HAL open science

# SENSORY SUBSTITUTION: LIMITS AND PERSPECTIVES

Charles Lenay, Olivier Gapenne, Sylvain Hanneton, Catherine Marque, Christelle Genouëlle

▶ To cite this version:

Charles Lenay, Olivier Gapenne, Sylvain Hanneton, Catherine Marque, Christelle Genouëlle. SENSORY SUBSTITUTION: LIMITS AND PERSPECTIVES. Yvette Hatwell; Arlette Streri; Edouard Gentaz. Touching for Knowing, 53, John Benjamins Publishers, pp.275-292, 2004, Advances in Consciousness Research, 9789027251855. 10.1075/aicr.53.22len . hal-02434266

HAL Id: hal-02434266
https://hal.science/hal-02434266

Submitted on 9 Jan 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# SENSORY SUBSTITUTION:
# LIMITS AND PERSPECTIVES

Charles Lenay, Olivier Gapenne, Sylvain Hanneton[1],
Catherine Marque et Christelle Genouëlle
29/08/2003
Université de Technologie de Compiègne
COSTECH - BIM
Groupe Suppléance Perceptive[2]

A quarter of a century ago, in the preface to « Brain Mechanisms in Sensory Substitution », Paul Bach y Rita wrote:

> "This monograph thus risks becoming outdated in a very short time since the development of refined sensory substitution systems should allow many of the question raised here to be answered, and some of the conclusions may appear naive to future readers." (BACH Y RITA, 1972)

As it turns out, this prediction is far from having been fulfilled: in spite of their scientific and social interest, their real effectiveness and a certain technological development, prosthetic devices employing the principle of "sensory substitution" are not widely used by the blind persons for whom they were originally destined. After a brief recall of the general principle of sensory substitution, we will advance several hypotheses to account for this situation. We will then identify some elements which may favour the conception and, especially, the usability of future devices. To this end, we will focus our analysis on the work of Bach-y-Rita, particularly well documented, devoted to TVSS (Tactile Vision Sensory Substitution) since the 1960's. This choice is motivated by the extensive and exemplary nature of this research, devoted to the rehabilitation of a handicapped population, as an enterprise which is both technical and scientific in character. We will also present the specific interest of substitution systems employing tactile stimulation, and we will emphasize the essential coordination of fundamental and technological research in this area. In addition, besides their direct utility for handicapped persons, these devices open broad experimental and theoretical perspectives on cognition in general (brain plasticity, perception, intentionality, etc....)

---

[1] Sylvain Hanneton is also a member of the Laboratoire de Neurophysique et Physiologie du Système Moteur, CNRS - FRE 2361, Paris V.

[2] The group expresses its thanks to Clotilde VanHoutte and John Stewart.

# 1. A REVIEW OF SENSORY SUBSTITUTION DEVICES

## *1.1. General functional principles*

In general, the so-called "sensory substitution" systems transform stimuli characteristic of one sensory modality (for example, vision) into stimuli of another sensory modality (for example, touch). A sensory substitution system can be decomposed into three distinct components. A sensor permits the conversion of a certain form of energy (light, sound, mechanical or other) into signals that can be interpreted by an (electronic) coupling system which is then responsible for the coordinated activation of a stimulator. The stimulation is generally addressed to the cellular receptors of a sensory organ, and thus consumes electrical energy which can be converted into sound energy (as in the case of visual-acoustic devices) or into mechanical energy (visual-tactile devices). The sensors can be "active", that is to say they can emit and receive signals. This is the case, for example, in devices where the "sensor" component employs a telemetric principle (e.g. laser or ultrasound).

The term "sensory substitution", as such, denotes the ability of the central nervous system to integrate devices of this sort, and to constitute through learning a new "mode" of perception. It is to be noted that *action* on the part of the subject plays an essential role in this process, a point to which we shall return. In other words, sensory substitution can only be constituted and can only function through an ongoing exploratory activity with the sensors. Finally, the access to a mode of perception that is offered by sensory substitution devices after the requisite learning period can be described as "implicit", in other words it makes no call on conscious reasoning concerning the sensations produced by the system of stimulation.

## *1.2. A non-exhaustive panorama*

On account of the relative independence of the three components of these systems, and the great diversity of types of sensors and stimulators which are available at the present time, there are a large number of potential sensory substitution systems, many of which have been realised. In this section, we cannot therefore give a detailed comparative inventory of all such prosthetic devices, even restricting ourselves to the tactile modality. These devices are technically very varied, since their development corresponds to diverse objectives: aids for handicapped persons, the ergonomics of interfaces, fundamental research or, again, performance in the realms of games or art. This pluridisciplinary aspect means that the literature dealing with this approach is highly dispersed, but the reader may consult several works which present a certain number of these techniques (BARFIELD & FURNESS, 1995 ; O.F.T.A., 1996 ; SAMPAIO, 1994 ; WARREN & STRELOW, 1985).

It nevertheless seems desirable to give the reader an overview of the "state of the art" in this domain. To this end, we present a table of examples of systems incorporating various sensory modalities. Some of the technologies cited are not complete sensory substitution systems (they are only single components, sensors or stimulators), but these elements are likely, in our view, to participate in the future evolution of these devices. It is to be noted that from the point of view of their technological development, many of these systems currently benefit from the miniaturisation of sensors and stimulators. For example, high-performance cameras, of very small size, are now available on the market at low cost (in particular the camera using the CMOS technology); and some research groups are working on tactile stimulation systems which provide high resolution on a very small surface (Exeter Fingertip Stimulator Array, CHANTER & SUMMERS, 1990). We shall return in what follows to the important role of miniaturisation in the appropriation of these prosthetic devices.

| Type | Sensors | Stimulators | References |
|---|---|---|---|
| ETA[3] | 5 ultrasound sensors | Stereophonic | Sonic Pathfinder™ (Heyes, 1984) |
| ETA | 2 ultrasound sensors | Monophonic | UltraSonic Torch™ (Kay, 1965) |
| ETA/SSS[4] | 3 ultrasound sensors | Stereophonic | Sonic Glasses™ (Kay, 1974) |
| ETA/SSS | 3 ultrasound sensors | Stereophonic | TriSensor (Kaspa™) distributed by SonicVison LTD |
| ETA/SSS | 1 ultrasound sensor | Tactile (EM) | Mowat Sensor (Pulse Data Int. Ltd) |
| SSS | Video camera | Stereophonic | The Voice™ (Meijer, 1992) |
| SSS | Video camera | Tactile (EM) | TVSS (20x20 tacteurs, Bach y Rita 1963) |
| SSS | CCD camera | Tactile (ET) | VideoTact™ (1996) Unitech Research Inc. |
| SSS | Acoustic (micro) | Tactile (EM) | Tactile Sound Transducer (Clark Synthesis) |
| SSS | Tactile (CG) | Tactile (EM) | EVTS (Orbitec, up to 20 stimulators) |
| SSS | CCD camera | Tactile (ET) | Tongue Display Unit (Bach y Rita et al. 1998) |
| | ? | Tactile (PE) | Exeter Fingertip Stimulator Array, Chanter & Summers, 1998 (10x10 sur 1cm$^2$) |
| | ? | Tactile (EM) | Tactile Feeling Display, Shinoda et al., 1998 |
| | ? | Tactile (SMA) | Form memory activators (Grant et Hayward,1997) |
| | | Tactile (CA) | Stimulation using compressed air (Shinoda et coll., unpublished) |
| | CMOS camera | ? | Low-cost technology allowing high miniaturisation of the sensors |
| | Ocular implant | ? | Stimulation of retinal ganglion cells Wyatt et Rizzo, 1996 |
| | Cortical implant | ? | Schmidt et al., 1996 |

**Table 1. A non-exhaustive list of various sensory substitution systems. This table also includes single components (sensors or stimulators) which are available for incorporation in**

[3] ETA : « electronic travel aid ».

[4] SSS « Sensory Substitution System».

**this context. Abbreviations: (EM) electromagnétic, (ET) electrotactile, (SMA) shape memory alloys, (PE) piezo-electric, (CA) compressed air, (CG) constraint gauge.**

### 1.3. *The results obtained with the TVSS*

The TVSS (« tactile vision substitution system ») makes it possible to convert the image captured by a video camera into a "tactile image". In the standard version, the tactile image is produced by a matrix of 400 activators (20 rows and 20 columns of solenoids of one millimeter diameter). The matrix is placed either on the back (first version), or on the chest, or on the brow (COLLINS & BACH Y RITA, 1973). Many technical improvements have been introduced (miniaturisation, image definition, electrical stimulation, etc), and this device is still commercially available under the label VideoTact™ (Unitech Research Inc). Finally, it has recently been adapted with a view to being used by young babies (current research by E. SAMPAIO).

Equipped with the TVSS, blind (or blindfolded) subjects are almost immediately able to detect simple targets and to orient themselves. They are also rapidly able to discriminate vertical and horizontal lines, and to indicate the direction of movement of mobile targets. The recognition of simple geometric shapes requires some learning (around 50 trials to achieve 100% correct recognition). More extensive learning is required in order to identify ordinary objects in different orientations. The latter task requires 10 hours of learning in order to achieve recognition within 5 seconds.

An essential observation is that this capacity to recognize forms is accompanied by a "projection" of the objects which are perceived as existing in an external space. Initially, the subject only feels a successions of stimulations on the skin. But after the learning process described above, the subject ends up by neglecting these tactile sensations, and is aware only of stable objects at a distance, "out there" in front of him. A number of experimental observations confirm this externalisation. For example, if the zoom of the camera is manipulated unknown to the subject, causing a sudden expansion of the tactile image, the subject takes characteristic evasive action (moving backwards and raising his arm to shield himself from what is interpreted as a dangerously approaching object[5], BACH-Y-RITA, 1972, page 98). According to the accounts given by the subjects themselves, the irritations which can be caused by the tactile matrix are clearly distinguished from the perception itself. Blind persons discover perceptive concepts which are quite new for them, such as parallax, shadows, and the interposition of objects. Certain classical optical illusions are also reproduced (BACH Y RITA, 1982; GUARNIERO, 1977). The TVSS has also been used successfully in a work situation, by a blind person who was able to perform a certain number of delicate operations on an automatic production line for diodes (for more details, see SAMPAIO, 1994).

---

[5] Whereas in fact the matrix of tactile stimulators is placed on the back of the subject.

However, once the initial flush of enthusiasm has passed, it is legitimate to 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. Paradoxically, an analysis of the possible reasons for this relative failure raises some of the most interesting questions concerning these devices. One way of addressing this question is to critically discuss the very term of "sensory substitution", which carries with it the ambiguity, and even the illusory aspect, of the aim of these techniques.

## 2. SENSORY SUBSTITUTION : A DOUBLE ILLUSION

### *2.1. It is not a sensory substitution*

It is easy to understand, as a means of publicity and marketing, the value of the term "sensory substitution" in order to describe the devices developed by Paul Bach-y-Rita: the device "enables the blind to see". Is this not an accomplishment close to a divine miracle? Nevertheless, the term is misleading and in many ways unfortunate. It implies that the essence of the innovation consists merely in a change in the sensory input, in providing a new channel for the acquisition of information about the world of light. In this case, the device would merely substitute the classical visual input via the eyes, by a hybrid input consisting of the video-camera and the matrix of tactile stimulators. If this were really all that is at stake, the work of Bach-y-Rita, while not negligeable, would have only a limited significance. If all that is to be achieved is to create artificial sensory inputs, would it not be better to use a matrix of electrodes directly implanted in the retina (WYATT & RIZZO, 1996) or even in the brain (BRINDLEY, 1973, DOBELLE & MLADEJOVSKY, 1974, DOBELLE et al., 1976, SCHMIDT et al., 1996)? This would make it possible to short-circuit the clumsy detour by the tactile stimulation, and to increase the quantity of information delivered.

However, this would be to miss the real point of Bach-y-Rita's work. On the contrary, his major discovery is that a mere sensory substitution is of little use. The great merit of his device is actually to demonstrate this very point experimentally. If one presents a blind person with static forms on the tactile matrix (the video-camera is immobile, simply placed on the table), the subject will merely feel a vague tickling sensation or irritation ; he will be capable only of very vague distinctions. There will be no question of recognizing or locating external, distal objects :

> « The process of perceptually learning to identify these forms with the TVSS is particularly revealing. The performance of all the subjects was never better than chance, even after 60 trials, if (1) the subjects were not able to manipulate the camera, and (2) if they were not given feedback as to whether their responses were correct. » (SAMPAIO, 1994 : 9)

On the other hand, if the handicapped person was able to manipulate the camera (movements from left to right, up and down, zoom back and forward, focussing, and the diaphragm), the subject rapidly developed spectacular capacities to recognize forms. He starts by learning how variations in his sensations are related to his actions. When he moves the camera from left to right, he feels on his skin that the stimuli move from right to left. When he uses the zoom, the stimuli "expand" or "contract". After having learned to point the camera in the direction of the target, he discriminates lines and volumes, and then recognizes familiar object of increasing complexity, to the point of being able to discriminate faces.

The work of Bach-y-Rita is therefore important not only because it is a useful technological innovation, but also because it provides original experimental tools for exploring fundamental mechanisms in perception. These tools make it possible to follow with precision the constitution of a new sensory modality in the adult. In particular, by providing the means to observe and reproduce the genesis of intentionality, i.e. consciousness of something as external (the "appearance" of a phenomenon in a spatial perceptive field), these tools make it possible to conduct experimental studies in an area usually restricted to philosophical speculation.

From a neurophysiological point of view, sensory substitution opens new possibilities for studying the extraordinary plasticity of the brain that the use of these prosthetic devices seem to imply. Tactile sensory input is quite different from visual input from the retina, and control of camera movements by the hands is quite different from commands to the eye muscles. Nevertheless, the brain appears to be able to organize a perceptive world with forms and events quite analogous to those given in visual perception. Moreover, if the matrix of tactile stimulators is displaced from the chest to the back, and the camera held in the hands is replaced by a miniature camera fixed to the frame of some spectacles, the adaptation is practically instantaneous. The subject recovers a distal perception in a few seconds. The functional restructuring of the brain poses fascinating problems for conceptualizing and modelling the mechanisms of the reorganization of functional neural networks.

On a functional level, these devices put into question the classical conception of perception and cognition based on parallel processing of passively received information. In that conceptual framework, the cognitive system is only a computational system which receives input information which is then processed in order to produce representations of objects and events ; reasoning on the basis of these representations then, in certain cases, leads to decisions concerning subsequent adaptive actions. It is well known that this conception of cognition is based on the computer metaphor, and carries the implication that computers could, in principle, be *substituted* for any other cognitive system. As a corollary, it is generally considered that the cognitive system is immersed in a world which contains information, a world which in the last resort *is* nothing other than information. This conception finds a concrete technical expression in systems of "virtual reality", with the horizon of entirely *substituting* reality by a system which delivers sensory input in the form of information which has been calculated on the basis of a virtual "environment" which includes the effects of the actions of the subject (LUCIANI, 1996). Thus, in modern technological developments, the current conception of cognition as information processing finds two sorts of concrete manifestations which serve both as a guiding analogy and as a theoretical horizon: on the side of the subject, the computer as a system of computation and decision; on the side of the object, virtual reality as a system for computing the information available to the subject. By contrast, when we consider the devices of Bach-y-Rita as they actually function in practice, it is no longer possible to conceive of cognition and perception as the simple processing of information received from the outside. This radical criticism of the computational theory of mind has hitherto been based on philosophical considerations and certain results in experimental psychology. Here, however, the empirical proof is direct: *there is no perception without action.*

This key idea, that there is no perception without action, finds a particularly vivid illustration in an experiment that we have carried out recently with a substitution device simplified in the extreme : a single photoelectric cell fixed on a finger is connected to a simple vibrator held in the other hand. (LENAY, CANU & VILLON, 1997). The vibrator is activated in all-or-none fashion above a threshold in the photoelectric cell; the receptive field is quite wide, corresponding to a cone of about 20° visual angle. Thus there a single point of tactile stimulation, corresponding to a single receptive field (compared with the TVSS which has 400 points of stimulation corresponding to the same number of distinct receptive fields in the retina of the camera). Nevertheless, after several minutes of exploration, a blindfolded subject who is able to freely move the arm and the hand with the photoelectric receptor is able to succeed in localizing a light source, i.e. to indicate its direction and approximate distance. When the subject achieves greater mastery of the active production of tactile stimulations, he is conscious of the presence of an object situated in the space in front of him. It seems to the subject that the temporal succession of sensations derive from different "contacts" with a single distal object. It is to be noted that the vibrator can be moved to another region of the skin without disturbing this perception of the distal object. In fact, the subject appears to ignore the position of the tactile stimulations (unless he consciously refocusses his attention on that aspect of the situation) to the benefit of an apprehension of the spatial position of the light source. Conversely, artificial stimuli produced independently of the movements of the finger on which the photoelectric cell is placed are not associated with a distal perception, but continue to be perceived proximally at the level of the skin. Similarly, if the movements cease, the distal spatial perception disappears. If the finger is completely immobilized, the tactile stimulation is either continually present, or continually absent, but in either case nothing induces the subject to infer an external distal source. In order for perception to arise, a continual activity is necessary, consisting of oscillatory movements of the hand together with displacements of the wrist in such a way that the stimulation continually appears and disappears.

In a similar vein, in order to enlarge this field of empirical research, we have embarked on a research program concerning the perception of 2-dimensional shapes. This program involves both the technological development of simple prosthetic devices, and the elaboration of experimental protocols concerning the forms of activity which lead to successful perception and recognition of the shapes. Our preliminary results (HANNETON et al, 1998; ALI AMMAR et al., 2002; SRIBUNRUANGRIT et al., 2002) clearly demonstrate that shape recognition is possible with even minimal forms of sensori-motor coupling. A point of interest in this approach is that the perception of shapes takes time, and requires the external deployment of exploratory activity. Precisely for this reason, traces of the patterns of exploration can be easily stored for subsequent analysis. Analysis of these dynamic patterns shows that experienced subjects deploy identifiable strategies, which can and must be learned in order for rapid and reliable perception to occur successfully.

The essential role of action in the progressive emergence of structured percepts strongly suggests that what is perceived, or recognized, does not derive from invariants in the sensory information, but rather from invariants in the sensori-motor *cycles* which are inseparable from the activity of the subject. It is by his action that the subject seeks and constructs the "rules" of constant relations between actions and subsequent sensations. Spatial localisation, as well as form recognition, correspond to temporal syntheses of successive sensations in accordance with a rule relating action and sensation[6]. This conception is now quite widespread in current research on sensori-motor coupling in general (GIBSON, 1966,; PAILLARD, 1971; BERTHOZ, 1991; TURVEY & CARELLO, 1995) and its genesis (LEPECQ, JOUEN & GAPENNE, 1995).

If, as seems to be the case, perception is only possible when the subject can actively master the means of acquiring sensations, it follows that the device of Bach-y-Rita does not so much achieve a simple sensory substitution, but rather a *sensori-motor* substitution. The richness of the perception depends quite as much on the qualities of the actions (mobility, rapidity, zoom, etc.) as on the qualities of the sensations (sensitivity, spectral width, number of sensors, etc.). This is well illustrated by the astonishing capacity to recognize faces with devices which only give 400 points of sensory input. The face that is recognized results as a higher-level invariant on the basis of changes in sensation associated with active exploration.

### ***2.2. It is not a sensory __substitution__***

If one had to persist with the idea of a substitution, the notions of "*sensory-motor* substitution system", or "*perceptual* substitution", would be preferable to "sensory substitution". However, we now wish to argue that the second reason why the phrase "sensory substitution" is misleading and unfortunate, is that what is at stake is not a substitution. The warning came from the visually handicapped persons themselves, who expressed disappointment at the very time when they began to discover this novel mode of access to objects situated at a distance in space. Certainly, these devices made it possible to carry out certain tasks which would otherwise have been impossible for them. However, this was not the fundamental desire which motivated the blind persons who lent themselves to these experiments. A blind person can well find personal fulfilment irrespective of these tasks for which vision is necessary. What a blind person who accepts to undergo the learning of a coupling device is really looking for, is rather the sort of knowledge and experience that sighted persons tell him so much about : the marvels of the visible world. What the

[6] A proper definition and/or modelling of the notion of "sensori-motor invariant" remains however to be formulated.

blind person hopes for, is the *joy* of this experiential domain which has hitherto remained beyond his ken.

Now the problem is that this is not what the device procures. In fact, there are a large number of differences between this artificial coupling device and normal vision : there is no colour, a small number of points, a camera whose movements are limited and clumsy, all of which slows down the recognition of a situation. This novel sensori-motor coupling resembles vision in many ways, but the quality of lived experience that it procures is quite different - as can be readily appreciated by sighted subjects who are blindfolded for the purposes of the experiment. The device of Bach-y-Rita does not produce a sensory *substitution,* but rather an *addition,* the creation of a new space of coupling between a human being and the world. The sensory substitution devices upset the classical definitions of the diverse sensory modalities.

It would be vain to believe that one has alleviated the suffering of a blind person just by giving him access to a sort of information. What is always at stake, is the insertion of the person in a world of shared meanings, which depend on a personal history whose coherence must not be brutally shattered. Now what is cruelly missing in this new perceptual modality is what Bach-y-Rita calls the *qualia,* i.e. the values and the quality of lived experience associated with perceived entities. If one shows a person blind from birth an image of his wife, or if one shows some students pictures of nude women, the disappointment is complete : their perception does not convey any emotion. But after the event, it is clear that it is the reverse which would have been astonishing. Meaning or emotional significance are not things that are already there, in the world, just waiting to be picked up like a piece of information. Here again, by the failure of its initial ambition, the device of Bach-y-Rita provides a crucial empirical proof: an isolated subject cannot attribute an existential meaning to objects and events that he perceives simply on the basis of a new perception. Does it follow that something essential is lacking in these devices? Unable to give a "content" to the perception (colour, value), they demonstrate what distinguishes natural perception from a simple capacity to discriminate and categorize. There is a striking similarity between these observations, and reports of the absence of emotion and meaning felt by persons blind from birth who recover sight by removal of a cataract. In other words, it is not the principle of sensory substitution as such which is responsible for the impossibility of gaining access to qualia (GREGORY, 1990).

It is remarkable that in all the observations reported in the literature, it is always a question of a purely individual use of these devices. The user is surrounded by sighted persons, but is isolated in his particular mode of perception. Now it is plausible to suppose that perceptual *values* are closely linked to the existence of a shared history and collective memory, a memory which can only emerge in the course of interactions between several subjects in a common environment. This suggests possible experiments in the future. In any event, it seems to us that the term "perceptual supplementation" is more appropriate than "sensory substitution". This new term implies that these devices do not exactly remedy a deficit, but rather that they introduce perceptual modalities that are quite original.

The sensori-motor coupling devices thus give rise to experimental research into a deep problem, classically restricted to philosophy and psychology, concerning the origin and the nature of the *value* attached to things. A purely intellectual link inferred between a perceived form, and a feeling of pleasure or pain in another sensory modality, does not seem to be immediately sufficient to confer an emotional value to the form in question.

# 3. DEFINING THE CONDITIONS OF APPROPRIATION

## *3.1. Ergonomic constraints*

The ergonomic properties, in a wide sense, play an important role in determining the acceptability of these devices. The necessary qualities are in large part dictated by the principles just referred to which condition the success of "sensory substitution". Thus, given the importance of the role of action in the deployment of these new modes of perception, a prosthetic device which hinders the exploratory movements of the subject is to be avoided. This constraint leads to a requirement for developing systems which are light and autonomous. The systems of tactile stimulation which employ electromagnetic transducers do not currently fulfil this requirement. Even though they are very effective and simple to use, in their present state of development they are heavy and require a large amount of energy, so that in order to be autonomous they require batteries which are also heavy. Of course, the difficulties involved in producing a device which is light and autonomous increase with the resolution of the tactile stimulation. In addition, in order to function well as a prosthetic device, the ideal system should be easy to "put on" or to "take off", like the spectacles used by sighted persons. However, the device should also be robust. Since the aim is that the device should integrate the daily life of a person who already has to cope with the anxiety and stress of a partial inadaptation to the environment, it would not be reasonable to propose a system which is fragile and liable to break down.

When it comes to aesthetic criteria, an apparent contradiction arises: the device should lend itself to being "forgotten" by the user and those around him, yet at the same time it should "advertise itself" when the situation requires. A sensory device should be sufficiently discreet so as not to reinforce the handicap, and to avoid the user being perceived as a "technological monster". Miniaturisation is not the only solution to this problem; it is quite possible to follow the shape of usual objects present on the site where the device is to be used. For example, a device aimed at providing access to graphic information on a computer screen could advantageously take the form of a mouse. At the same time, even though it may seem to contradict the previous principle, the appearance of the device can also fulfil a symbolic function. The traditional white colour of a blind person's cane has the advantage of signalling to others the fragility of this person while undertaking a journey. Finally, another aspect which is important even if it is not strictly ergonomic is the cost of the device. Systems analogous to the TVSS currently available on the market employ advanced technology, and are produced in small numbers, with the result that their cost is virtually prohibitive (45000 $ for VideoTact, the electrotactile stimulation system with 768 points produced by the Unitech company).

### *3.2. Adaptation to real expectations*

It seems to us that the appropriation of a sensory substitution device depends on it corresponding to a real need of the relevant population. We have identified two main preoccupations. The first need concerns the population of visually handicapped persons using computer technology to study, work or simply communicate. The availability of vocal synthesis, Braille keyboards and systems for optical character recognition has until now at least partially fulfilled this need in the case of operating systems (Dos, Unix) which code the information in the form of asci characters. However, the rapid and inexorable development of operating systems which employ mainly a graphical access to computers functionalities is leading to serious discouragement in this population which has already made a tremendous effort to adapt. To the extent that the transformation of graphic or iconical information into the form of tactile stimulation does not present a major technological difficulty, the application of sensory substitution techniques to this area ought to be fairly easy (for example, ee the Internet site of the Unitech company: http://www.execpc.com/~unitech/winhapt.html).

The second need concerns a wider population. The traditional white cane gives precious assistance in locomotion and avoiding obstacles. However, it does not give access to a distal perception, without contact, of the global scene. A mode of distal perception, ideally coupled with the cane without replacing it, would greatly facilitate the anticipation of movements, for example by making it possible to extract from the environment static or mobile silhouettes of obstacles to be avoided. Other potential applications, such as the access to reading or writing in black and white (such as the Optacon) are less crucial, particularly since they are in competition with proven systems such as Braille. It is quite possible to imagine a system which would fulfil conjointly the two needs just described, the reading of graphical information on a computer screen and the distal perception of the structure of a scene. Such a system would have the immense advantage of authorizing a perceptual continuity in the daily life of a visually handicapped person, and would be all the more easily accepted.

### *3.3. The importance of the mode and protocols of learning*

Even if the observations reported by Paul Bach-y-Rita indicate that adaptation to the TVSS can be surprisingly rapid, it is important to remain realistically lucid and to recognize that even the most user-friendly device will inevitably require a substantial learning process. It is revealing that the Optacon device is delivered with an instruction manual which includes a set of progressive exercises which are essential for learning to use it effectively. This manual associates instructions in Braille and a corresponding "black" figure. The pedagogical quality of the instructions is clearly a key factor in successful appropriation, and is in itself a subject for further research. However, it seems to us that it is also important to take into account the conditions under which the learning is conducted. It is indeed possible that one of the reasons for the relative failure of sensory substitution systems to date lies in the nature of the relation which arises, in the laboratory, between the blind person and the experimentalist who "tests" the capacity of the subject to "see" the objects that are presented to him. When designing a learning protocol, it is important to bear in mind that a sensory device does not give rise to a sort of "degraded vision", but rather to an entirely new mode of perception which should be *shared* by the instructor and the pupil. Using the system should give rise to a *shared* experience, and it is only in this context that one can hope that learning will also produce the attribution of qualia to the percepts.

Finally, we also consider that it would be vain and pretentious to imagine that sighted persons could know, in advance, the best way of learning how to use a sensory device. Thus, the immersion of the system in an appropriate environment will not only make it easier to take into account the experience and the suggestions of the people for whom the system is designed, but may well lead to the emergence of modes of use and appropriation which were not foreseen by the designers.

### *3.4. The "intrinsic" effectiveness of sensory substitution*

When the conditions of appropriation are properly taken into account as just discussed, the intrinsic effectiveness of sensory sensation is, perhaps paradoxically, the point which leaves the least room for discussion. The basic possibility of "sensory substitution" seems to be a very general principle, having its source in the plasticity of the central nervous system and for that reason being relatively independent of sensory modalities involved. A question does arise as to the incapacity of the scientific community to mobilize for a project which is fascinating and useful (both from the point of view of fundamental research and technological innovation), but which does disturb conventional barriers between academic disciplines.

## 4. TOUCH AND SENSORY SUBSTITUTION

To start with, we will note some of the advantages of a tactile sensory input, rather than auditory input as in a number of existing devices (Sonic Guide, The Voice). The advantages of touch are of three types. Tactile stimulators can be easily dissimulated ; the person using the device is thus the only one with access to the stimulation. Secondly, if the tactile stimulations are situated on regions of the skin that are rarely used (the chest, the back of the hand...), they do not interfere with other sensory modalities that are inevitably strongly exploited by visually handicapped persons. Finally, stimulation of the cellular receptors which contribute to the sense of touch make it possible to transmit information *in parallel* to the central nervous system. This parallelism of the sense of touch has been the object of some discussion (see for example BACH Y RITA, 1972, page 15). However, a number of experiments (including those with the TVSS) have shown that this parallelism can be exploited, and that sensory substitution devices are able, via the sensory-motor coupling, to give rise to perceptive resolutions superior to those of the material resolution of the matrix of stimulators. This property, shared by "natural" perceptive systems, is called "hyperacuity". By comparison, in the case of an auditory stimulation, it is more complicated to use the parallel properties of the internal ear. The conversion of an image into an auditory event requires the invention of a coupling device capable of recoding into two sound waves (if stereophonic sound is used) the spatio-temporal properties of an image (MEIJER, 1992). On the other hand, it is theoretically possible to reproduce the topography of a visual image directly on the surface of the skin.

It must nevertheless be noted that, even if these three properties mean that tactile stimulation is probably the best solution for sensory substitution, certain technological obstacles remain to be overcome. Indeed, the two techniques of stimulation that have been used to date have certain defects that are almost prohibitive. Electromagnetic stimulatory systems are heavy and consume a large amount of energy. The electrotactile systems produce stimulations that are often felt as "disagreeable itching" on the skin, and furthermore require the use of a conducting gel. However, we may take the risk of sharing the optimism of Paul Bach-y-Rita; recent developments give reason to hope that these obstacles will soon be overcome. Bach-y-Rita et al (1998) are currently experimenting with a system of stimulation in the mouth, which make it possible in particular to dispense with a conducting gel. In addition, there are new alternative technologies with great promise, involving piezoelectric transductors (CHANTER & SUMMERS, 1998) or alloys with shape-memory (GRANT & HAYWARD, 1997). It must be emphasized, however, that the development and optimisation of effective stimulators with low energy requirements will only be possible if the physiological characteristics of the sensory receptors involved in touch are taken into account. Thus the electromagnetic systems, usually tuned to a frequency of about 250 to 300 Hz, mainly stimulate in a diffuse fashion sensory receptors with wide receptor fields on the skin. There would be a great advantage in exploiting the great variety in the sensitivity of the different cell-types involved in touch, in order to enrich the transductive capacities of these tactile interfaces (see SHINODA et al., 1998).

## 5. CONCLUSION

As long as one holds fast to a classical conception of perception in terms of the acquisition of information, one will be stuck with the principle that it is always better to have access to more information. In this framework, persons with sensory handicaps will inevitably be considered as defective. We have proposed an alternative conception, in which "sensory substitution systems" are rather thought of as *supplementation* devices which bring about new modes of coupling with the environment. They do not make a difference disappear; rather, they create new differences - and they have applications which are not exclusively reserved for handicapped persons (for example, artistic applications, games, augmented reality, the development of portable and intuitive systems for the detection of heat, radioactivity....). In spite of appearances, it is the classical perception which carries the germ of exclusion since it considers that the problem of handicapped persons lies in a quantitative difference. By contrast, true respect for the world of handicapped persons lies with better knowledge and understanding of the qualitative difference of possible perceptual modes.

**REFERENCES**


Ali Ammar, A., Gapenne, O., Lenay, C. & John Stewart (2002). Effect of bimodality on the perception of 2D forms by means of a specific assistive technology for blind persons. In *Proceedings of the Conference (CVHI'2002) on Assistive Technology for Vision and Hearing Impairement* (pp 45-52). Grenade, Espagne.

Bach y Rita, P. (1972). Brain mechanisms in sensory substitution. New York : Academic Press.

Bach y Rita, P. (1987). Brain plasticity as a basis of sensory substitution. *Journal of Neurological Rehabilitation*, *2*, 67-71.

Bach y Rita, P. (1997). Substitution sensorielle et qualia. In J. Proust (Ed.), *Perception et intermodalité. Approches actuelles de la questions de Molyneux* (pp. 81-100). Paris : PUF.

Bach y Rita, P., Kaczmarek, K.A., Tyler, M.E. & Garcia-Lara, J. (1998). Form perception with a 49-point electrotactile stimulus array on the tongue: A technical note. *Journal of Rehabilitation Research and Development*, 35, 427-430.

Barfield, W. & Furness, T.A. (1995). *Virtual environments and advanced interface design*. Oxford : Oxford University Press.

Berthoz, A. (1991). Reference frames for the perception and control of movement. In J. Paillard (Ed.), *Brain and space* (pp.81-111). Oxford : Oxford University Press.

Brindley, G.S. (1973). Sensory effects of electrical stimulation of the visual and paravisual cortex. *The Journal of Physiology*, 196, 479-493.

Chanter, C. & Summers, I. (1998). The Exeter fingertip stimulator array for virtual touch : a preliminary investigation (http://newton.ex.ac.uk/medphys/index.html)

Collins, C.C. & Bach y Rita, P. (1973). Transmission of pictorial information through the skin. *Advances in Biological Medecine and physiology*, *14*, 285-315.

Dobelle, W.H. & Mladejovsky, M.G. (1974). Artificial vision for the blind : electrical stimulation of visual cortex offers hope for a functional prosthesis. *Science*, 183, 440-444.

Dobelle, W.H., Mladejovsky M.G., Evans, J.R., Roberts, T.S. & Girvin, J.P. (1976). « Braille » reading by a blind volunteer by visual cortex stimulation. *Nature*, 259, 111-112.

Epstein, W., Hughes, B., Schneider, S. & Bach y Rita, P. (1986). Is there anything out there? : a study of distal attribution in response to vibrotactile stimulation. ¨*Perception*, *15*, 275-284.

Gibson, J.J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.

Grant, D., Hayward, V. (1997). Variable Structure Control of Shape Memory Alloy Actuators. *IEEE Systems and Control Magazine* 17(3), 80--88.

Gregory, R.L (1990). Recovery from blindness. In *Eye and brain : the psychology of seeing* (pp. 191-200). Oxford University Press.

Hanneton S., Lenay C., Gapenne O., Vermandel S., et Marque C., (1998). Dynamique de la reconnaissance de caractères via une interface haptique. In D. Kayser, A. Nguyen-Xuan & A. Holley (Eds.), *Proceedings of the VIIe Colloque de L'Association pour la Recherche Cognitive ARC'98* (pp. 343-347).

Hatwell, Y. (1986). *Toucher l'espace*. Lille : Presses Universitaire de Lille.

Kaczmarek, K.A. & Bach y Rita, P. (1995). Tactile displays. In W. Barfield & T.A. Furness, (Eds.), *Virtual environments and advanced interface design* (pp. 349-414). Oxford : Oxford University Press.

Lenay, C., Canu, S. & Villon, P. (1997). Technology and Perception : the Contribution of Sensory Substitution Systems. In *Proceedings of the Second International Conference on Cognitive Technology, Aizu, Japan* ( pp. 44-53). Los Alamitos: IEEE.

Lepecq, J.C., Jouen, F. & Gapenne, O. (1995). Sensorimotor organization and cognition in infancy: some francophone contributions. *Cahiers de Psychologie Cognitive*, 14, 121-150.

Luciani, A. (1996). Ordinateur, geste réel et matière simulée. In M. Borillo & A. Sauvageot (Eds.), *Les cinq sens de la création* (pp. 79-89). Seyssel : Editions Champ Vallon.

Meijer P.L.B. (1992). An Experimental System for Auditory Image Representations. *IEEE Transactions on Biomedical Engineering*, 39 (2), 112-121.

O.F.T.A. (1996). *Nouvelles interfaces homme-machine*. Série Arago, Vol.18. Paris : OFTA Editeur.

Paillard, J. (1971). Les déterminants moteurs de l'organisation de l'espace. *Cahiers de Psychologie*, *14*, 261-316.

Sampaio, E. (1994). Les substitutions sensorielles adaptées aux déficits visuels importants. In A.B. Safran & A. Assimacopoulos (Eds), Le déficit visuel. Des fondements neurophysiologiques à la pratique de la réadaptation (pp. ). Paris : Masson.

Schmidt, E.M., Bak, M.J., Hambrecht, F.T., Kufka, C.V., O'Rourke, D.K. & Vallabhanath,P. (1996). Feasibility of a visual prosthesis for the blind based on intracortical microstimulation of the visual cortex. *Brain* 119, 507-522.

Shinoda, H., Asamura N., and Tomori, N. (1998). Tactile Feeling Display Based on Selective Stimulation to Skin Mechanoreceptors. *Proc. 1998 IEEE Int. Conf. Robotics and Automation*, Vol.1, pp. 680-686.

Spillman, L. & Wooten, B.R. (1984). *Sensory experience, adaptation and perception*. Londres : Lawrence Erlbaum.

Sribunruangrit, N., Marque, C., Lenay, C., Gapenne, O., and Vanhoutte, C. (2002). Braille Box: Analysis of the parallelism concept to access graphic information for blind people. In *Proceedings of the Second Joint Meeting of the IEEE Engineering in Medicine and Biology Society and the Biomedical Engineering Society (EMBS-BMES 2002)* (pp.2424-2425). Houston, USA.

Warren, D.H. & Strelow, E. R. (1985). *Electronic spatial sensing for the blind*. Dochdrecht : Martinus Nijhoff Publishers.

White, B.W., Saunders, F.A., Scadden, L., Bach y Rita, P. & Collins, C.C. (1970). Seeing with the skin, *Perception and Psychophysics*, *7*, 23-27.

Wyatt, J.L. & Rizzo, J.F (1996). Ocular implant for the blind. *IEEE Spectrum*, 33, 47-53.

**KEY WORDS**

Sensory substitution, sensori-motor coupling, active perception, handicap, tactile stimulation, brain plasticity