays usually are stimulating the skin. Hence they do not - unlike as is the case with for example auditory or visual stimulation - occupy senses that are already in use while transmitting information.

- *Rapid and high quality transmission*. As the stimulation concerns to the tactile cellular receptors, information is transmitted directly to the central nervous system. Also, compared to former devices, tactile displays offer a quite high resolution and stability.

Tactile displays offer several methods for stimulation which differ in the kind of actuators. Common methods are mechanical deformation, vibrotactile stimulation, electrotactile stimulation, force feedback, thermal feedback and air or liquid jets. Most tactile displays use vibro- or electrotactile stimulation. For vibrotactile stimulation, objects, usually small pins, vibrate against the skin to transmit information. In modern devices, vibrotactile displays mostly are replaced by electrotactile displays. Electrotactile displays use a current passed through the skin that causes nerve stimulation. For an effective stimulation, contact force and consistency of the skin (moisture, hairiness and oiliness) are very important [30]. Therefore Bach-y-Rita and others developed an electrotactile display called Tongue Display Unit system (TDU) that is placed on the tongue, which offers a lot better conductivity than ordinary skin [5].

4.3 Classification

For the following presentations of applications, sensory substitution systems are divided in the two main fields accessibility and sensory augmentation. However, to get an overview, the devices are also regarded to the senses they refer to. *Fig. 3* shows the categories to which the presented applications can be allocated. These categories are named depending on the senses which are substituted or enhanced and on the senses which are used for perception. So for example tactile vision enables vision through tactile perception. Although sensory substitution usually refers to two senses, it can also refer to only one sense, as for example for tactile sensory relocation [4]. The applications presented in this paper are allocated to the categories *audible vision*, *tactile hearing*, *tactile vision*, *tactile balance*, *tactile sensory relocation*, *audible spatial awareness and orientation* and *tactile spatial awareness and orientation*. As also can be seen in *Fig. 3*, most of the devices use tactile stimulation. Finally, when discussing the future potential of sensory substitution systems, other forms of substitution which are not shown in *Fig. 3* may be brought up.

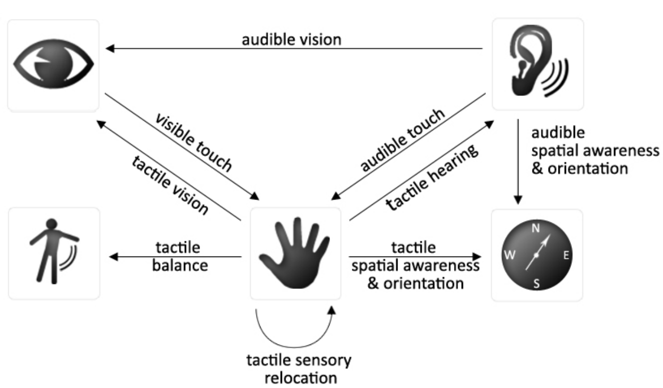

Fig. 3. Classification of sensory substitution systems. Each category is represented by an arrow that points from the sensory modality which is used for perception to the one which is substituted.

Table 1. Classification of the presented sensory substitution systems, including the kind of sensory input and stimulation.

Description	SS	Sensory input	Stimulation
BrainPort	TV	camera images	electrotactile display (TDU)
Tactile feedback prostheses	TSR	tactile data	pressure based actuators
Balance improvement	TB	pressure data	electrotactile display (TDU)
The vOICe	AV	camera images	loudspeakers
The Emoti-Chair	TH	audio data	voice coils
Hyperbraille	TV	screen content	tactile pins
VoiceOver, TTT	AV	screen content	loudspeakers
Enactive Torch	TSA, ASA	ultrasonic, infrared	vibrotactile display / loudspeakers
Haptic Radar	TSA	infrared	vibrotactile display
Aural Antennae	ASA, TH	microphone	vibrotactile display
TSA System	TSA	navigation system	vibrotactile display
FeelSpace belt	TSA	compass system	vibrotactile display
CI Surgery	VT, AT, TSR	camera images, tactile data	screen, loudspeaker, tactile display

5 Applications

To give a review of the different forms of sensory substitution systems, several devices are presented below. As mentioned above, listed applications are divided into the two main categories accessibility and sensory augmentation. However, there sometimes occur overlapping due to the various application possibilities of some devices. *Table 1* shows the kind of sensory substitution (SS) of the presented systems, according to the categories (AV = audible vision, VT = visible touch, TV = tactile vision, TB = tactile balance, TSR = tactile sensory relocation, AT = audible touch, TH = tactile hearing, TSA / ASA = tactile / audible spatial awareness and orientation) described above (see *Fig. 3*). In addition, the kind of sensory input and stimulation of the devices are shown.

5.1 Accessibility

Especially former sensory substitution systems have been developed for and tested by sensory impaired people. As a result, later releases mostly took place in the field of accessibility with the aim to design sensory aids for the daily use. In this chapter, several current auxiliary devices like travel or vision aids are presented.

5.1.1 BrainPort vision device

Since Bach-y-Rita developed the first version of the Tactile Vision Substitution System in the 1960s, many derivatives have been developed. The BrainPort vision device, shown in *Fig. 4*, is a current development implementing the principle of *tactile vision* [32]. It uses a camera mounted on sunglasses, from which signals are sent to a base unit. The base unit processes a stimulation pattern that is transmitted via a Tongue Display Unit (TDU). Thereby translation happens according to brightness. That means that the white pixels of an image frame result in strong stimulation of the corresponding actuator, whereas gray pixels are displayed as a medium and black pixel without stimulation. This form of translation can also be inverted by a controller that also enables to zoom the image.

The TDU used in today's BrainPort vision device prototypes consists of 400 to 600 electrodes, which is sufficient resolution for a good contrast. In *Fig. 4* a picture of a car is shown in different resolutions to illustrate the quality, reached by the BrainPort device. As the tongue is supposed to be capable to perceive much more information, future versions of the device are proposed to have a much higher resolution than today's. Studies using a prototype have shown that the use of the vision device is quite fast to learn. So users were able to recognize the position of objects after about one hour of training. Further practice even resulted in users identifying complex shapes like letters and numbers. Finally, although the device is still in a stage of development, later versions may be highly suitable for aiding visual impaired people in everyday life [32].

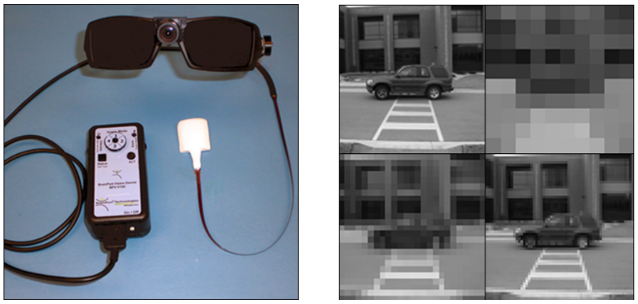

Fig. 4. *Left:* The BrainPort vision device consisting of a base unit, a camera mounted on sunglasses and a TDU. *Right:* Illustration of how an image may be displayed on the tongue with different resolutions: original resolution, 100 points, 625 points, 3600 points (from left to the right and top down) [32].

5.1.2 Prostheses with tactile feedback

As already mentioned, sensory substitution systems must not refer to two different senses, but may also implement the transfer of one type of sensory information to a sense of the same type. The following device creates sensory feedback from a hand prosthesis system using *tactile sensory relocation* [2]. Originally, mechanoreceptors on the skin provide stimulating information that is important for the use of a hand. Furthermore, stimulation is necessary for the awareness that an extremity is part of the body. Therefore, people using a prosthesis without tactile feedback may have great difficulty in intuitive usage. The presented device enables the transmission of tactile stimulation from the prosthesis to a part of the skin on the forearm.

The system consists of tactile sensors and a tactile display. Sensors are mounted on the finger tips of the artificial hand in order to send signals if they are stimulated. The tactile display consists of five pressure based actuators mounted on the forearm, each of them representing one artificial finger tip. As the spatial resolution of the forearm skin is quite bad, the distance between the stimulating elements has to be about four centimeter. Otherwise the user would not be able to feel the different positions of stimulations. In addition, the actuators are placed according to the form of a hand, to enhance intuitive usage.

Fig. 5 shows the tactile display placed on the forearm with the actuators arranged according to the real arrangement of the finger tips. An actuator is realized as a servomotor with an element that may be pushed against the skin. Depending on the received signal, the contact element is pressed against the skin with different force. So it is possible that the user can recognize which finger was used and with how much force the artificial hand has touched something [2].

5.1.3 Pressure based tactile balance improvement

The sensory substitution system described in the following enables *tactile balance* based on pressure sensors and electrotactile feedback [31]. The device was developed with the intention to prevent pressure sores, which may occur from spinal cord injuries, and to compensate loss of balance, which may occur in consequence of aging or disability. A pressure mapping system is used to measure the pressure distribution the subject causes while standing or sitting on it. Depending on the purpose of the device, the pressure mapping system is placed on a seat beneath a sitting person (for pressure sores prevention) or beneath the feet of a standing person (for balance improvement). A tongue display unit (TDU), originally developed by Bach-y-Rita, acts as stimulating sensory display. To enhance suitability of daily use, the

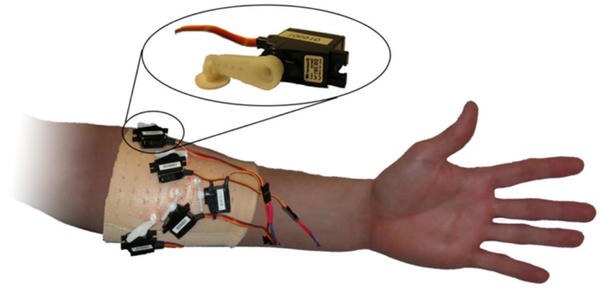

Fig. 5. Tactile display consisting of five actuators, placed on the forearm according to the arrangement of the finger tips of an opened hand [2].

system uses a wireless version of the TDU, consisting of a 6 x 6 matrix of miniature electrodes.

If the pressure sensors recognizes an overpressure zone, the TDU is activated to give a tactile feedback to the user. For example an overpressure at the left side involves an activation of the corresponding electrodes on the left side of the matrix. So the user is able to adjust his position by leaning to the side contrary to the activated electrodes. *Fig. 6* represents the principle of pressure based tactile balance improvement to compensate loss of balance: as in the initial posture *(1)* too much pressure is measured on the subject's right foot *(2)*, the right actuators on stimulation pattern are activated *(3)* to suggest the subject to relocate pressure to his left foot *(4)*. Experiments concerning both use cases (pressure sore prevention and compensation of loss of balance), showed that the described system enables postural and balance improvement for young and healthy persons. Based on these results, the developers suggest that the system may successfully be used in rehabilitative areas [31].

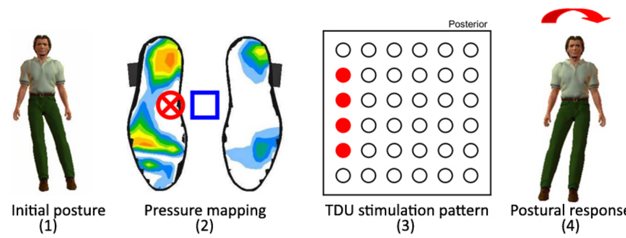

Fig. 6. Principle of pressure based balance improvement [31].

5.1.4 The vOICe

The vOICe (OIC conforms to 'oh I see') is a software for *audible vision* systems [20]. It is based on an real-time image-to-sound mapping that scans the image frames captured by a camera. At an interval of one second, frames are scanned from the left to the right. Thereby shapes are converted into sounds by representing elevation by pitch and brightness by loudness. So for example a bright point on dark ground results in a short loud beep. If the vertical position of the point increases, the pitch of the beep moves up, if it decreases, the pitch moves down. A higher amount of points results in the corresponding amount of beeps. Hence a bright horizontal line is displayed as a loud continuous tone.

A vertical line consists of points with different vertical positions. Therefore it is displayed as a brief sound consisting of tones with different pitches. Due to the left-to-right direction, objects on the left side of the frame occur earlier than objects on the right side. Shapes with low brightness appear equally, except that their sound is less noisy. Depending on the richness of detail of the watched image, the system provides less or more complex soundscapes. Thus it is necessary to start with simple images in order to get used to this way of visual substitution. To enable portability and intuitive movement of the camera, a sensory substitution device using The vOICe usually consists of a small head-mounted video camera, a notebook computer as coupling system and earphones (see *Fig. 7*). The vOICe devices like these are already in daily use by blind people. Meanwhile, a version of the program is even available as free application for smartphones [19, 20].

Fig. 7. The vOICe device consisting of a notebook, earphones and sunglasses including a camera [20].

5.1.5 Emoti-Chair

The Emoti-Chair realizes *tactile hearing* with the aim to transfer the emotional part of music [13]. The user can experience sounds by sitting on a chair with an implemented Model Human Cochlea (MHC) system (see *Fig. 8*) [14]. The MHC is a sensory substitution system that converts sounds into vibrations which are transmitted by multiple loudspeakers. Its design refers to the functionality of the human cochlea. Just as the cochlea uses tiny hair cells to receive different frequencies, the MHC uses several audio channels, each assigned to a specific frequency range. Vibrating devices, which in turn are assigned to these channels, are responsible for tactile stimulation. *Fig. 8* shows a prototype of a MHC, consisting of eight speakers used as vibrating devices. The quality of the experienced sensation through the MHC system can be increased by increasing the number of channels, as more individual frequencies can be distinguished by the user. Thus the distinction of different parts of music may be improved.

The MHC which is used in the Emoti-Chair consists of eight audio-tactile channels. Voice coils are used as vibrating devices, as they are directly driven by audio signals. They are arranged on the chair as a two column by eight row array. The input sound first is processed by an eight channel sound card and divided into different frequency bands. The signals of each frequency band are transmitted to an amplifier and assigned to the corresponding audio channel. Finally, vibrotactile stimulation to the skin is caused by the voice coils. According to subjects who have used the Emoti-Chair, it is clearly possible to distinguish between different songs, genres and qualities of music. [13, 14]

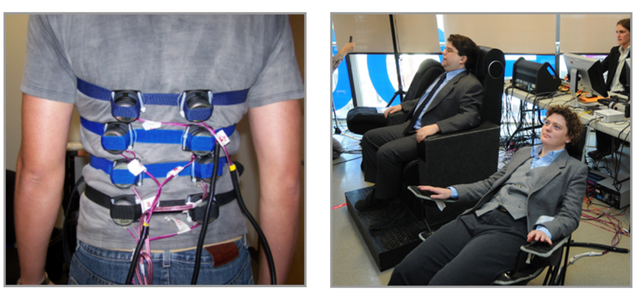

Fig. 8. *Left:* MHC prototype with four audio channels and eight speakers [14]. *Right:* Two prototypes of the Emoti-Chair, used to experience music (picture detail from [27]).

5.1.6 HyperBraille

Devices like the Brailledisplay already enable a non-visual use of digital information and navigation on the Internet. Yet, documents or websites that have a complex construction or a lot of graphical content are hardly usable for blind people. The HyperBraille system enables to read and interpret digital information, especially graphical elements, through *tactile vision* (see *Fig. 9*) [21]. The main element of the system is a touchable field that consists of 7200 tactile pins which are adjustable in height. The pins are arranged in a two dimensional 120 x 60 matrix at a distance of 2.5 mm. Similar to classic Braille, the user is able to recognize shapes by moving the fingers over the display. Besides the Braille display, there are also additional buttons that support navigation. The device is connected to a computer via USB and implements several software components which allow the use of popular office and Internet applications. Furthermore it includes the Braille Window Manager, a software that provides an overview over the screen structure [21].

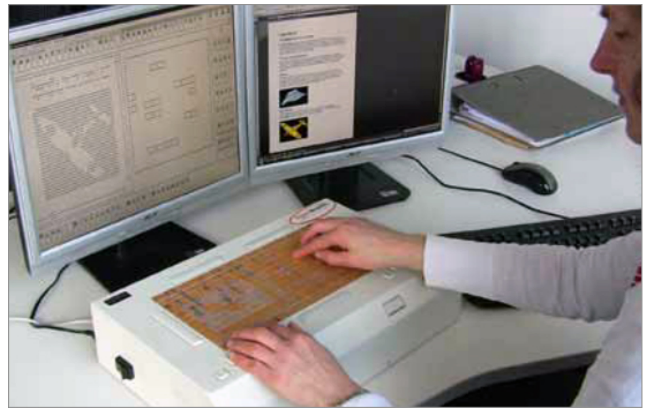

Fig. 9. HyperBraille device used to display graphical content [21].

5.1.7 Voice-based touch screen accessibility

Voice-based screen readers are *audible vision* devices that enable visually impaired people to interact with computers. Thereby, the content of the screen is scanned and displayed in audible form with speech or sounds. However, as these systems usually are based on keyboard and mouse input, it is hardly possible to interact with touch screens in this way. Due to the increasing usage of touch screens during the past years, above all in handhold devices like smartphones, some assistive applications have been developed to solve this problem [28].

Current touch screen accessibility interfaces still rest upon voice-based screen reading. Hence, the user is able to explore the content on the screen by simply touching it. If an element is selected in this way, it is read out without being activated. To activate an recognized element it usually has to be selected a second time. Two applications that realize audible vision for touch screens in this way are Apple's VoiceOver and the Talking Tap Twice (TTT) for the Android operating system. In addition, VoiceOver also supports alternative ways of navigation by using finger gestures [28].

5.1.8 Enactive Torch

The Enactive Torch is a sensory substitution system that provides *tactile spatial awareness and orientation* [8]. The handheld device consists of a ultrasonic or infrared sensor and a portable operation unit as can be seen in *Fig. 10*. The sensor is used to measure the distance to an object it is pointed to. Continuous vibrotactile stimulation on the user's hand is used to convey the distance information to the user. Different distances are displayed by varying strength of vibration. In addition the user is able to switch to another mode of perception whereby the distance is represented by audio signals. Therefore the Enactive Torch may also be categorized as *audible spatial awareness and orientation* system.

Studies have shown that the effective usage of the Enactive Torch device as travel aid takes only short time to learn. So blindfolded subjects were able to recognize relatively small obstacles in space like a lamppost, after about about ten minutes of training. Furthermore, compared to a conventional mobility cane, the Enactive Torch does not require direct contact to regarded objects. As a result it allows exploratory movements without interfering other people and therefore is highly suitable for daily use [8] [9].

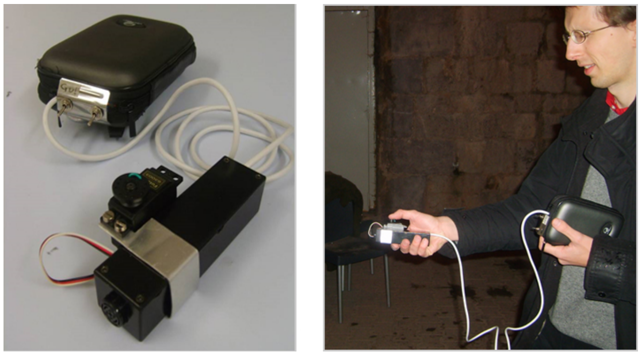

Fig. 10. *Left:* Enactive Torch prototype [9]. *Right:* Usage of the Enactive Torch device [9].

5.2 Sensory Augmentation

With technological progress, another area of sensory substitution came along. Developers started to think about sensory substitution systems that enhance existing senses or even add completely new ones. In current devices also non-human senses like for example infrared vision or magnetic perception are used to enhance human perception. Some sensory augmentation systems developed during the last past years are presented in the following.

5.2.1 Haptic Radar

The Haptic Radar was developed to enhance spatial awareness, using tactile stimulation [6]. Therefore it may be allocated to the category of *tactile spatial awareness and orientation* systems. The system is based on a network of several identical modules, each consisting of an infrared sensor and a vibrotactile device. Besides local stimulation by one module, the connections between the single modules enable also global stimulations. Therefore, a system composed of a high number of modules can result in a 'spatially extended skin'. As the sensors and vibrotactile devices only provide low visual information, a user is able to react in a very fast, reflexive way to a stimulation. Hence, the modules can be compared to insect antennae or artificial hairs.

The first prototype presented in this paper is a headband with six modules arranged around. Every module uses an infrared proximity sensor which watches its environment within an angle of 30 degrees and within a distance of 80 cm. If a sensor recognizes a nearing object, it gives tactile feedback to its stimulation device. In this way a user wearing the headband is able to perceive if, and from which direction, an object is nearing. *Fig. 11* shows a subject using the Haptic Radar headband prototype to avoid a nearing ball. In this experiment, subjects avoided the nearing object in 18 out of 30 trials. The developers suggest that this currently not significant rate will increase with further developed prototypes and increasing training time. So in future the Haptic Radar may be used as travel aid for visually impaired people or for example as enhancement of spatial awareness in hazardous working environments (see *Fig. 11*) or traffic [6].

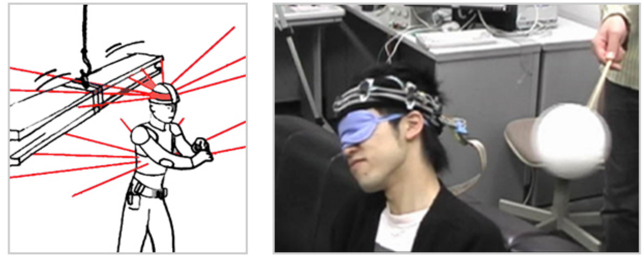

Fig. 11. *Left:* Use of Haptic Radar in a hazardous working environment [6]. *Right:* Testing a Haptic Radar headband prototype [6].

5.2.2 Aural Antennae

The Aural Antennae system provides the tactile perception of sound signals and may be rated among *tactile hearing* or *audible spatial awareness and orientation* systems [26]. The Aural Antennae device (see prototype in *Fig. 12*) is based upon the concept of the Haptic Radar which enables to feel distance information. Instead of infrared sensors, Aural Antennae uses an electret microphone as sensory input modality. A vibrotactile display is used to transmit audio information to the user's skin. Depending on the field of application, the system may be adjusted to process certain frequencies in a certain range of reception. So it is possible to perceive also high frequencies similarly to the vibrating perception of low frequencies, as one experiences when for example standing in front of a bass loudspeaker.

In this way it is also possible to enable the perception of frequencies that usually are out of the human acoustic range. One possible application of Aural Antennae would be a wearable system of multiple networked antennae that enables to feel the intention and direction of sound signals. In this context, the developers suggest the usage of the Aural Antennae system in road traffic: a driver who is not able to perceive an audible warning signal like honking (or a siren) because of hearing impairment or environmental noise, may be alerted by tactile stimulation on the part of the body which is nearest to the signal source [26].

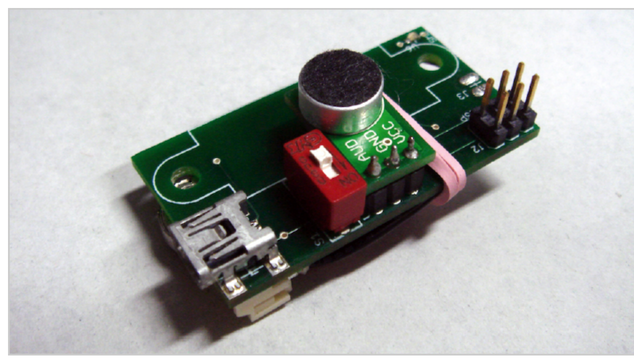

Fig. 12. Aural Antennae prototype [26].

5.2.3 Tactile Situation Awareness System

The Tactile Situation Awareness system (TSAS) is another *tactile spatial awareness and orientation* system [18, 23]. It was developed to enable pilots to use their sense of touch for preventing spatial disorientation. Especially in aircraft navigation, situations of low visibility or sensory overload may occur, so that the pilot can not rely on his visual and auditory senses. For example helicopter landings often take place on conditions of restricted sight as dust is blown up by the rotor blades. As a result, the pilot is not able to orientate himself by watching the horizon. The TSAS helps to perceive information about the aircraft's position, attitude and the movement around the aircraft's axis.

This information is measured by the aircraft's integrated navigation and attitude reference system and transmitted to the TSAS. If the device recognizes unbalanced or asymmetric movements, the pilot is alerted by vibrotactile stimulation. The tactile stimulation devices are integrated into a vest, worn on the torso (see *Fig. 13*). As it is developed to prevent accidents that mostly occur under extreme conditions, TSAS particularly applies to military fields of applications. In addition TSAS might also thought to be used as orientation aid for astronauts [18, 23, 30].

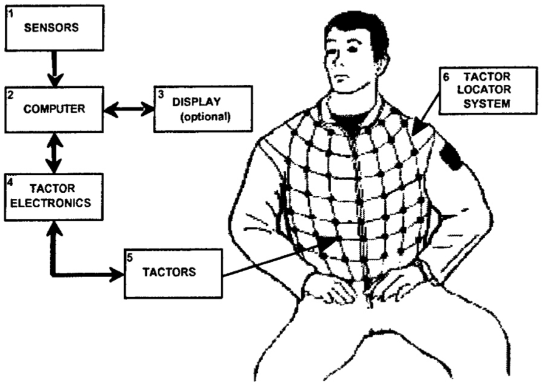

Fig. 13. Concept of the Tactical Situation Awareness System [18].

5.2.4 FeelSpace belt device

Many animals are known to have 'supernatural' senses for orientation. So for example pigeons are able to sense magnetic fields, which helps them to navigate. Inspired by the animal world, the FeelSpace belt device was developed to enable a kind of sense of magnetic perception to humans [24]. The device augments the human modality of spatial perception by using a compass system for *tactile spatial awareness and orientation*. The compass system, consisting of several components like accelerometers and magnetic sensors, is used to deliver information for orientation.

The current position of the North Pole is continually calculated and transmitted to a vibrotactile display. The display consists of 13 motors mounted on a belt which can be worn around the waist (see *Fig. 14*). The actuator which is pointing north is permanently vibrating, so that the user is informed about his alignment. The device has been tested with subjects during a training period of six weeks. The subjects had to wear the belt the whole day, including outdoor activity at least 90 minutes per day. Experiments in navigation during and after the training period have shown that the belt had positive influence on the orientation skills of the subjects. In addition it was found that humans after some time of training, in general can get used to new, unusual sensory perceptions [24].

Fig. 14. Prototype of the FeelSpace belt with 13 vibrating motors [24]
.

5.2.5 Computer Integrated Surgery

Computer Integrated Surgery (CIS) describes the use of robotic devices, sensors and human-machine interfaces to enhance the performance and decrease the error rate of medical surgeries and thus enable minimal invasive surgery (MIS) [10]. Therefore, the surgeon does not operate a patient directly using handheld surgical instruments, but using a surgical robot. A popular computer-instrumented interface is the Da Vinci Surgical System, which consists of several robotic arms, equipped with surgical instruments and a 3D-camera for visual feedback (see *Fig. 15*). The surgeon moves these arms by a controller according to the feedback he gets from the camera.

Despite the benefits surgical robots offer, the lack of force feedback is a large disadvantage which may result in the use of too much force and thus in an increasing amount of surgical errors. Therefore several systems, using different forms of sensory substitution, have been developed to enable force feedback for surgical robots [10, 15]. *Fig. 15* shows a *visible touch* approach that uses different colors to display the force applied to the surgical instruments of a Da Vinci system. The picture shows snapshots of a knot tying task. Thereby, force is represented through a circle which is displayed on the system's video stream besides each instrument. If no or low force is applied to an instrument, a green colored circle is displayed. A yellow colored circle represents ideal force, whereas red color shows excessive force [1].

In addition there have also been developed systems that use audible feedback, which therefore realize *audible touch*. However, the created sounds that represent the different force levels prone to interfere with the sounds created by other devices that usually are present during an operation. Both types, audible and visual force feedback systems, have been found to improve the performance of a surgeon using a surgical robot. Yet, haptic force feedback is even more promising but also more difficult to realize. Thereby, research has resulted in different types of sensory displays for *tactile sensory relocation*, including piezoelectric, electromagnetic, pneumatic and servo motor based feedback devices [29].

Fig. 15. *Left:* The Da Vinci Surgical System [10]. *Right:* Visible force feedback on a surgical robot [1].

6 Future potential of sensory substitution

After about 50 years of research and development in sensory substitution systems, the question arises how much further future potential this research area offers. According to the classification in this paper, potential future devices are viewed considering the fields of application accessibility and sensory augmentation. In the field of accessibility, assistive sensory substitution devices still suffer from missing acceptance through impaired people [25]. So for example, referring to Bach-y-Rita's TVSS, Lenay and others ask 'why these devices, first developed in the 1960's, have not passed into general widespread use in the daily life of the blind community.' [16]. Reasons for that may be low quality in displayed information, low portability and miniaturization or high training effort. However, one may expect that the spread of devices like the BrainPort or The vOICe will increase with increasing quality and usability.

Due to the technological progress, quality and miniaturization quite likely will be improved in the coming years. For example concerning tactile vision devices like the BrainPort, higher quality may be achieved by a higher resolution of tactile displays and the transmission of additional visual information like colors. The next step of miniaturization possibly will lead towards implantation of sensory displays to enable a fastest possible transfer of sensory information, and even a direct stimulation of the brain [4, 16]. In contrast to the slight use of complex sensory substitution systems that serve for example as navigation aid, the increasing ubiquity of computers in the human environment seems to cause a high need for applications that enable access to other technical devices like smartphones and computers. So applications like VoiceOver or Talking Tap Twice seem to have high future potential, quite independent from miniaturization and implantation techniques.

The second viewed field of sensory substitution systems, sensory augmentation, seems to provide a lot of potential for future developments. Bach-y-Rita mentioned in 2003 that devices may be used in space and underwater scenarios, serve in automobiles or airplanes and in surgery devices [5]. Devices like the TSAS and the force feedback systems on surgical robots already have been found to provide benefits in these field of applications and therefore will be further developed and improved [10, 23]. Yet, besides the technological enhancement of existing devices, future inventions might also concern entirely new approaches of sensory substitution. Thereby a source of inspiration may be the animal world, as it has been for the development of the Haptic Radar and Aural Antennae. Infrared vision, sonar, high performance vision or thermal detection are possible capabilities to be enhanced or transmitted by a sensory display in order to avoid the overload of other senses.

However, as an average person usually does not need infrared vision in daily use, devices of that kind may be especially developed for military use and for people working under extreme conditions. So for example a vision device that uses thermal information as input instead of usual camera images, may be used as targeting aid for soldiers or as vision aid for firefighters in low vision environments like smoke filled rooms [7, 11]. A statement made by a speaker of the Defense Advanced Research Projects Agency (DARPA) of the United States shows, that sensory substitution techniques concerning sensory augmentation have high future potential above all in the military sector. So, according to TechNewsWorld, the speaker revealed that the DARPA is interested in the use of sensory substitution systems as navigation aid for military divers and therefore sponsors relevant studies [7].

The classification of sensory substitution systems, shown in *Fig. 3* may, depending on the used sensors and actuators, be complemented by new combinations of senses and abilities. As a result new categories like for example *visible electric perception* are possible. Again, considering all possible combinations of (human) senses in this way reveals the - at least in theory - 'infinite' possibilities of sensory substitution.

7 Conclusion

From a bulky dentist chair to a small display worn on the tongue and to the vision of brain implants. The devices described in this paper show the development and the impressing possibilities of sensory substitution. Yet, the results of current sensory substitution systems for the compensation of sensory impairments sometimes may be disappointing for the user due to the expression 'substitution'. Although accessibility devices offer a kind of perception corresponding to an impaired sense, they are not able to completely substitute it. So for example a tactile vision system like the BrainPort device enables a blind user to 'see' shapes and therefore to recognize his environment. Nevertheless, according to Bach-y-Rita and others there may be a lack of emotional content due to missing details [5].

Hence it is important to consider that sensory substitution does not mean full-value compensation of a sense and that therefore the introductory statement of 'allowing blind people to see and deaf people to hear' may be sort of misleading [16]. Anyway sensory substitution devices provide useful support for impaired people - currently above all concerning orientation and communication. Future technological progress may promise highly interesting developments in the field of accessibility as well as in the field of sensory augmentation. However, developers should keep in mind ethnic principles when thinking about the development of super soldiers and brain implants. As a result, advancements may possibly increase the acceptance and therefore the spread of sensory substitution systems not only in specific scenarios, but also in daily use.

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