Technologies to Access Space Without Vision. Some Empirical Facts and Guiding Theoretical Principles

Charles Lenay and Gunnar Declerck

A large number of technical devices attempt to help blind persons improve their spatial perception and facilitate their mobility. We wish to present here the principles on which these prosthetic perceptual devices function, the conditions of their appropriation, and the general perspectives they open concerning the role of technical objects and systems in the constitution of human experience. A technical device for assisting perception has to compensate for a sensory deficit by mobilizing other subsisting sensory modalities which remain available. We therefore have to understand the relationship between perceptual activity and sensory input. In addition, we shall see that the technical devices which assist perceptual activity can in return serves as tools for experimental scientific research on the mechanisms of perception in general.

The analyses presented in the preceding chapter seem to show that perceptual experience of the space which surrounds us is the experience of the availability of a system of actions, in other words an organized set of possible journeys and operations that can be performed in the world. Whatever the sensory modalities that a subject has at her disposition (be they visual, auditory or tactile), we can suppose that her perception of a space which surrounds her corresponds for her to the presence of a field of possibilities of this sort, which enables her to localize objects, to choose gestures and movements, to decide which actions to perform, etc. The tools and prosthetic devices she can use aim at modifying and enriching this field of possibilities, which will give access to new actions and perceptions. Our aim in this chapter is to propose several hypotheses to explain the mechanisms by which

C. Lenay (✉) · G. Declerck
Sorbonne Universités, Université de Technologie de Compiègne,
EA 2223 Costech (Connaissance, Organisation et Systèmes Techniques),
Centre Pierre Guillaumat - CS 60 319-60 203, Compiègne, France
e-mail: charles.lenay@utc.fr

G. Declerck
e-mail: gunnar.declerck@utc.fr

E. Pissaloux and R. Velázquez (eds.), *Mobility of Visually Impaired People*,
DOI 10.1007/978-3-319-54446-5_2

perception can be transformed according to the tools and prosthetic devices employed, and to show that in each case this transformation amounts, finally, to a reconfiguration of a field of possibilities. To do this, we shall start from the extreme situation of the so-called 'sensory substitution' systems; we will then decline several variations so as to better understand in each case the way in which the technical mediation transforms the relations between sensation and perception, and thereby modifies the field of accessible possibilities.

1 Sensory Substitution

The so-called 'sensory substitution' devices correspond to the ambition, which may seem naïve, to replace a deficient sensory input by another modality which is still functional. A more detailed presentation of these devices in all their diversity will be given later (Chapter "Scene Representation for Mobility of theVisually Impaired"). Here, we will focus on the most emblematic and most radical device of perceptual aid to compensate for the absence of vision: the Tactile Vision Substitution System (TVSS) proposed by Paul Bach y Rita at the end of the 1960's [4, 5]. The TVSS consists of a square matrix of 400 tactile stimulators connected to a digital camera. The image captured by the camera is simplified and converted into black and white pixels (without intermediate grey levels), and then used to control the activation of a 'tactile image' of 20 $\times$ 20 pixels, i.e. 400 tactile stimulators which are raised or not according to whether the corresponding element of the image is black or white. This tactile matrix is applied to the skin, either on the back (the first version), or on the chest or the forehead [13], and more recently on the tongue [7, 9] (Fig. 1).The first trials with this sort of device provided three fundamental results.

(i) First of all, the presentation of shapes to an immobile camera procured only a very limited discrimination of the tactile stimuli, which were perceived as being on the surface of the skin. Thus, the simple substitution of a sensory input through the optic nerve by a tactile entry does not, in itself, give access to a spatial perception.

(ii) However, if the user was active (moving the camera by translations and rotations, and zooming), he developed spectacular capacities for recognizing shapes. After 15 h of practice, he discriminated increasingly complex familiar objects, to the point of being able to recognize faces.

(iii) Moreover, this capacity to recognize shapes was accompanied by an *external projection* of the percepts. The user no longer felt tactile stimuli on the skin, and instead perceived stable objects 'out there' in front of him in a three-dimensional space [5]. The perception of a stable object 'out there' is quite distinct from the succession of variable sensory stimuli that the subject receives as he constantly moves the camera. The blind person begins by learning how variations in his sensations are related to his actions: when he

Fig. 1 The tactile vision substitution System. Here the matrix of 20 × 20 tactile stimulators is placed on the chest and the camera is placed on the frame of a pair of spectacles

> moves the camera from left to right, the stimuli on his skin move from right to left; when he zooms forward, the stimuli move apart, etc. He also discovers perceptual concepts that are new to him such as parallax, shadows, occlusion, etc. Certain classical visual illusions are spontaneously reproduced [6, 24]. This sort of experiment can be performed not only by a blind person but just as well by a sighted person who is blindfolded.

Through these initial results, we see that a whole set of very fundamental questions are posed concerning perceptual learning, the localization of objects in a distal space and the recognition of shapes. It therefore seems to us that study of this very particular extreme situation of sensory substitution could be useful for shedding light on the general problems involved in the appropriation of perceptual aid systems. Indeed, this sort of device makes it possible to follow the genesis of a novel prosthetic perceptual modality; and in particular, to follow the constitution of a *space of perception* in which objects can be perceived as being external [1, 38]. One can then carry out in parallel an objective analysis in a third-person perspective of the resolution of perceptual tasks, coupled with the description in a first-person perspective of the corresponding lived experience.

We will first of all examine the question of spatial localization and the perception of the three-dimensional space which surrounds us; we will then study the perception of shapes and arrangements in the two-dimensional space of writing and reading; before concluding in a more general way on technical mediation of perception.

2 Spatial Localization

2.1 The General Problem

In the course of learning, the TVSS user first of all feels the successive stimulations on her skin. However with the progressive use of the device, she ends up forgetting these tactile sensory inputs and comes to perceive stable objects at a distance, out there in front of her. The very first device transmitted the tactile stimuli to a matrix placed on the back. Bach y Rita thereupon remarked: ‘When asked to identify static forms with the camera fixed, subjects have a very difficult time; but when they are free to turn the camera to explore the figures, the discrimination is quickly established. With fixed camera, subjects report experiences in terms of feelings on their backs, but when they move the camera over the displays, they give reports in terms of externally localized objects in front of them.’ [49: 25] Thus, according to the witness accounts of the users, the proximal irritations provoked by the tactile plate are quite different from perception as such [5, 42, 48]. The device and the tactile sensations it procures are no longer perceived as such, when the device procures a perception of objects in a distal space.

What we want to understand, then, is this appropriation which occurs by a sort of ‘switch’ in perceptual experience, which started out as a series of proximal events, i.e. the tactile stimulations, and which at some point becomes centred on objects which are separate from the body and which are situated in a distal space. One of the keys to this transition seems to be the activity of the perceiving subject, the movements of the receptor system (the camera). But what exactly is the role of these movements? *How* does this activity participate in the emergence of a distal perception?

Two main approaches are possible.

(i) First there is a representationalist approach, according to which one considers that the actions of moving the captor have the sole function of acquiring relevant information (in this case, mainly information about the relative positions of the body and external objects) in order to construct an internal representation [10]. According to this view, the actions are not properly constitutive of the perception (if equivalent information could be obtained *by means other than action*, there could quite well be perception without action).

(ii) Alternatively there is an enactivist approach, where one considers that the actions are indeed constitutive and therefore absolutely necessary in the very course of the perception of the distance of the objects. On this view, the perceptual experience results directly from the sensory-motor dynamics, without any need for recourse to the intermediary step of representations.

For the first, representationalist approach, the sequences of activation of the matrix of tactile stimulations makes it possible to progressively infer the distal spatial coordinates of the perceived objects. The question of the proximal-distal switch is then understood as a problem of 'distal attribution' [15, 33], namely 'the ability to attribute the cause of our proximal sensory stimulation to an exterior and distinct object' [1: 506]. Distal attribution would be a solution to a *causal inference* problem, because the most likely environmental cause of incoming vibro-tactile or electro-tactile stimulation—contrary to the default haptic interpretation—is a distant scene. This position belongs to what is traditionally called the 'representationalist-inferentialist' approach to perception: perceiving is equivalent to constructing (or inferring), on the basis of the available sensory data, a representation of the objects which are supposedly the cause of these sensations [16, 21, 22]. 'Perception' is a process of elaborating hypotheses; its functioning is basically heuristic and probabilistic.[1] We may note in passing that this conception is not incompatible with certain sensori-motor approaches to perception (see for example [40]).

However, this way of considering the phenomenon of the proximal-distal switch is debatable, in the sense that the problem here is not to *attribute* the incoming tactile data to external causes. Right from the start, there is a form of distal attribution, since the novice user of the TVSS is quite conscious that the pressure on her skin is produced by something external to her body, i.e. the matrix of tactile stimulators. The tactile sensations are not brute data which have not yet achieved a 'representational' function (or a 'figurative' function as Husserl would say). Via the 'tactile data' it is already an objective environment which is perceived by the user: a set of pressures exerted on her skin. The point is rather than these pressures cannot yet be deciphered in terms of objects located in the environmental space (for example 'a chair over there') or a spatial configuration of rooms (for example 'a corridor', 'a door', 'a wall'). It is like when one looks at a figurative picture without yet having succeeded in seeing what it represents, and one only perceives in the beginning a system of shapes without any 'meaning'. Auvray and Myin [3] quite rightly compare sensory substitution to reading: before they have appropriated the device, sensory data are like the words of a language that one does not speak.[2]

---

[1] "The content of the perceptual state formed in response to a particular pattern of stimulation—the brain's operative 'hypothesis' about the structure of the impinging environment—is the cause to which the highest probability is assigned given all the available endogenous and exogenous evidence. In the case of vision, this will normally be one of indefinitely many possible three-dimensional scenes." (Briscoe, *forthcoming*: [10:6]).

[2] But, as Heidegger insists: "It requires a very artificial and complicated frame of mind to 'hear' a 'pure noise. […] In the explicit hearing of the discourse of the other, too, we initially understand what is said […]. Even when speaking is unclear or the language is foreign, we initially hear *unintelligible* words, and not a multiplicity of tone data." (Heidegger 1927, §.34, p. 153 [p. 164]).

For the second sort of approach, that may be termed enactivist, the activity is an indispensable component, not only for learning the prosthetic device, but also for achieving the perceptual experience as such. Spatial perception is constituted as much by the actions performed as by the variations in sensory input that they occasion. From this point of view, the phenomenon of the perceptual switch is not a problem of 'distal attribution', but corresponds to an alteration in the sensori-motor dynamics, the passage from a dynamics of the constitution of a perception of contact to a specific dynamics of the constitution of objects at a distance in space.

In order to discuss the relevance of these two approaches, and thus to clarify the status of action and the way in which the use of a tool can lead to the perception of objects in a distal space, we have employed a minimalist method.

2.2 A Minimalist Method

Our minimalist method consists of using the simplest possible perceptual device, in which the repertoires of action and the sensory feedbacks are drastically reduced to a bare minimum. The first point was to verify that the phenomenon of distal perception still occurs in these impoverished circumstances. This makes it possible to control quite precisely what are the objects that can be constituted in each case, and what are the operations that are necessary for this constitution. We have thus reduced the system of Bach y Rita to a single photo-electric cell connected to a single all-or-nothing tactile stimulator. When the total luminosity in the incident light field (a cone of about 20°) is greater than a certain threshold, the tactile stimulus is triggered (Fig. 2).

At each moment in time, the subject (who is blind or blindfolded) thus receives only minimal information, 1 bit corresponding to the presence or absence of the tactile stimulus. We have been able to show that even with such a simple device, the spatial location of luminous targets was still possible [28]. Initially, the subject only perceives a succession of tactile stimuli which accompany her movements. But quite soon, as she becomes familiar with the device and starts to master it, she no longer notices these sensations which are replaced by the perception of a target at a certain distance in front of her. Here, it is quite clear that perception cannot be

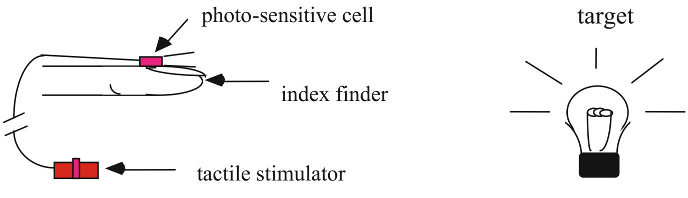


Fig. 2 The minimalist experimental device for spatial localization. The photo-sensitive cell is fixed on the index finger. When the amount of light received is above a certain threshold, the cell activates a tactile stimulator (that can be held in the other free hand)

grounded merely on an internal analysis of the input data (namely, the tactile input); the latter is simply a temporal sequence of all-or-nothing 1's and 0's which has nothing intrinsically spatial about it (contrary to the two-dimensional organization of the stimulators in the TVSS matrix).

It is quite understandable that it is possible to locate the target, even if the movements of the subject are simplified, and reduced to movements of the arm around the shoulder articulation, and movements of the hand around the wrist articulation. In Fig. 3, we consider only movements in a horizontal plane (three-dimensional space can be recovered by integrating up-and-down movements in the vertical plane). The situation is represented in (x, y) coordinates, with the subject place at the origin (0,0). The target is a point source, S, situated at a distance L from the subject with coordinates (0, L). The point P designates the wrist of the subject; its coordinates are (b.cosα, b.sinα), where b is the length of the arm, and the angle α = (Ox, OP) indicates the orientation of the arm. The angle at the wrist, between the arm and the hand, is designated by β = (PO, PS).

We may suppose that the subject is oriented with her chest facing the target, and finding a tactile stimulation with the arm point straight forwards and the finger aligned with the arm ($\alpha = 90°$, $\beta = 180°$). From a strictly mathematical point of view, a single pair of additional values (α, β) is then sufficient to determine the distance L. As shown in Fig. 3, L is given by a simple trigonometrical formula, if we consider that b, the length of the arm, is known.

In order to account for the perception of the position of the target, it therefore seems plausible to suppose that the subject relies essentially on the proprioceptive data concerning the positions of her limbs to construct an internal representation of the relation between the position of the captor at the end of her finger and the position of the target (an operation of triangulation [12]). The actions would serve only to establish this relation by allowing for an exploration of the scene (movements which in addition facilitate a more precise proprioception). In this case, the

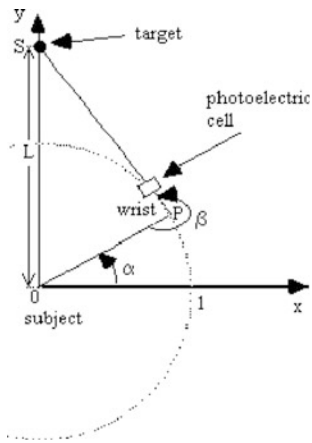


Fig. 3 The arm (forearm included) has a length b. The distance to the target L (0S) is given by the trigonometric formula: $L = b(\sin\alpha - \cos\alpha \tan(\alpha + \beta))$ (Eq. 1)

calculation of the position of the target would only require pointing at it a few times, several pairs (α, β) to inscribe the object in a space of internal representation.

However, observation shows that in order to maintain the perception of a target placed in front of her, *the subject must act continually*, moving the photo-electric cell so as to aim at the target in different ways. This can easily be understood if we look at things from the phenomenological point of view of the subject. As soon as the movements stop, the perception disappears. If she is immobile, there are only two possibilities: either she receives a continuous stimulus, or she does not. If she is pointing away from the target, she has only the memory of a perception which fades away. If she is pointing at the target, she receives a continuous sensory stimulation—but this does not give rise to the perception of an external object. On the contrary, consciousness is now filled by the presence of the tactile sensation as such.

If we wish to explain the necessity for this incessant activity in a representationalist approach, one might try to explain it by the need to constantly reactivate the sensitivity of the sensory cells which otherwise (by virtue of rapid adaptation) might cease to send signals to the central nervous system. However, the phenomenological description shows that if perception ceases when the concrete activity of moving the hand stops, it is not because the sensory data evaporate, but on the contrary because the tactile stimulation *as such* becomes only too present, thrusting the perception back on the place where it is directly felt. Here, there is not distal perception without action because spatial perception requires a constant *synthesis* of a temporal succession of actions and sensations.

If one admits this essential role played by action in the emergence of perception, then it must be admitted that what is perceived, recognized, is not really the invariants extracted from the sensations, by rather the invariants of sensori-motor loops related to the activity of the subject. This involves abandoning the passive conception of perception for which the system would receive as input certain information and then carry out a calculation to identify the objects and events before going on the produce representations in an internal space. On the contrary, perception is accomplished by mastery of sensori-motor regularities. The theoretical framework of active perception has been variously developed in the ecological approach to perception [19, 20, 46], and in sensori-motor or enactive approaches [11, 36, 37, 39, 41, 47]. By her action the subject seeks and masters the constant rules which relate action and sensation. The perception of an object consists in the discovery of regularities in the relation between variations of action (mobility of the organ of perception) and variations in sensations (produced by these actions), it is what Kevin O'Regan calls a 'law of sensori-motor contingency' [37]. The richness of perception should thus depend at least as much on the capacities for action (mobility, rapidity, zoom, etc.) as on the variety of sensory inputs (width of the spectrum, number of sensors, etc.).

As we have seen, in our minimalist experiment at least, there is no perception without action. One observes that the subjects perform regular oscillations around the target: generally small oscillations of the hand (β), accompanied by larger movements of the arm (α) which cause progressive changes in the position of the wrist. It is as though the subjects seek to identify and verify the functional relationship between α and β which must be respected in order to obtain a sensory feedback. There is perception of the position of the target when the subject masters the sensori-motor rule allowing him to aim at the target from different positions of the captor in space. The spatial exteriority of the target is constituted by the possibility of freely and reversibly coming and going around it, alternately leaving and refinding contact with it. The target is localized in direction and depth when the rule governing pointing towards it is mastered. This is a good illustration of a 'law of sensori-motor contingency' [37]. Any given position of the target corresponds to a particular *sensori-motor invariant*, i.e. a *rule* relating sensory feedback to the actions performed; this rule itself is stable over and above the constantly varying actions and sensations. The whole interest of the minimalist approach is then to permit a precise characterization of this rule (on condition of simplifying the space of action to reduce it to two rotations, here the rotation of the arm around the shoulder and the hand around the wrist) (Fig. 4).

With this in place, the different conceptions of prosthetic perception (and indeed of perception in general) will depend on the way that these rules (the laws of sensori-motor contingency) are envisaged:

- either they are internal (inscribed in the central nervous system) and abstract (represented in symbolic fashion)—this is the representationalist view;
- or else they are external (determined by the objective structure of the layout) and embodied (directly related to proprioceptive information)—this is the enactivist view.

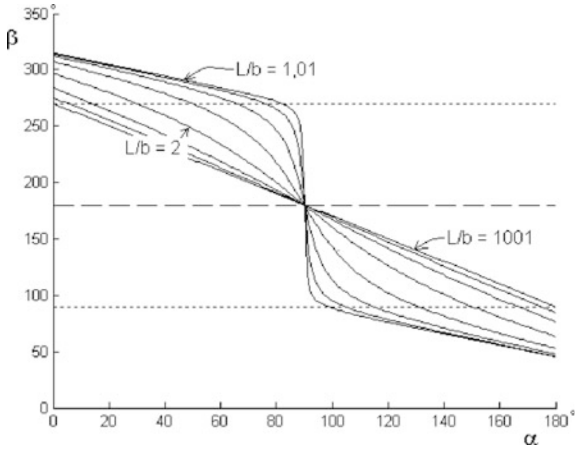
This question is particularly important for understanding the processes of the appropriation of devices for perceptual assistance.

3 Sensori-Motor Rules

In the first sort of approach, which is internalist, one might think that these rules correspond to an internal know-how, inscribed in the nervous system, constructed by association between the input sensations and information about the actions performed (this latter information could be based on proprioceptive signals and/or efferent copies of motor commands). However, a repetition of our experiments by Siegle and Warren [43] spreads fresh light on this question.

On the occasion of the same task of spatial localization, they separated the blindfolded subjects into two groups. In the first group, labelled 'Proximal attention', participants were explicitly instructed to attend to the location of the arm when the vibrating motor was active, and to consciously triangulate the location of the target by imagining their finger extending out into space. By contrast, in the second group labelled 'Distal attention', participants were explicitly told to not attend to their arms during the experiment, but to get an intuitive sense of the target's location and report how far away it felt. It was then observed that the instructions to attend to distal

Fig. 4 *Curves* representing the relation between the angle of the hand with respect to the wrist (β), and the angle of the arm with respect to the shoulder (α), when the target is at different distances from the subject. These distance (L) are expressed in units of the length of the arm (b)



properties during learning resulted in improved performance and more precise judgments of target distance, whereas participants instructed to attend to proximal variables showed no improvement. In addition, Siegle and Warren [43] observed that the improved distance judgments were significantly correlated with increased perception of a solid object; that is, the less participants were paying attention to their arms, the lower the error in distance judgments, the more they felt a concrete solid object was really present before them in space. This supports the claim 'that improved distance judgments reflect a distal perceptual awareness rather than an explicit cognitive strategy' [43: 220]. Moreover this improvement is conserved even if one turns the seat on which the subject is placed through 90°, or one switches the photodiode from the dominant to the nondominant hand. Even if the actions to be performed, and thus the proprioceptive data are quite different, the subjects still appeared able to mobilize the results of their learning to localize the target. This is reminiscent of an observation already made by Paul Bach y Rita: subjects who were well trained with the TVSS held in the hand and a matrix of tactile stimulators placed on the back were quite able, without any additional training, to use miniature camera place on a pair of spectacles and a matrix of tactile stimulators placed on their chest [8].

These results militate both against an internalist representationalist account which supposes that distal spatial perceptions are deduced from proprioceptive data, and against an associative internalist account consisting of directly extracting regularities from the correlations between sensations and the movements performed. As Siegle and Warren [43] rightly note: 'transfer to the opposite arm changed not only the joint angles but the joints and muscles involved […]. These data clearly indicate that the emergence of distal awareness [cannot] depend on a particular set of arm configurations at a muscle- and joint-specific level' and so 'undermine a muscle- or joint-specific version of the sensori-motor hypothesis, and indeed any other hypothesis defined at the level of limb configurations'. Apparently, the only possible way to account for this data in the frame of the sensori-motor account is to postulate 'a higher level sensori-motor contingency that is not joint-specific'.

In view of this, the question rebounds. What is the general structure of spatial perception that makes it possible to deduce in each situation the sensori-motor rule that applies? In the externalist perspective adopted by Siegle and Warren, which is close to the ecological theory of perception, it is posited that the gestures of pointing are determined in an allocentric reference frame, let us say the structure of the physical space of the layout. However, it is necessary to account for the transformations of lived experience that occur during the appropriation of technical devices for assisted perception. The sensori-motor rules depend as much on our possibilities for acting and feeling as on the concrete situation in which one is engaged [29]. It would rather seem, then, that perceptual learning leads to the discovery of the general organisation of the coupling between the subject and her environment, an organisation which makes it possible in each instance to master the rules of pointing towards objects.[3]

It therefore seems appropriate to adopt an externalist approach that we may call 'enactive' in the sense that spatial perception is constituted in the sensori-motor relationship itself: it neither precedes nor follows this relation [31]. In order for the perceptual experience at time t to have a spatial content (i.e. for it to present objects located in an external space), the subject must indeed be actively engaged in this relation. The laws of sensori-motor contingency (relating the movement of the captor to the sensory input) are thus defined by the action capacities of the organism and the way in which these actions, depending on the structure of the environment, determine the sensory input. The lived body, transformed by the technical device which is associated with it, brings forth a specific domain of coupling with the environment. The laws of sensori-motor contingency are defined by the coupling device, the position of the target in the environment, and the action strategies of the subject. In order to give rise to a perception, a prosthetic device must be an instrument of coupling which modifies the lived body by defining new repertoires of action and sensation. The interest of this approach is that the organism itself does not need to have any explicit knowledge of the coupling device with which it is associated (the position and mode of action of the captors and sensory stimulators). It is sufficient for the subject to engage in a relation with the world, to progressively acquire a perceptual mastery [37]. This conception of active perception can be schematically illustrated as follows: (Fig. 5).

On this view, perception is not an internal representation, but the result of dynamic coupling between the organism and its environment. This is why we situate perception at the heart of the coupling, and not unilaterally within the

[3]Incidentally, the concept of "pointing" used by Siegle and Warren actually presupposes already a spatial framework (if the subject thinks of her action in terms of the gesture of pointing in this or that direction, this means that she already has the experience of a space). This being so, the process whereby this framework is set up is precisely what we are trying to understand here: what is the process of setting up this framework which subsequently makes it possible to interpret gestures as gestures of pointing?

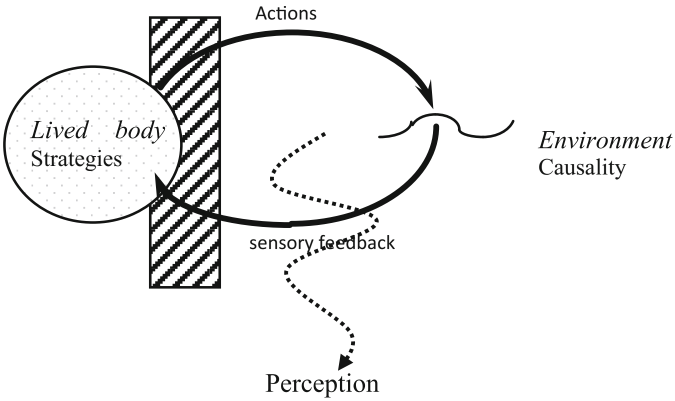


Fig. 5 Scheme of sensori-motor coupling. The system of prosthetic perception is a 'coupling device' which modifies the lived body by defining the repertoires of actions and sensations which are available to the subject. Via the environment, the actions '*a*' give rise to sensory feedback '*s*': $s = g(a)$; concomitantly, the organism implements a strategy for generating its actions and modulating them as a function of its sensory feedback: $a = f(s)$

organism. It is easy to understand that in this conception of perception, there is an important distinction to be made between 'sensory input' and 'perception'. The 'sensory input' delivered to the organism is quite different from the full 'perception', which is based on the law defining the sensory feedback for a full range of performed actions.

4 The Space of Possibilities

If we come back to the general conception of space itself as a system of positions and possible movements, we see that the use of the device has transformed this system of possibilities. Of course blindfolded subjects, like persons who are blind from birth or through injury, do already have knowledge of the space which surrounds them and the actions which they can perform, even if it is only through the world of sound or the space of bodily action with tactile and kinaesthetic feedback. Nevertheless, with the radically novel mediation provided by the technical device a new space of possibilities is opened up, with a new form of perceptual presence of objects, this time in exteriority at a distance in a distal space.[4]

The preceding analysis now makes it possible to specify the way in which the space of possibilities is reconfigured on the occasion of this proximal-distal switch.

[4]Epstein et al. (1986) have studied, in very controlled conditions, the question of the awareness of the existence of an external space through the use of a sensory substitution device—a question we considered again in Auvray et al. [1].

In the beginning, for the subject, blind or blindfolded, the field of possible perception (i.e. everything that the subject can apprehend by anticipation—eventually implicitly—as possibly being perceived by him) corresponds to the set of possible movements of the captor (here placed at the end of the finger) which explores the environment. In certain positions, the subject receives a tactile feedback that he can try to find again (this is not very difficult because the environment is immobile). But once the device is mastered, this field of possibilities is transformed and becomes the space of possible distal positions of the object. As for visual perception, the point of view, the position from which the object is perceived, is then spatially distinct from the distal position of the object.

The result of the instruction of distal attention in the experiment of Siegle and Warren seems to show that distal perception only occurs if the particular local actions are forgotten, relegated to oblivion, in favour of mastering the law of pointing towards the object. When attention is focused on the perception of an object, the stimulations delivered by the coupling device (be it natural or artificial) disappear from consciousness. Similarly, in natural vision, when we perceive a stable object at a certain distance in front of us, using our eyes and their movements, we have absolutely no consciousness either of the saccadic movements of our eyes, or of the variable sensory stimulations at the level of the retina [14]. What we are perceptually aware of is where the object is relative to us and where we are, as a point of view, relative to the object. Similarly here, there is only distal perception when one perceives the position of the object without paying attention either to the tactile stimulations, or to the variations in viewpoint which make it possible to determine this position.

In the case of proximal perception (we are considering here the case of tactile stimulation), there is spatial coincidence between the position of the perceived stimulation and the bodily position where the stimulation is received: for an ‘object’ occupying a given position, there is only one possible position of the captor, i.e. the position where the ‘contact’ occurs. By contrast, in the case of distal perception (in natural conditions of a visual or auditory type) there are an infinite number of possible positions of the captor for each position of the object (an object occupying a certain spatial position can be perceived from an infinite number of positions and orientations of the captor).

The nature of the switch from proximal to distal can thus be understood as a transformation of the sort of rule which relates the action to the sensory feedback. Whereas for proximal perception, the rule is that of identity between the position of the captor and that of the object, for distal perception this rule associates an infinite number of positions of the captor to each position of the object.[5] The duality between the particular fact and the general rule corresponds to the duality between

[5]The notion of “distal” implies at the same time the idea of “aspect” and of “perspective” on the object: the distal perception of an object, precisely because of the possibility of having access to the latter from an infinity of possible positions, is the perception of the object “under a given aspect”: the aspect that the object presents as “seen from here”.

the position of the point of view and the position of the object. This duality is constitutive of distality.

The space of possible positions in play in distal perception is thus radically different from the corresponding space in the case of proximal perception. In the space of proximal perception, the relative positions of the perceived object and of the captor are of the same nature, and can be defined in the bodily framework of the perceiving subject. By contrast, in distal perception the relative positions of the perceived object and the captor are specified by *rules* of pointing (rules which indicate, for a given position of the captor, in which direction the latter should be oriented in order to establish a ‘distal contact’ with the object), and are thus of a different nature than the particular bodily positions which can satisfy these rules. They take the status of possible ‘points of view’, i.e. the site from which the object is perceived. Each position of the object in the distal space is specified by the rule which specifies the set of all possible viewpoints on the object. But at the same time, each of the positions of the viewpoint, rather than being defined within the bodily system, corresponds itself to a position in this distal space, and in principle could thus be specified by the rule giving the set of all possible viewpoints on it. The space of distal perception thus becomes a space of possible viewpoints.

5 Shape Recognition

Beyond simple spatial localization, we have seen that a device such as the TVSS can also give rise to the recognition of shapes of varying degrees of complexity. Here again, it is possible to adopt a minimalist approach in order to analyze with precision the mechanisms which make this sort of performance possible. We have developed another system with the aim of providing blind persons with access to digital forms present on a computer screen. The ‘Tactos’ system [26] consists essentially of a device for controlling tactile stimulators (Braille cells which electronically generate the movements of small pegs) as a function of the movements of a cursor on a computer screen (Fig. 6).

Typically, the cursor is a 4×4 matrix of 16 receptor fields (two pixels wide), corresponding to a surface of 64 pixels on the screen. When one of the receptor fields encounters at least one black pixel, this triggers the all-or-none activation of the corresponding peg on the Braille cell. The subject is blindfolded, and moves the cursor by means of an effector (mouse, stylus on a graphic tablet, touchpad….). The tactile stimulation is delivered to the *other*, free hand—but, as we will see, this does not hamper the perception of the forms. This device of perceptual supplementation thus allows for the exploration of a virtual tactile image.

For practical applications, it is possible to increase further the number of receptor fields and the corresponding tactile stimulators; but from the point of view of fundamental research it is actually more interesting to *reduce* the sensory information to the limiting case of a single stimulator corresponding to a single receptor field [50]. Even in this minimal version, we observe that subjects are able to

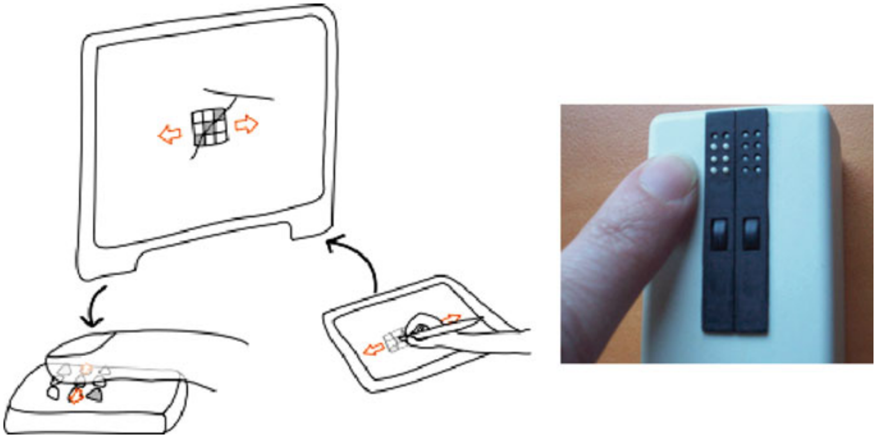


Fig. 6 **Tactos Device**. The pen on the tablet controls the movements of the cursor on the screen. The cursor corresponds here to a 3 × 3 matrix of receptor fields. When a receptor field covers a *black pixel* on the screen, the corresponding peg of an electronic Braille cell is activated. The picture on the right shows the two piezo-electric Braille cells combined to form a 4 × 4 matrix of 16 pegs

perceive forms [26]. These forms are not given to the sensory system as a complete two-dimensional pattern applied to the skin at each instant of time. When there is only a single receptor field, and thus a single sensation at each instant, there is again no intrinsic spatiality at the level of the input signal. If the subjects succeed in recognizing shapes in space—and they do—this can only be by virtue of an active exploration in the course of which they integrate their movements and the corresponding sensory feedbacks over time. Thus, by limiting the sensory input to just a single bit of information at each instant, we oblige the subjects to *deploy their perceptual activity in space and time*; and in this virtual reality situation it is then a simple matter to record and to analyze this activity. This is what we have called 'perceptual trajectories' (see Fig. 7) [30].

Here again and internalist perspective, in terms of the construction of a mental image by proprioceptive integration of the points of contact with the form, is quite impossible. The proprioceptive perception and memory of absolute position is too imprecise for the subject to be able to plot the positions of the hand which holds the effector (mouse, stylus…) in egocentric X-Y coordinates. It is thus quite impossible for the subject to scan the whole field of the screen, and to integrate the points of stimulation in order to construct a mental image of the form. In fact, if the subject inadvertently leaves the contour of the form she is immediately 'lost', and cannot even proprioceptively return to the last point of contact with the form.

Observation of the perceptual activity reveals some behavioural regularities. The subject starts out with large-scale exploratory movements, but as soon as she obtains a contact with a line, she converges to a *micro-sweeping* movement of small amplitude around the source of stimulation. This can be understood as essentially

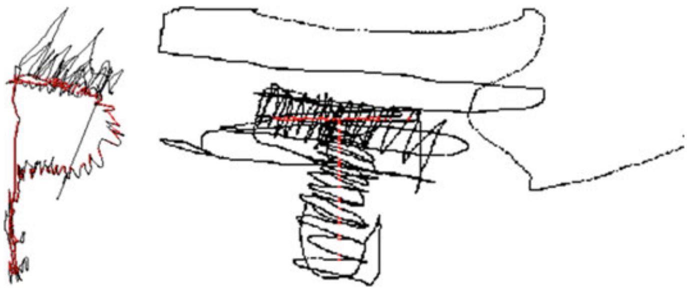


Fig. 7 Two examples of perceptual trajectories in Tactos

an operation of localization: the position of an immobile spatial singularity is *constituted* by a stable anticipation of the tactile stimulus according to the movements of the receptor field. The fact is that the imprecision and drift of the proprioceptive data do not allow their employment for a representation as an internal reconstruction of the form being explored (on the contrary, the proprioceptive system must be continually recalibrated by interactions with the environment). To the extent that there is no direct localization by proprioception in the absolute space of the graphic tablet, we have to admit that the subject's knowledge of her own position is indirect. The micro-sweeping movement enables the subject to identify her own position, not in absolute coordinates but relative to the form that she is exploring and perceiving. The subject situates herself in the allocentric reference frame of the figure she is actively exploring and perceiving: 'I am just a little to the right of the shape, that I just crossed, now I have come back to the left and I am pursuing it', etc. There is thus concomitantly localization of the singularity by oscillating movements, and localization of the movements of the receptor field relative to this singularity. At each instant, the subject situates herself relative to the shape that she is in the course of constituting. The 'viewpoint', i.e. the site from which the object is perceived, is not the finger under which the tactile stimulations are delivered, but the receptor field, because it is on the basis of this site that I define my actions. The place of perception (the cursor) corresponds to the point of action which is situated in the same space as the shape that is perceived.

At a higher level of organisation, the micro-sweeping movements around an initial point of contact are combined with a tangential displacement, following the local direction of the segment of the shape. This *contour following* is the realization of a second-order anticipation which bets on the stability of a temporal frequency of the sensations. However, if this strategy makes it possible to recognize straight or curved segments, it is not yet the recognition of more complex shapes such as letters. The latter only seems to be achieved when the subject is able to combine the gesture of micro-sweeping with a dynamic sequence of different segments which taken together reproduce the shape of the whole. When this is achieved, the receptor field traces the whole shape, with small oscillations and never losing contact.

We can appreciate here that perception is not the reception (and then the representation) of a shape, but rather its active construction. The trajectory is at one and the same time a *recognition* and a *constitution* of the shape. The categorization of perceptual data by integrating them into a known shape is realized by a gesture of *synthesis*. This gesture is like a scheme of construction of the shape, whereby the categories of the understanding apply to the data of sensorial intuition [27, 41]. Here the scheme of 'assimilation' corresponds to a concrete activity, deployed in the space of the movements of the subject. It is achieved by a 'gestural strategy' which produces, via the exteroceptive and proprioceptive sensory returns, a set of chained movements which make it possible at one and the same time to write the shape and to grasp it as a whole, in a single gesture of anticipation. Here, we can truly say that 'reading is writing'. This is indeed exactly what we do when we ask the subject to validate the perceived shape by drawing it free hand; in other words, to reproduce the gesture which directed her exploration. By studying the dynamics of the perceptual trajectories, we thus observe the concrete activity of the constitution of a shape in perception. We could hardly ask for a more telling example of perception as enaction—the bringing-forth of the perceived object—and not as 'representation'.

The perceptual modality instantiated by the Tactos system is indeed 'tactile'—for the reason that there is spatial coincidence between the receptor fields and the perceived shape. It is to be noted that this is independent of the fact that the sensory modality that is used is also that of touch. Indeed, in the case where there is only a single receptor field, it is quite possible to substitute the sensory return by a sound, or even by a flash of light. The perceptual activity would be exactly the same [18]. Thus, the perspective of perceptual supplementation leads us to put into question the classical definitions whereby the various perceptual modalities are *defined* solely by the sensory organ involved.

By reducing the sensory input to a single receptor field (just one bit of information at each instant), we have forced a spatial and temporal deployment of the perceptual activity, which has the advantage of facilitating its analysis. The tool functions here as a system for extracting operations which are habitually realized in the intimacy of the organism. Of course for practical applications there are advantages to restoring a degree of parallelism (with Tactos we routinely use a 4×4 matrix of 16 receptor fields, and in the initial version of the TVSS there were 400 receptor fields). When this is done, we observe an internalization of the perceptual activity: the economy of movement and memory allows for perception which is more rapid and more precise. What is to be noted, however, is that the parallelism of the captors is *formally equivalent* to a movement already performed between the diverse positions of the receptor fields [17, 44, 45]. This is similar to the situation of binocular vision: mobilizing two eyes and extracting the distance of the perceived object by their convergence is formally equivalent to using just one eye and a slight displacement of the head. Indeed this is what we do spontaneously to evaluate the respective positions of two objects by parallax, and this operation is equivalent to the triangulation that we studied in the previous section.

6 Technical Mediations of Perceptual Activity

We consider that the concepts developed above in the case of devices that are deliberately limited and simplified to the extreme can be generalized to the most varied systems of perceptual aids, in particular for better understanding the mechanisms of their appropriation.

6.1 Sensory Modalities and Perceptual Modalities

Following the analyses we have just proposed concerning the transformation of perceptual activity using technical devices, it appears that it is important to distinguish on one hand the ‘sensation’ (i.e. the sensory input delivered to the organism), and on the other hand the ‘perception’ which is specified by the rule which defines, for a given perceptual content, the sensory returns as a function of the actions performed. In completely analogous fashion, in the case of the use of a device for perceptual supplementation, it is important to distinguish on one hand the ‘sensory modality’ being used, which corresponds to the type of sensory input to the central nervous system; and on the other hand, the ‘perceptual modality’ which is defined by the sort of sensori-motor contingency law that the device gives access to. For example, for ‘The Voice’ [34] and the TVSS the sensory modalities that are mobilized are different, respectively auditory and tactile. Nevertheless, for The Voice as for the TVSS, one can say that the *perceptual* modality is basically of a visual type, since both these systems give access to the position and the shape of distant objects (by exploratory actions of translation and rotation). As noted by Grice [23], four criteria are generally used to distinguish between perceptual modalities: sensory organ, nature of the physical stimuli, properties being accessed, qualitative experience (see especially Auvray and Myin [3] for a discussion of the nature of the sensory-substituted experience in light of Grice’s analysis). O’Regan and Noë [37] add the criteria of sensori-motor equivalence, which refers to the type of sensory changes a given type of action produces. To this list, we propose to add the criterion of *proximal-distal organization*, which refers to the type of spatial and functional relations between the perceptual ‘point of view’ and the perceived object. The criterion of proximal-distal organization is of the same kind as the criteria of sensori-motor equivalence, but is focused on a different functional level and aims to account for *phenomenological* differences, more precisely differences in the *spatial content* of perceptual experience: how one situates oneself in space relative to the object being accessed perceptually, where one ‘feels’ oneself to be. Its leading principle concerns the functional difference between proximal and distal perceptual awareness: while *proximal perception* is characterized by the spatial coincidence between one’s ‘point of view’ and the perceived object (in order to perceive the object, one cannot do without being in contact with it), *distal perception* is characterized by a spatial noncoincidence between one’s ‘point of view’ and the perceived object: in order to perceive the object, one cannot avoid occupying a *different* position than the object itself. One noteworthy point is that whereas perceptual modalities can generally be classified as pertaining to one type or the other (distal or proximal), the sensory organ they normally make use of (eyes for vision, ears for audition, skin for touch, etc.) cannot: as demonstrated in an exemplary way by the TVSS case, the skin can be used to enact a distal-type perceptual awareness; conversely, one can make use of the eyes and ears to enact a proximal-type perceptual awareness.

The criterion of proximal-distal organization is especially useful to account for the technical diversity of prosthetic devices. For example, a perceptual modality of the visual type would be defined in purely functional terms as a situation where the point of perception (the point of view) is separate and at a distance from the perceived object. This would involve captors which specify infinite receptor fields, such that their movements are rotations and translations in the three dimensions of space. By contrast, 'touch' could be defined by the spatial coincidence of the site of perception (the receptor fields) and the perceived object. This would involve receptor fields with a finite dimension, and whose movements would be translation with respect to the object.

6.2 The Tool 'in Hand'

Whatever the system of perceptual aid, it is—like any tool which can be taken up in the hand—a device for artificial coupling between the organism and the environment to which it gives access. The new link which it creates, between the actions and the sensory returns delivered to the user, gives rise to the constitution of specific percepts. We find a common principle of functioning with the TVSS, the use of a computer mouse, games in virtual digital spaces, systems of tele-presence or virtual reality… In the case of the TVSS, the coupling between the actions (movements of the camera) and sensations (tactile stimuli) passes through the physical environment. By contrast, in the case of a computer mouse, the coupling between the actions (movements of the mouse) and sensory feedback (movements of the cursor on the computer screen) passes by a digital calculation. But in both cases, once the tool has been grasped and mastered, the tool itself disappears from consciousness in favour of the space of perception and action that it gives access to. The tactile stimuli on the skin and the camera in the hand are both forgotten in favour of the perception of an object 'out there' in a distal space; the computer screen and the movements of the mouse are forgotten in favour of the perception of the cursor and the operations that it makes it possible to perform in the digital space.

In these two examples, the technical mediation highlights features that are actually quite general in the use of tools of all sorts. When I grasp a stick in order to explore the surface of the ground, it is not the stick that I perceive as an object, but the bumps on the ground at the end of the stick. This has been well described by phenomenology: 'The stick of the blind person has ceased to be an object for him, it is no longer perceived as such, the end of the stick has been transformed into a sensitive zone, it augments the range and the scope of action of touch, it has become analogous to vision' [35]. In a similar vein, when I drive a car, I forget for the moment the vibrations of the steering-wheel and the seat, and instead I have the impression that I feel the gravel or the edge of the pavement under '*my* wheels'. These examples can be generalized to all the technical 'appendices' which transform our power of action.

The successful appropriation of a technical device occurs when the user 'becomes as one' with it. The device becomes invisible in the same way that our own body is invisible for use: we see neither our eyes, nor our optic nerves, nor our spectacles (if they are not too dirty!). One observes the same sort of result with other devices of sensory substitution such as the visual-to-auditory substitution systems the vOICe system [2, 3, 34] or the VIBE [25]. A coupling device which is properly appropriated becomes invisible precisely because it enables the subject to see. The invisibility of the lived body and of a tool that is grasped 'in hand' is explained by their constitutive role in perception. Participating in the constitution of the perceived object, they are no longer themselves the object of conscious experience. However, like all tools, they can also be 'put down', separated from the body and hence become again objects of perception. This reversible passage between the 'in hand' mode and the 'put-down' mode can of course be more or less convenient and rapid according to the device in question, from an implant to a pair of spectacles. In the case of the TVSS this passage can be rapid, the device being alternately considered as a perceived object (the blind person pays attention to the irritation produced by the tactile matrix on his skin) or invisible (when the blind person pays attention to the distal objects that the device enables him to constitute). Indeed it is often in this very interplay structured by the reversibility that a technical object takes on its meaning as such [32].

7 Conclusion: Perceptual Supplementation

In the light of these considerations, it seems that the denomination of systems of 'sensory substitution' to designate devices such as the TVSS of Paul Bach y Rita or the Voice of Peter Meijer is awkward and lacks generality. On one hand, we have seen that the conception and design of a system of perceptual aid should not only accomplish a transfer between different sensory modalities, but should also take into account the modes of action that it permits. If there is a 'substitution', it would be better to talk of 'sensori-motor' and not only 'sensory', because the relevant lived experience is not restricted to an analysis of the received sensation, but is rather produced by the complete dynamics of the sensori-motor coupling.

But on the other hand, is it even appropriate to talk of 'substitution'? Whatever the outcome of the debates about the nature of the perceptual experience procured by these devices, it must be recognized and admitted that it does not *replace* that of the absent modality; rather, it offers an original perceptual experience, specific to the repertoires of action and sensory return that are proposed by the device. In order to designate the whole set of devices which modify, enrich or transform perceptual activity, we propose to speak of *Perceptual supplementation* rather than 'sensory substitution'. Indeed, the term *supplementation* has the merit of expressing at one and the same time the act of compensating for a deficiency, and the act of positively expanding or increasing a capacity.

References

1. Auvray M, Hanneton S, Lenay C, Kevin O'Regan (2005) There is something out there: distal attribution in sensory substitution, twenty years later. J Integr Neurosci 4(04):505–521
2. Auvray M, Hanneton S, O'Regan JK (2007) Learning to perceive with a visuo-auditory substitution system: localisation and object recognition with 'the voice'. Perception 36 (3):416–430
3. Auvray M, Myin E (2009) Perception with compensatory devices: from sensory substitution to sensorimotor extension. Cogn Sci 33(6):1036–1058
4. Bach-y Rita P, Collins CC, Saunders F, White B, Scadden L (1969) Vision substitution by tactile image projection. Nature 221:963–964
5. Bach-y-Rita P (1972) Brain mechanisms in sensory substitution. Academic Press, New York
6. Bach-y-Rita P, Kercel SW (2003) Sensory substitution and the human-machine interface. Trends Cogn Neurosci 7(12):541–546
7. Bach-y-Rita P, Kaczmarek KA, Tyler ME (2003) A tongue-based tactile display for portrayal of environmental characteristics. Virtual and adaptive environments, 169–186
8. Bach-y-Rita P (1984) The relationship between motor processes and cognition in tactile vision substitution. In: Cognition and motor processes. Springer, pp 149–160
9. Bach-y-Rita P (2004) Tactile sensory substitution studies. Ann New York Acad Sci 1013:83–91
10. Briscoe, R (2017) Bodily action and distal attribution in sensory substitution. In: Macpherson F (ed) Sensory substitution and augmentation. Proceedings of the British Academy (forthcoming) Consulté le 15 mars 2016. http://philpapers.org/rec/BRIBAA
11. Brooks R (1999) Cambrian intelligence. MIT Press, The Early History of the New AI
12. Cabe PA, Wright CD, Wright MA (2002) Descartes's blind man revisited: bimanual triangulation of distance using static hand-held rods. Am J Psychol 116(1):71-98
13. Collins CC, Bach-y-Rita P (1973) Transmission of pictorial information through the skin. Adv Biol Med Phys 14(1973):285–315
14. Ditchburn RW (1973) Eye-movements and visual perception. Clarendon, Oxford
15. 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(3):275–84
16. Fodor JA, Pylyshyn ZW (1981) How direct is visual perception? Some reflections on Gibson's 'ecological approach'. Cognition 9(2):139–196
17. Gapenne O, Lenay C, Stewart J, Bériot H, Meidine D (2001) Prosthetic device and 2D form perception: the role of increasing degrees of parallelism. In: Proceedings of the conference on assistive technology for vision and hearing impairment (CVHI'2001), pp 113–18
18. Gapenne O, Rovira K, Lenay C, Stewart J, Auvray M (2005) Is form perception necessary tied to specific sensory feedback?. In: Proceedings, 16. Monterey, CA
19. Gibson JJ (1966) The senses considered as perceptual systems. Houghton Mifflin, Oxford, p 1966
20. Gibson JJ (2014) The ecological approach to visual perception: classic edition. Psychology Press

21. Gregory RL (1970) The intelligent eye. Weidenfeld and Nicolson, London
22. Gregory RL (1980) Perceptions as hypotheses. Philos Trans Roy Soc Lond B Biol Sci 290 (1038):181–197
23. Grice HP (1962) Some remarks about the senses. In: Butler RJ (ed) Analytical philosophy (first series). Basil Blackwell, Oxford, pp 248–268
24. Guarniero G (1977) Tactile vision: a personal view. J Vis Impairment Blindness 71(3):125–130
25. Hanneton S, Auvray M, Durette B (2010) The vibe: a versatile vision-to-audition sensory substitution device. Appl Bion Biomech 7(4):269–276
26. Hanneton S, Gapenne O, Genouel C, Lenay C, Marque C (1999) Dynamics of shape recognition through a minimal visuo-tactile sensory substitution interface. In: Third international conference on cognitive and neural systems
27. Kant I (1781) Critique of pure reason. Translated by P. Guyer & A.W. Wood. Cambridge University Press, Cambridge, 1998
28. Lenay C, Canu S, Villon P (1997) Technology and perception: the contribution of sensory substitution systems. Cognitive technology, Los Alamitos, CA. IEEE Computer Society, USA, pp 44–53
29. Lenay C, Gapenne O, Hanneton S, Marque C, Genouëlle C (2003) Sensory substitution: limits and perspectives. In: Hatwell Y, Streri A, Gentaz E (eds) Touching for knowing, cognitive psychology of haptic manual perception. John Benjamins Publishing Company, Amsterdam/Philadelphia, pp 275–92
30. Lenay C, Thouvenin I, Guénand A, Gapenne O, Stewart J, Maillet B (2007) Designing the ground for pleasurable experience. In: Proceedings of the 2007 conference on Designing pleasurable products and interfaces. ACM, New York, pp 35–58
31. Lenay C, Steiner P (2010) Beyond the internalism/externalism debate: the constitution of the space of perception. Conscious Cogn 19(4):938–952
32. Lenay C (2012) Separability and technical constitution. Foundations of science (FOS) Special issue opening up the in-between: interdisciplinary reflections on science, technology and social change, vol 4, pp 379–84. doi:10.1007/s10699-011-9245-8
33. Loomis JM (1992) Distal attribution and presence. Presence Teleoperators Virtual Environ 1(1):113–119
34. Meijer PB (1992) An experimental system for auditory image representations. Biomedical Eng IEEE Trans 39(2):112–121
35. Merleau-Ponty M (1945) Phénoménologie de la perception. Paris: Gallimard, Phenomenology of Perception trans. by Colin Smith (New York: Humanities Press, and London: Routledge & Kegan Paul, 1962); trans. revised by Forrest Williams (1981; reprinted, 2002); new trans. by Donald A. Landes. Routledge, New York, 2012
36. Noë A (2004) Action in perception. MIT press, Cambridge
37. O'Regan JK, Noë A (2001) A sensorimotor account of vision and visual consciousness. Behav Brain Sci 24(05):939–973
38. Pacherie E (1997) Du problème de Molyneux au problème de Bach-y-Rita. *Perception et intermodalite, approches actuelles du probleme de molyneux*, pp 255–93
39. Paillard J (1971) Les déterminants moteurs de l'organisation de l'espace. Cahiers de Psychologie 14(4):261–316
40. Philipona D, O'Regan JK, Nadal JP (2003) Is there something out there? Inferring space from sensorimotor dependencies. Neural Comput 15(9):2029–2049
41. Piaget J (1936) The origins of intelligence in children. Traduit par Margaret Cook et W. W. Norton. vol 8. 5. International Universities Press, New York
42. Segond H, Weiss D, Sampaio E (2005) Human spatial navigation via a visuo-tactile sensory substitution system. Perception 34(10):1231–1249
43. Siegle JH, Warren WH (2010) Distal attribution and distance perception in sensory substitution. Perception 39(2):208–223
44. Sribunruangrit N, Marque C, Lenay C, Gapenne O, Vanhoutte C (2002) Braille box: analysis of the parallelism concept to access graphic information for blind people. In: Engineering in

medicine and biology, 2002. 24th annual conference and the annual fall meeting of the biomedical engineering society EMBS/BMES conference, 2002. Proceedings of the second joint, vol 3, pp 2424–25

45. Sribunruangrit N, Marque CK, Lenay C, Hanneton S, Gapenne O, Vanhoutte C (2004) Speed-accuracy tradeoff during performance of a tracking task without visual feedback. Neural Syst Rehabilitation Eng IEEE Trans on 12(1):131–139
46. Turvey MT, Shaw RE (1979) The primacy of perceiving: an ecological reformulation of perception for understanding memory. In: Wilsson LG (ed) Perspectives on memory research. Lawrence Erlbaum Associates, Hillsdale, N.J., pp 167–222
47. Varela FJ (1979) Principles of biological autonomy. The North Holland series in general systems research 2. Elsevier North-Holland, Inc., New York, 1979
48. Wall SA, Brewster S (2006) Sensory substitution using tactile pin arrays: human factors, technology and applications. Sig Process 86(12):3674–95
49. White BW, Saunders FA, Scadden L, Bach-Y-Rita P, Collins CC (1970) Seeing with the skin. Percept Psychophys 7(1):23–27
50. Ziat M, Lenay C, Gapenne O, Stewart J, Ammar AA, Aubert D (2007) Perceptive supplementation for an access to graphical interfaces. In: Universal access in human computer interaction. Coping with diversity. Springer, New York, pp 841–50

Springer
http://www.springer.com/978-3-319-54444-1

Mobility of Visually Impaired People
Fundamentals and ICT Assistive Technologies
Pissaloux, E.; Velazquez, R. (Eds.)
2018, XIX, 652 p. 160 illus., 109 illus. in color.,
Hardcover
ISBN: 978-3-319-54444-1